

**AN INTEGRATED PROGRAMME**  
**FOR POWER SYSTEMS SIMULATION**  
**USING**  
**PERSONAL COMPUTERS (PC'S)**

**BY**

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**THESIS PRESENTED IN FULFILMENT OF THE REQUIREMENTS FOR THE  
MASTERS DIPLOMA IN TECHNOLOGY AT THE CAPE TECHNIKON**

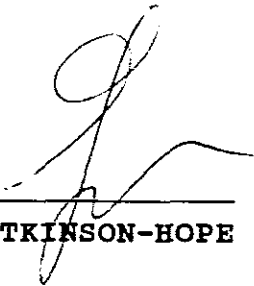
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**JUNE 1993**

DECLARATION

I hereby declare that the work for this thesis was done by myself, that I wrote it myself and that it has not been submitted to any other educational institution in order to obtain a qualification.



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G. ATKINSON-HOPE

JUNE 1993

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## ABSTRACT

The research objectives were to:

Formulate a training structure covering conventional power systems topics;

Research existing PC based power systems software resources;

Develop a structure for a PC based power systems course;

Research the capabilities of the software resources chosen;

Develop a structure for a modern PC based power systems course taking into account the capabilities and limitations of the selected software programs;

Develop for the PC based power systems course, task orientated computer based laboratory set-ups.

The set-ups provide:

An introduction into the topics concerned;

An explanation of the usage of each program applied, where usage means an explanation of the Input and Output Data of each program;

User friendly simulation experiments.

These set-ups, together with software programs and a personal computer integrate into a training programme and realize a power systems simulation course.

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## **1. INTRODUCTION**

### **1.1 EXPOSURE TO POWER SYSTEMS**

In general power systems students, technologists and engineers have few chances to understand the complex principles of power systems through direct exposure.

It is however very important for these persons to obtain exposure to the advanced technology involved in analysing, designing and controlling of power systems.

### **1.2 NEED FOR A COMPUTER BASED TRAINING PROGRAMME**

There is wide consensus that electric power systems laboratory experience is vital in the education of electrical technologists and engineers. (Krein,1992).

Power systems are physically too large to lend themselves to laboratory experimentation. (Alden,1988). Where direct experimentation is done on these large power systems the experimenting may be expensive, time consuming or dangerous. Traditionally in a power systems course, use has to be made of field trips to substations, generating stations, control rooms, etc, to provide exposure to some of the relevant parts of the real world of power systems. It is therefore not practical nor is it possible to borrow a total existing power system for testing purposes. (Cegrell, 1986). Simulation by computers helps to a certain extent to overcome these drawbacks.

A need therefore exists for the development of a computer based training programme in power systems, where the programme will serve to bridge the gap between theory and practice.

### **1.3 EXPLANATION OF THE TITLE**

#### **1.3.1 INTEGRATION**

Integration means a learning environment in which a learner not only learns theoretical knowledge but also learns how to apply knowledge. In such an environment a learner can use multisensory channels (visual, audio, hands-on) and multifaceted media (video, voice, speech, music, graphics, image, text, animation) to shape a more complete knowledge base. (Chiou,1991).

Computer simulation in terms of this dissertation, will mean a computer based learning environment.

#### **1.3.2 SIMULATION**

Computer simulation is a numerical technique for conducting experiments with certain types of mathematical models which describe the behaviour of a complex system on a digital computer. (Geerdts, 1987).

From this definition, simulation is an exercise in advance before implementing a real life situation.

For the purpose of this dissertation, simulation means imitating conditions creating a likeness to a real power system.

### 1.3.3 PROGRAMME

In terms of this dissertation programme means a PC based power systems training course. The programme uses hardware, software programs and a series of integrated experiments. Together they combine as a tool and train users to analyse and design power systems by simulation.

### 1.4 AIMS AND SCOPE OF THIS DISSERTATION

#### 1.4.1 RESEARCH OBJECTIVES

- a. Formulate a structure covering conventional power systems topics.
- b. Research existing PC based power systems software resources.
- c. Develop a structure for a PC based power systems course.
- d. Research the capabilities of the software resources chosen.
- e. Develop a structure for a modern PC based power systems course taking into account the capabilities and limitations of the selected software programs.
- f. Develop for the course, computer based laboratory set-ups which are user friendly and modular.
- g. To gear the programme mainly at Technologists but also at others with similar backgrounds.

#### 1.4.2 SCOPE OF DISSERTATION

The research will assess the current problems linked with the use of existing power systems software resources. The specific purpose will be the rapid assimilation of the characteristics and features of electrical distribution/transmission networks and multi-bus power systems. The research will be directed at but not limited to the specific needs of Technologists. It will be geared at fifth and sixth semester Technikon students/graduates and to those of similar backgrounds. The classical analytical methods of mathematics as used for hand calculations will be introduced and it will be shown how simulation software can replace such time consuming manual calculations. (Gungor,1988).

The programme will therefore address a wide range of common power systems topics and computer based laboratory set-ups for these topics will be prepared.

## 1.5 PC AS A LEARNING MEDIUM

### 1.5.1 ROLE OF THE COMPUTER

Its duty is to provide information which is instructionally sound and is logically well organised. Since it is difficult to be physically situated in every real world learning environment, the question is how can we model the real-world into a medium/learning environment and let the learners feel that they are situated in that very environment. Using the PC as a learning medium, the focus is on the PC screen and the challenge for simulated programme writers is how to make sure that it will support effective understanding. The challenge must be to create a situated learning environment. (Chiou,1992). The role of the tutor is also decreased. The PC thus delivers information and aids learning. The PC keeps track of information as one progresses through a task. It thus removes some of the tedious and time-consuming chores from the task. The PC can do complex mathematical computations quickly and accurately and can provide an environment conducive to learning. It can enhance the rate of learning by providing an integrated programme. (Geerdts,1987).

### 1.5.2 ADVANTAGES OF SIMULATION

Leading power system authors are convinced of the necessity for simulation studies and have included software programs with their textbooks. (Glover, 1987), (Gungor, 1988) and (Wollenberg, 1984). Likewise there are leading firms specialising in this simulation field. This having come about from the need of industry. (Bengiamon, 1992).

Simulation is used to extend classroom instruction. Theory is first studied and then to get a more realistic view students use simulation. Simulation is seen as a good complement to a course as well as providing a link between theory and practice. Moreover once basic computational skills have been mastered, students can put emphasis on understanding engineering concepts rather than spending hours in tedious calculations.

It is a useful complement to laboratory work. Simulation is a third way of learning besides theory and physical hands-on. It is practical but not physical. It prepares a student to adapt to the industrial environment. It also improves education.

It enhances motivation and interest. When interacting, for example, with a power system via simulations, one experiences and sees the effects of parameter changes. Simulation provides opportunities for learning in much the same way as ordinary laboratory work. (Geerdts, 1987).

The main focus of this dissertation is to achieve the above mentioned advantages.

## 1.6 WRITING OWN PROGRAMS VERSUS USING EXISTING SOFTWARE

Because software development for power systems analysis and design is difficult and extremely time-consuming, the question is should educators develop their own instructional software rather than purchase existing commercial packages? As power systems programs are the result of many many hours of effort it seems that the task should be left to professional teams made up of instructional developers, content specialists, professional computer programmers, whose combined expertise would enable production of a product genuinely worthy of use. (Maddux, 1992).

In the authors opinion there is a greater need at present in providing computer based laboratory set-ups which show how to use and apply power systems programs in a user-friendly manner and to enhance learning and to bridge the gap between theory and practice. It is for this reason that the author has undertaken this research. (See Appendices).

## CHAPTER TWO

### 2. DEVELOPMENT OF A STRUCTURE FOR A PC BASED POWER SYSTEMS COURSE

#### 2.1 FORMULATION OF A STRUCTURE COVERING CONVENTIONAL POWER SYSTEMS TOPICS

##### 2.1.1 CONVENTIONAL POWER SYSTEM STUDIES

Before developing a structure for a PC based power systems course, it was firstly necessary to ascertain what topics are currently being covered in modern power system courses.

To ascertain these topics reference was made to sources written by well known authors in this field, namely:

##### a. ELEMENTS OF POWER SYSTEM AND ANALYSIS: (Stevenson, 1982).

This textbook covers a broad range of power system topics. The four main topics are load flow, economic dispatch, fault calculations and system stability. The author retained transmission line parameters and steady-state operation of transmission lines and added the bus impedance matrix and system protection.

##### b. IEEE RECOMMENDED PRACTICE FOR INDUSTRIAL AND POWER SYSTEM ANALYSIS: (IEEE, 1976).

From this the most common power system studies which are performed are load flow analyses, short circuit studies, motor starting studies, reliability analysis studies, harmonic analysis and grounding studies.

##### c. MODERN POWER SYSTEM ANALYSIS: (GÖNEN, 1988).

It refers to an electric power system as being large and complex and its main components (or subsystems) are the generation system, transmission system and the distribution system. These three systems are the basis of the electric power industry. This text is unique in that it is written specifically for an in-depth study of the modern power transmission subsystem. The book includes topics on transmission line parameters, steady-state performance of transmission lines, symmetrical components and sequence impedances, balanced and unbalanced faults, load flow and system protection.

##### d. ELECTRICAL POWER SYSTEMS: (WADHWA, 1991).

This book covers conventional topics like line constants, performance of lines, load flow studies, economic load dispatch, symmetrical components and fault calculations and power system stability.

**e. COMPUTER ANALYSIS OF POWER SYSTEMS: (ARRILLAGA, 1990).**

The book describes the main computer modelling techniques that have gained universal acceptance and which constitute the basic framework of modern power system analysis. It prescribes a basic knowledge of power system theory, matrix analysis and numerical techniques. The book covers three phase and AC-DC loadflow, fault studies, stability, transients and harmonic propagation. It discusses a "package" which is already being used in undergraduate laboratory exercises in New Zealand.

**2.1.2 POWER SYSTEM STUDIES WITH PC APPLICATIONS**

**a. POWER SYSTEM ANALYSIS AND DESIGN: (GLOVER, 1987).**

The objective of this book is to present methods of power system analysis and design particularly with the aid of a personal computer.

A computer software package "POWER" including a set of programs stored on a floppy disk and a user's manual accompanies this text. All programs run on PC's.

The topics covered are symmetrical components, transmission line parameters, steady-state operation of transmission lines, power flows, fault studies, electromagnetic transients and transient stability.

**b. POWER SYSTEMS: (GUNGOR, 1988).**

This book provides a solid foundation in classical methods and modern techniques in power system engineering.

Personal computer programs are provided which support the academic content of the textbook. These academic programs introduce a student to the manner in which computers are used in power systems and can serve to bridge the gap into industrial grade programs. They are included as a tool to enhance learning and to show how time-consuming hand calculations can be done quicker and accurately by a computer.

The book covers transmission line constants, steady-state transmission lines (two port) and multinode representation emphasizing Ybus and Zbus matrices, load flow, economic operation, symmetrical components and fault studies and power system stability.

**c. POWER GENERATION OPERATION & CONTROL: (WOLLENBERG, 1984).**

The purpose of this text is to introduce a number of engineering and economic matters involved in planning, operating and controlling power generation and transmission systems in electric utilities. It is intended for post graduate students.

The book covers, among others, economic dispatch, load flow and state estimation.

Software programs for use with this book are available.



**2.1.3 STRUCTURE OF TOPICS FOR A CONVENTIONAL POWER SYSTEMS COURSE**

From the above the modern core topics of power systems are:

NO.	CONVENTIONAL POWER SYSTEM TOPICS
a.	Matrix Analysis
b.	Line Parameters
c.	Steady-State Operation of Transmission Lines. (Two port)
d.	Ybus and Zbus Matrices (Multi-bus Representation)
e.	Load Flow
f.	Symmetrical Components and Sequence Networks
g.	Fault Studies
h.	Stability studies
i.	Economic Dispatch
j.	Motor Starting Studies
k.	Harmonic Analysis
l.	Grounding Studies
m.	Electromagnetic Transient Analysis
n.	State Estimation

TABLE 2.1

As it is the intention to develop a PC based power system course it was necessary to research software programs and to ascertain whether they cover these modern core topics.

**2.2 PC BASED SOFTWARE PROGRAMS RESEARCHED**

The following existing software resources were researched:

**2.2.1 THE "POWER" PACKAGE (GLOVER, 1987) .**

The software package can be run on an IBM PC or any compatible PC. The package comprises of 9 programs:

NO.	POWER PACKAGE - PROGRAMS
1	MATRIX OPERATIONS
2	SYMMETRICAL COMPONENTS
3	LINE CONSTANTS
4	TRANSMISSION LINES - STEADY-STATE OPERATION
5	POWER FLOW
6	SYMMETRICAL SHORT CIRCUITS
7	SHORT CIRCUITS
8	TRANSMISSION LINE - TRANSIENTS
9	TRANSIENT STABILITY

TABLE 2.2

The general capabilities of the programs are:

### 1. MATRIX OPERATIONS

This program computes sums or products of real and complex matrices. It inverts and transposes real and complex matrices and computes the complex conjugate of a complex matrix.

### 2. SYMMETRICAL COMPONENTS

This program contains three symmetrical component sub-routine programs, namely:

- SEQVEC - This computes the complex sequence vector  $V_s$  &  $I_s$
- PHAVEC - This computes the complex phase vector  $V_p$  &  $I_p$
- SEQIMP - This computes the complex sequence impedance matrix  $Z_s$

### 3. LINE CONSTANTS

This program computes the series impedance and shunt admittance matrices of overhead single and double circuit three phase transmission lines. The program also computes the strength of the electric field at the surface of the phase conductors and computes the ground-level electric field strength and plots its profile.

### 4. TRANSMISSION LINES STEADY-STATE OPERATION

This program computes the ABCD parameters and equivalent  $\pi$  circuit values for a single phase or completely transposed three phase transmission line. The program also computes the sending end quantities, voltage, current, real, reactive and apparent powers, and power factor for a given receiving-end load, with or without compensation. Voltage regulation and maximum power flow are also computed. It also computes the propagation constant, wavelength and surge impedance loading.

### 5. POWER FLOW

This program computes the voltage magnitude and phase at each bus in a power system under balanced three phase steady-state operation. Bus voltages are then used to compute generator, line and transformer loadings. The program also provides for four bus types (a swing bus, a load bus, a voltage controlled bus and for a voltage controlled bus with a tap-changing transformer). Fixed transformer tapplings can also be selected. The program uses the Newton-Raphson iterative method for solving the power flow.

### 6. SYMMETRICAL SHORT CIRCUITS

This program computes the symmetrical fault current for a bolted three phase short circuit at any bus in an N-bus power system. It also computes contributions to the fault current from synchronous machines, transmission lines and transformers connected to the faulted bus. It also computes the bus voltages during the fault as well as the positive sequence bus impedance matrix.

### 7. SHORT CIRCUITS

This program computes for an N-bus power system, balanced 3 phase faults, single line-to-ground faults through a fault impedance, line-to-line faults through a fault impedance or a double line-to-ground fault through a fault impedance. It also computes contributions to the fault current from synchronous machines, transmission lines and transformers connected to the faulted bus and the bus voltages during the fault as well as the zero, positive and negative sequence bus impedance matrices.

### 8. TRANSMISSION LINE TRANSIENTS

This program computes voltage transients for a single phase circuit.

### 9. TRANSIENT STABILITY

This program computes machine power angles and frequencies in a 3 phase system subjected to disturbances. It also computes machine angular accelerations, machine electrical power outputs and bus voltage magnitudes. Before running this program it is first necessary to run the "POWER FLOW" program.

#### 2.2.2 THE "GUNGOR" PACKAGE (GUNGOR, B.R. 1988):

The package comprises of 15 programs:

NO	GUNGOR PACKAGE - PROGRAMS
1	Real equations/real matrix inversion (SIMAT)
2	Delta-Star, Star-Delta conversion (YDELTA)
3	Complex matrix inversion (CMINV)
4	Complex simultaneous equations (COSIME)
5	Line printer/plotter (PLOT)
6	Formation of bus matrices (ZYBUS)
7	Formation of bus matrix (ZBUS)
8	Transmission line operation (TRLIN)
9	D.C. power flow (DCPF)
10	A.C. power flow - Gauss-Seidel (ACPF1)
11	A.C. power flow - Newton-Raphson (ACPF2)
12	Three phase short circuit (SHORT3)
13	Single phase to ground short circuit (SHORT1)
14	Real power optimisation (REOP)
15	Transient stability (TRST)

TABLE 2.3

The general capabilities of the programs are:

1. SIMAT

This program will solve a set of real simultaneous equations of the form  $AX = b$ . It also inverts a real matrix, for example:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

where the elements of the matrix are real numbers.

2. YDELTA

This program will convert star impedances ( $Z_1, Z_2$  and  $Z_3$ ) into delta impedances ( $Z_A, Z_B,$  and  $Z_C$ ) and delta impedances into star impedances. For entering, impedances must be in rectangular form. The output impedances (star or delta) is also computed only in rectangular form.

3. CMINV

This program will invert a complex matrix, for example:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

where the elements of the matrix are in rectangular form.

4. COSIME

This program will provide a solution for a set of complex simultaneous equations by Gauss reduction method. The complex elements must be in rectangular form. The output is a list of complex variables also in rectangular form.

5. PLOT

This program will print or plot or print and plot 5 curves (all functions of the same variable) with same scaling, for example:

X1 against T, X2 against T, up to X5 against T. T is plotted on the vertical axis and X1 to X5 on the horizontal axis. The symbols used to plot X1 to X5 are . + \* - 0.

6. ZYBUS

This program will form a Ybus matrix of a power system from line impedance data and invert a Ybus to obtain a Zbus, then invert a partitioned Zbus to produce a YEQ. Positive, negative and zero sequence bus impedance matrices are also obtainable. (See Section B, Appendix E for more details).

7. ZBUS

This program will form the Zbus matrix of a system directly from the system data. (See Section B, Appendix E for more details).

8. TRLIN

This program relates to the steady-state operation of transmission lines. The input to the program consists of length, resistance, inductive reactance, shunt susceptance, sending-end voltage, receiving-end voltage and initial, final and incremental values of the receiving-end power and power factor. The program then identifies the line as a short, medium or long line and computes the "A" and "B" parameters for the line. It then proceeds with the calculations for Vr constant, Vs constant or both constant for an initial Pr, and increments and repeats the calculations up to a maximum specified Pr (calculated when either Vs alone or both Vr and Vs are constant. Calculated values are printed for each Pr and plots are produced as desired. Typical plots are Vs versus Pr for constant Vr. Vr versus Pr for a constant Vs and PF versus Pr with Vs and Vr constant

9. DCPF

This program will provide a D.C.(linearized) power flow solution for a system. (See Section 1c, Appendix F for more details)

10. ACPF1

This program will provide an A.C. power flow solution of a power system using Gauss-Seidel iterations with voltage controlled generator buses. (See Section 1a, Appendix F for more details).

11. ACPF2

This program will provide an A.C. power flow solution of a power system using Newton-Raphson iterations. There are no voltage controlled buses other than the swing bus. (See Section 1b, Appendix F for more details).

12. SHORT3

This program will calculate the fault currents and the line flows of a power system for a 3-phase symmetrical fault (A-B-C) at one or more buses. The 3-phase short circuit can be a zero impedance fault or it can be faulted through reactances. The bus voltages of the faulted system is also computed. The input requires results from an AC power flow solution, as well as a bus impedance matrix, and the system line data. The input must be in per-unit on a 100 MVA base.

13. SHORT1

This program will calculate the fault currents and the line flows of a power system for a line-to-ground (a-g) fault at one or more buses. The fault can be bolted (metallic) or through a reactance. The bus voltages of the faulted system is also computed. The input requires an AC power flow (ACPF1 or ACPF2) solution, as well as the positive-sequence and zero-sequence bus impedance matrices and the line data. The input must be in per-unit on 100 MVA base.

14. REOP

This program relates to the economic operation of a power system and will optimize real power by using a loss formula based on the so-called B-coefficients. The optimization problem is one of minimising the cost of operation under the constraints imposed on various system quantities.

15. TRST

This program is a transient stability program. It follows the step-by-step procedure used for hand calculations, for a system with a generator connected to an infinite bus through two transformers (both Y-grounded) and two parallel lines with different reactances. A three phase fault at five locations or a one-phase fault at three locations can be simulated with two switching operations. The calculated swing curve (time versus power angle) can be plotted.

2.2.3 THE "NETWORK MATRIX" PROGRAM: (AUBURN, Department of Electrical Engineering, Virginia Polytechnical Institute)

The software program is called "NETWORK MATRICES" and its general capabilities are that it will build both Bus Admittance and Bus Impedance matrices for a multi-bus power system. It can build either a Ybus or a Zbus directly but separately or it can build both simultaneously. It can also compute Positive or Zero Sequence Bus Admittance/Bus Impedance matrices for multi-bus networks.

The program is IBM PC compatible.

2.2.4 THE "SYMCOMP" PROGRAM: (ESKOM WCR, 1991 Ver. 0.1).

The general capabilities of this program is that it computes and displays in colour on the PC screen the positive, negative and zero sequence components of assymetrical voltages and currents as phasor diagrams, using red, yellow and blue colours as phasor legs on each diagram. The program is IBM PC compatible.

2.2.5 THE "WOLLENBERG" PROGRAMS: (WOOD, A.J. & WOLLENBERG, 1984).

The programs are IBM PC compatible and have the following general capabilities:

(1) THE "LOADFLOW" PROGRAM

This program solves load flows by Gauss-Seidel or Newton-Raphson algorithms. It computes bus voltage magnitude and angle, MW and MVAR generation, MW, MVAR and MVA flows, Total MW and MVAR generation, Total MW and MVAR load, Total  $I^2R$  MW losses, Total  $I^2X$  MVAR losses and Total charging MVAR.

(11) THE "ECONOMIC DISPATCH" PROGRAM

This program allows a user to experiment with two commonly used economic dispatch solution algorithms (lambda search or table lookup) using three different generation heat rate or incremental heat curve representations. It computes the lambda limits, then for each generator the MW output, the incremental cost (\$/MWhr), the penalty factor, the operating cost, the Total MW generated and the lambda value providing the economic dispatch solution.

**2.2.6 THE "ROETTGER" PROGRAMS: (ROETTGER ENG. SOFTWARE CO., USA).**

The programs are IBM PC compatible and have the following general capabilities:

(1) "EZ FLOW" PROGRAM

This program is a PC based interactive load flow program with graphic capabilities. It utilizes the Gauss-Seidel solution technique. The program can accommodate voltage controlled buses, fixed tap transformers and branch line charging. The loads can be modelled as either constant MVA and/or constant impedance. Bus over voltage and under voltage are flagged as are branch overloads. A total of 250 buses and 600 branches can be modelled. It has capabilities for both loop and radial systems. The branch data can be in ohm/unit length or per unit. The graphic output is not a complete single line of the entire system, just one bus at a time.

(11) "EZ FAULT" PROGRAM

This program is a PC based interactive program with graphic capabilities. The program is used mainly to calculate the three phase short circuit level at each bus. It also displays the post fault voltages of all buses directly connected to the faulted bus along with the corresponding fault contribution through that particular branch. The program can also be used to calculate line-to-ground fault current levels by running twice, once with the positive sequence network and then with the zero sequence network. A hand calculation must then be used to find the ground fault current magnitude. A total of 169 buses and 600 branches can be modelled. It has capabilities for both loop and radial systems. The branch data can be in ohm/unit length or per-unit. The graphic output is not a complete single line diagram of the entire system, just one bus at a time.

**2.2.7 THE "ETAP" PACKAGE: (OPERATION TECHNOLOGY INC., USA Ver 6.52 1993).**

It's name is "Electrical Transient Analyser Program" and is IBM PC compatible.

The ETAP package is accompanied with a very comprehensive "User Guide". The manual is written to provide instructions on how to use ETAP and it is comprehensive.

ETAP is a user friendly, menu driven, Integrated Software Package of sophisticated computer programs designed to assist in the design and analysis of power systems.

The author had the opportunity of attending a one week workshop on ETAP at Operations Technology Incorporated, in the USA during November 1992.

The workshop showed how to use the package. The sophistication of the Input Data reflects the wide range of variables with which an engineer needs to deal with when analysing and designing power systems.

The leading feature of the Package is its Library. The library includes manufactures data of common component parts found in power systems, for example, synchronous machines, induction motors, transformers, cables etc. The parameters and operating curves are stored in the library and can be accessed when modelling a system. This saves entering time and reduces errors. The library can be added to or subtracted from if necessary.

Once a system has been modelled, the package includes a program for drawing and displaying a ONE-LINE DIAGRAM. Analysis can then be done to check design adequacy. If inadequate an alternative can be selected from the library and substituted until the required constraints are met.

An impressive feature of the package is that it includes and meets IEEE/ANSI/NEC standards for the design of high voltage systems. The package therefore includes internationally accepted practical multiplying factors as provided by these standards, to ensure design adequacy.

The package has outstanding colour graphics, for example, starting curves, stability curves, ground grid design of substations etc.

It has the following programs:

NO	ETAP PACKAGE - PROGRAMS
1	LOADFLOW
2	SHORT CIRCUIT
3	MOTOR STARTING
4	TRANSIENT STABILITY
5	LOAD SCHEDULE
6	OVERALL ONE LINE DIAGRAM
7	DETAILED ONE LINE DIAGRAM
8	PROTECTION COORDINATION

TABLE 2.4



The programs have the following general capabilities:

#### **1. LOAD FLOW PROGRAM**

The load flow program calculates the bus voltages as well as branch power factors, currents and power flows throughout the electrical system. The results are presented in an easy to follow format which can be used to determine feeder capacity, capacitor rating, system voltage profile, steady-state stability limits, transformer rating and tap setting, current limiting reactor rating and total power loss demand. ETAP allows for regulated (generation) and unregulated (load) buses and multiple utility (swing buses). Each bus can have any combination of motor load (constant kVA type) and static load (constant impedance type) such as lighting, shunt reactors/capacitors.

#### **2. SHORT CIRCUIT PROGRAM**

The short circuit program analyses the effect of three phase, line-to-ground, line-to-line and line-to-line-to-ground faults on the electrical system. The program calculates the fault current contributions of individual motors, generators and utility ties in the system. The program calculates the momentary fault current, the interrupting fault current and the fault current after 30 cycles.

#### **3. MOTOR STARTING PROGRAM**

ETAP provides two methods for motor starting; quick design and full study. The quick design approach allows you to start a new motor (one which is not modelled in your ETAP database), on any bus in the system. This method provides a snapshot solution which calculates the voltage profile of the entire system before starting and at the moment of starting as well as the reduction in starting torque. This approach allows one motor at a time to be started. The full study allows existing motors (which are already defined in your database) to be started (with either a snapshot solution or a full acceleration study. This method allows up to 50 motors to be started during the study, and provides for 12 time events to be specified when each motor should be started during the simulation.

#### **4. TRANSIENT STABILITY PROGRAM**

ETAP simulates the dynamic (transient) behaviour of the electrical system during and after sudden changes or disturbances such as faults, load/generator rejection, switching events and impact loading. The effects of these changes or disturbances on the system voltages, frequencies, power angles and motor slips can be tabulated or plotted for determining protective system setting, load shedding requirements, frequency and out-of-step relay settings.

## 5. LOAD SCHEDULE PROGRAM

The package includes a load scheduling program making it a very powerful package for system modelling. Actual curves of machines and their loads are modelled together, the load curve being superimposed onto a motor curve for operating point determination, and this is done for all motors at a particular bus including static loads, such that these are lumped together and modelled as one per unit value of P and Q for a particular bus. All other buses are done on a similar manner. These are then transferred to the one-line-diagram and analysis follows. An analysis can then be done under starting conditions, under steady state conditions and fault conditions.

## 6. OVERALL ONE-LINE DIAGRAM PROGRAM

This program automatically generates a true one-line diagram of the electrical system. It is compatible with CAD platforms. Load flow and/or short circuit results can be included on the diagram.

## 7. DETAILED ONE-LINE DIAGRAM PROGRAM

This program works directly with the Load Schedule program. For a specified bus number, this module reads the data for all the load items associated with that bus (specified in Load Schedule) and creates a detailed one-line diagram.

## 8. PROTECTION CO-ORDINATION

This is a Protective Device Co-ordination program called TC Curve. It is a sophisticated extension for ETAP short circuit results. It has a library of relay curves and creates one-line diagrams

## 2.3 SUITABILITY AND COST OF PACKAGES OR PROGRAMS RESEARCHED

### 2.3.1 BRIDGING SOFTWARE VERSUS INDUSTRIAL GRADE SOFTWARE

From the general capabilities of the above programs researched it became apparent that the following are ideal bridging gap software programs, useful for bridging between theory and practice:

- a. The "Glover" power package (2.2.1)
- b. The "Gungor" package (2.2.2)
- c. The "Auburn" network matrix program (2.2.3)
- d. The "Eskom" Symcomp program (2.2.4)
- e. The "Wollenberg" program (2.2.5)

and that the following are inclined towards industrial grade programs.

- f. The "Roettger" programs (2.2.6)
- g. The "ETAP" programs (2.2.7)

2.3.2 COST OF PACKAGES OR PROGRAMS RESEARCHED

NAME OF PACKAGE OR PROGRAM	APPROXIMATE SINGLE COPY PRICE PER PACKAGE OR PROGRAM
POWER	R300-00
GUNGOR	R200-00
AUBURN	R200-00
SYMCOMP	R200-00
WOLLENBERG	R200-00
ETAP *	R6016-00
ROETTGER *	R7680-00
TOTAL COSTS = R14796-00	

TABLE 2.5

Textbooks back the Power, Gungor, Auburn and Wollenberg packages/ programs. It is not always automatic that when purchasing these textbooks that software packages/programs are included in the price of the textbook. This is a block for teaching based only on academic software.

Approximate costs are given as the prices depend upon the exchange rate.

\* Special discounts are available to educational institutions and site licences can also be arranged.

## 2.4 STRUCTURE FOR A PC BASED POWER SYSTEMS COURSE

### 2.4.1 TREE STRUCTURE OF PC BASED POWER SYSTEMS COURSE

The author of this dissertation decided on the basis of the research done that his PC based course should have the following structure:

**TREE STRUCTURE  
OF  
PROGRAMS**

#### PC BASED COURSE STRUCTURE

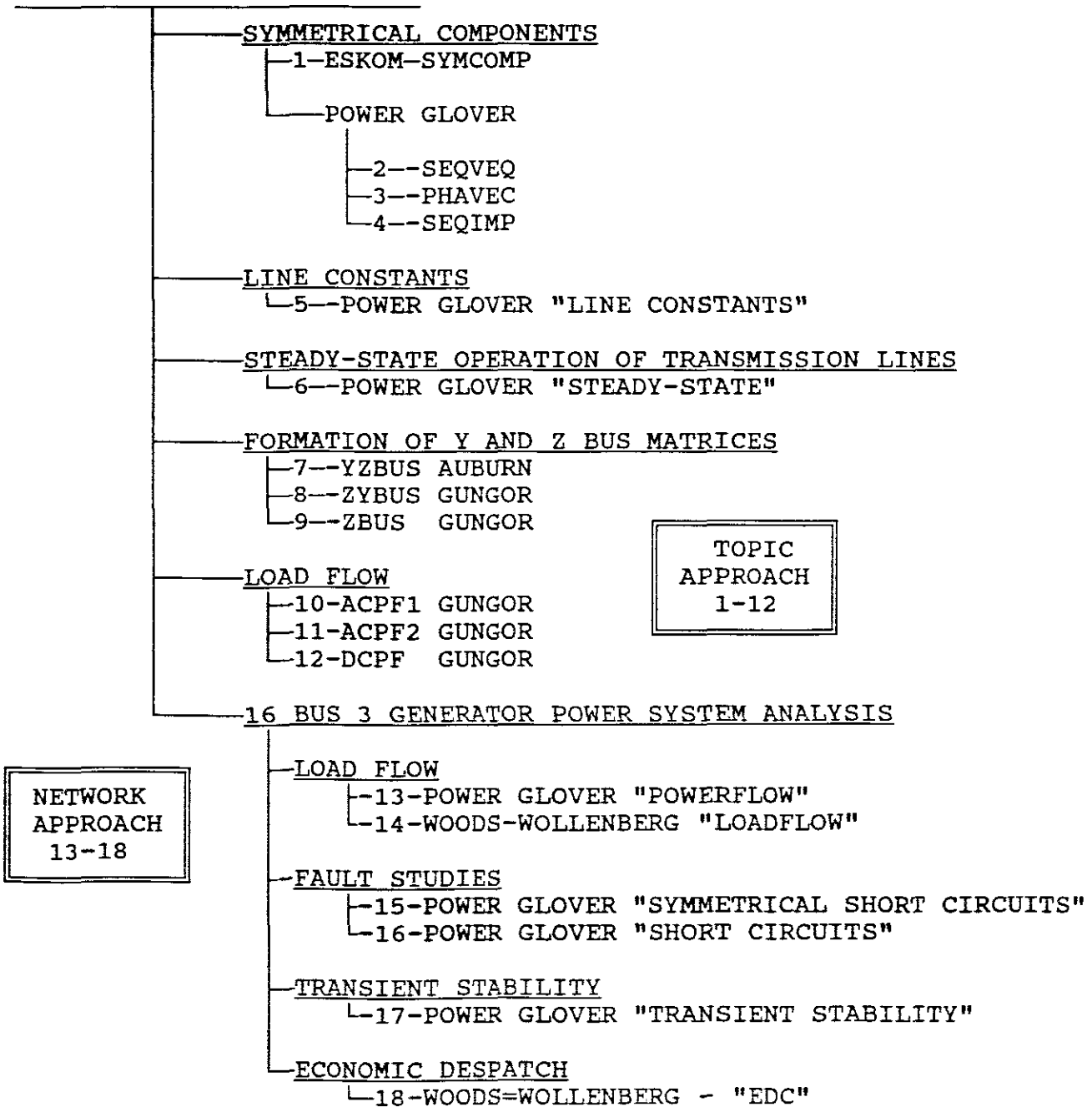


FIGURE 2.1

The reasons for the above structure is now explained.

## 2.5 REASONS FOR THE STRUCTURE

### 2.5.1 LOW COST - TOTAL SOFTWARE COSTS

The structure chosen uses available low cost software programs.

From Figure 2.1 the approximate Total Software Costs for the PC based course will be:

NAME OF PACKAGE OR PROGRAM	APPROXIMATE TOTAL SOFTWARE COST FOR PC BASED COURSE
POWER	R300-00
GUNGOR	R200-00
AUBURN	R200-00
SYMCOMP	R200-00
WOLLENBERG	R200-00
TOTAL COSTS = R1100-00	

TABLE 2.6

From Table 2.5 the total software costs equal R14796-00.

In terms of the total costs of Table 2.5, the R1100-00 represents only 7.43%. The Roettger and ETAP packages making up 92.56% of the total costs.

This total cost is the cost per single user. The software cost per each user of this programme would thus be R1100-00 if purchased individually.

If, for example, there are 20 students following this program the cost would be 20 times R1100-00 = R22000-00.

Each student would then be the owner of the software he has purchased. The software programs would be like textbooks. Students could bring them to their place of learning (e.g. Technikon or industry) and make use of them at home.

If on the other hand the programs are installed on a network at the place of learning only, the cost for the 20 students may be less than R22000-00 as only single copies of each program need to be purchased. However "site licenses" would have to be paid. A cost saving may be made by using a network but the costs would be carried by the programme organisor and not by the student. A network has the disadvantages that home studies and distance learning are excluded. Also the portability of the programme would be hindered.

It can therefore be seen that the course chosen has an advantage of being a low software cost structure.

### 2.5.2 BRIDGING COURSE

Another reason for this structure is to provide a bridging course into power systems in industry and into industrial grade software programs/packages.

As topics "a" to "i" in Table 2.1 are considered the minimum topics which should be covered in an introductory power systems course, they have formed the core of the PC based course covered by this dissertation.

The software chosen (Figure 2.1) adequately covers these topics. If good software is not backed by a good curriculum which it exploits it will fail. (Geerdts,1987).

The remaining topics and others could form the basis for future research.

### 2.5.3 SEQUENTIAL COURSE STRUCTURE

"Sequential" is defined as meaning "forming a sequence" or a "set of things one after another belonging next to one another".

The sequential structure chosen (Figure 2.1) commences with symmetrical components and is followed by Line Constants, Steady-State Operations of Transmission Lines, Formation of Y and Z bus matrices, Load flow, Fault studies, Transient Stability and Economic Dispatch.

As Line Constants(App.C), Ybus/Zbus Formation(App.E) and Fault Studies(App.G) make use of +,- and zero sequence impedances, symmetrical components(App's.A & B) are used to introduce the course.

### 2.5.4 TOPIC VERSUS NETWORK APPROACH

The structure in Figure 2.1 is divided into a Topic and Network Approach stage:

**TOPIC APPROACH**

Software programs 1 to 12 being used for the topic stage. During this stage each individual program is taken and the topic in question is applied to different networks (e.g. 3bus, 5bus, 7bus power systems etc.)

The Topic Approach therefore uses different size networks and serves as introductory background.

**NETWORK APPROACH**

Software programs 13 to 18 being used for the network stage. During this stage each individual program is applied to a single network (16 bus power system).

The Network Approach uses one network from which different topics are addressed and serves as an application stage of the course and provides the main focus bridging the gap into the power system industry and into industrial grade software.

#### **2.5.5 FORM A WHOLE**

The Topic and Network Approach together ensure that the chosen structure forms a whole and gives a user an overall understanding of the topics of power systems.

#### **2.5.6 COMPREHENSIVE**

The course covers a wide scope. In the authors opinion it is the first time in South Africa that such a PC based bridging course in power systems has been researched and developed.

#### **2.5.7. RESEARCH AND DEVELOPMENT TIME FACTOR**

The author considered it necessary to limit the structure to the eighteen programs selected so that the research and development could be completed it in a reasonable time.

#### **2.5.8 USERS TIME FACTOR**

The time taken by a user to work through the prepared course from scratch to its end and to fully understand its content is another reason why the author limited it to the content chosen.

Also a bridging course should not be too lengthy but should prepare a learner to progress as rapidly as possible towards industrial applications.

#### **2.5.9 OTHER RESOURCES**

##### **a. TEXTBOOKS**

Another important reason for the chosen structure is that the programs used, except programs 1 and 7, are backed by textbooks written by well known authors in the field of power systems.

##### **b. SOFTWARE USERS MANUAL**

The programs 2,3,4,5,6,13,15,16, and 17 of the Package "Power" have a software users manual which accompanies them.

A description and usage of the programs 8,9,10,11,12 is provided at the back of the authors textbook.

## CHAPTER THREE

### 3. DEVELOPMENT OF LABORATORY SET-UPS FOR THE PC BASED POWER SYSTEMS COURSE

#### 3.1 MEANING OF THE TERM LABORATORY SET-UPS

Three components are needed by a user participating in this training programme, namely:

- (1) Hardware
- (2) Software programs
- (3) Laboratory Set-Ups

A "Laboratory Set-Up" means a written document which when used with hardware and software enables simulation to be performed.

The Laboratory Set-Up is thus a written document which is the primary interface between a user and the application software.

In general, a "Laboratory Set-Up" will describe procedures and attempt to make them easily implementable, user friendly with little or no reference to other sources and which will provide the required exposure to bridge the gap into the power systems industry and into industrial grade software. Each "Laboratory Set-Up" in the PC Based Course will be modular but together they will form a manual.

#### 3.2 NEED FOR LABORATORY SET-UPS

Technologists want tools that will help them solve their problems and enhance the way they work. (Williams, 1991).

If Laboratory Set-Up procedures are lacking, a user will use a trial and error method when using programs on their own. They may even abandon the program altogether. Without adequate documentation of the procedures to be followed and standards to be used, the user would not be able to understand the system, use the system effectively or understand all the input requirements or outputs provided. This is true whether the user is a novice or an experienced user with only minor questions about the system. (Richards, 1988).

Manuals help user goal attainment and in this way serve to bridge the user-system gap.

Conventional manuals promote neither easy knowledge acquisition nor pleasure in novice users. They tend to be incomprehensible. Conventional manuals usually promote the product only. This is because documentation is frequently ignored especially with computers. For many professionals, writing is the least interesting software related activity and is therefore neglected. Documentation is considered by many as just paper work and is perceived to have little challenge for the professional and most system developers lack training in documenting their system. (Nazir, 1989).



It is for this reason that a new course has been introduced in the USA which combines software engineering and software documentation into a unified course. It is pointed out that the most significant benefit is the improved software engineering abilities of students. They see the importance of presentation and writing skills in the software development process. (Young, 1992).

The "Laboratory Set-Ups" written by the author will thus demonstrate how to use the software for analysis and design and they will concentrate largely on **task orientation** rather than the conventional **product orientation**. Product orientation describes the general capabilities of programs whereas task orientation uses these capabilities and shows how to apply them as a series of tasks. These tasks being industrially related (for example see section headed "experimentation using these programs for analysis" in Appendix G). To the authors knowledge, such a comprehensive task orientation as is envisaged by him, has to date not been done in power systems in the RSA.

As the complexity of the task increases the greater is the need for documentation. (Haselkorn, 1986). Documentation thus becomes an essential component of the programme and is needed to speed up the process of bridging the gap into industry. It integrates the hardware and software into an integrated environment. Its success depends upon the quality of the documentation as together they combine to form a training simulator. (Leigh, 1992).

From this, one can conclude that software programs must be accompanied by documentation which easily explains to a user how a program is applied. (Rutigliano, 1984). Therefore software needs better task orientated documentation.

As state of the art PC hardware is used and as no attempt has been made by the author to improve algorithms of programs, a need therefore arose for the development of Laboratory Set-Ups.

### **3.3 GENERAL FACTORS CONSIDERED BEFORE DEVELOPING LABORATORY SET-UPS**

Before developing the "Laboratory Set-Ups" the following general factors were considered:

#### **3.3.1 READABILITY**

This means the document must be legible, must have interest for the reader and have ease of understanding.

#### **3.3.2 IDENTIFICATION OF CORE TASKS**

Identify the core tasks which users need. The first and most critical task is to determine what should be included. This means the identification of what lessons are needed and then to embody them in a conceptually clear manner. As in all software engineering, a better product can be expected if methodical steps are followed rather than relying on intuition. (Leigh, 1992).

### **3.3.3 MISINTERPETATION**

Explain or define any concepts first to ensure that user ambiguity will not arise. The principal idea is to implement the essential concepts underlying the subject software program in a clear manner so that its basic nature can be readily grasped. (Leigh,1992).

### **3.3.4 USABILITY**

Ease of use by which users achieve their objectives minimizes the magnitude of reader effort and discomfort. The document must be logically arranged and procedures should be solely to the documentation and not to extra sources. Users of documents prefer a simple consistent style of writing. (Guillemette,1987).

### **3.3.5 ACCESSIBILITY**

The document must include overviews, tables of content, indexes, cross references and glossaries.(Guillemette,1987).

### **3.3.6 GRADED EXAMPLES**

The document must include an adequate number of relevant examples to accomodate different users.

### **3.3.7 MEANINGFUL TASKS**

A user must be allowed to get started fast. The document must not initially be too detailed and tasks must be meaningful. The training must be directed at real tasks, therefore real work should be introduced quickly. It must also exploit what people already know and this information must be built upon. (Ramsy,1992).

### **3.3.8 TIMELINESS**

The use of the document must save time for users and bridge the gap to industry as quick as possible.

### **3.3.9 PRACTICAL SENSE**

PC based experimentation should be introduced at an early stage and should be applied throughout a course so that a user can develop a good practical sense as quickly as possible.

### **3.3.10 FEEDBACK**

Documentation must allow a user to obtain feedback by including self grading exercises.

3.4 TABLE OF PC BASED LABORATORY SET-UPS

The "Laboratory Set-Ups" developed by the author are given in the "appendices" and can be summarised as follows:

PC BASED POWER SYSTEMS LABORATORY SET-UPS				
APPENDIX	TITLE	PROGRAM(S)	PAGES	APPROACH
A	COMPUTER-AIDED LABORATORY SESSION ON SYMMETRICAL COMPONENTS	SYMCOMP	1-12	T O
B	COMPUTER-AIDED LABORATORY SESSION ON SYMMETRICAL COMPONENTS AND THE USE OF MATRIX OPERATIONS	SEQVEQ PHAVEC SEQIMP (POWER)	1-24	P I C
C	COMPUTER-AIDED LABORATORY SESSION ON TRANSMISSION LINE CONSTANTS	LINE CONSTANTS (POWER)	1-48	A
D	COMPUTER-AIDED STUDY PROGRAMME ON THE BALANCED STEADY-STATE OPERATION OF TRANSMISSION LINES	STEADY-STATE (POWER)	1-73	P P
E	THE USE OF THE COMPUTER FOR EXPERIMENTATION ON THE FORMATION OF A YBUS AND ZBUS IN MULTI-BUS POWER SYSTEMS	ZBUS (AUBURN) ZYBUS/ZBUS (GUNGOR)	1-77	R O A
F	THE USE OF GUNGOR'S COMPUTER PROGRAMS ACPFB AND DCPFB FOR EXPERIMENTATION ON LOAD FLOW ON MULTI-BUS POWER SYSTEMS	ACPF1B ACPF2B DCPFB  (GUNGOR)	1-85	C H
G	THE USE OF A COMPUTER TO ANALYSE A 16-BUS 3 GENERATOR POWER SYSTEM WITH REGARDS TO LOADFLOW, FAULT STUDIES, TRANSIENT STABILITY AND ECONOMIC DISPATCH	POWERFLOW (POWER) LOADFLOW (WOLLENBERG) SYMMETRICAL FAULTS (POWER) SHORT CIR- CUITS (POWER) TRANSIENT STABILITY (POWER) ECONOMIC DISPATCH (WOLLENBERG)	1-153	N E T W O R K  A P P R O A C H

TABLE 3.1

3.5 TABULATED ORIENTATION AND OVERVIEW OF LABORATORY SET-UPS

3.5.1 APPENDIX A

APPENDIX A	
COMPUTER-AIDED LABORATORY SESSION ON SYMMETRICAL COMPONENTS	
HEADINGS	PAGE NUMBERS
1. PROGRAM ACCESS	1
2. VOLTAGE CALCULATIONS	5
3. VERIFICATION OF RESULTS AND CHANGING OF PARAMETERS	7
4. EXISTENCE OF SYMMETRICAL COMPONENTS	8
5. LIMITATIONS OF PACKAGE	11
6. SELF EVALUATION EXERCISE	12

OVERVIEW

In this laboratory set-up a small amount of theory and a few numerical examples have been integrated with a step by-step explanation of how to use the "Symcomp" program to solve basic problems on symmetrical components of voltages and currents. The results being displayed as colour phasor diagrams. Also included is a PC based self evaluation exercise.

TABLE 3.2

3.5.2 APPENDIX B

APPENDIX B	
COMPUTER-AIDED LABORATORY SESSION ON SYMMETRICAL COMPONENTS AND MATRIX OPERATIONS	
HEADINGS	PAGE NUMBERS
1. PROGRAM ACCESS	1
2. MATRIX OPERATIONS	1
3. USE OF SUB-ROUTINE PROGRAMS	7
4. SOLUTION USING SOFTWARE PACKAGE	14
5. SELF EVALUATION EXERCISE	24

OVERVIEW

In this laboratory set-up the use of matrices was introduced for solving symmetrical components moving from phase to sequence domain and vice-versa. The program contains 9 sub-routines and those sub-routines which handle complex rather than real matrices was concentrated on. For example, the multiplication, the inversion, the transpose and the conjugate of complex matrices.

Also introduced was the use of three more sub-routines, SEQVEC, PHAVEC and SEQIMP. In this write-up some theory, a few numerical examples have been included and integrated with a step-by-step explanation of how to use these sub-routines to solve problems on symmetrical components emphasising phase and sequence domain culminating in the determination of complex power in these domains. Also included is a self evaluation exercise.

TABLE 3.3

3.5.3 APPENDIX C

APPENDIX C	
COMPUTER-AIDED LABORATORY SESSION ON TRANSMISSION LINE CONSTANTS	
HEADINGS	PAGE NUMBERS
1. INTRODUCTION TO THE THEORY OF LINE CONSTANTS	2
2. EXPLANATION OF THE USAGE OF THE PACKAGE	17
3. EXAMPLES SOFTWARE SOLUTIONS	20
4. SELF EVALUATION PROBLEMS	39

OVERVIEW

In this laboratory set-up a new approach in regards to headings has been introduced. This structure has been basically followed for the subsequent appendices. It was necessary to approach it in this manner so as to provide a proper base for understanding and interpreting the I/O data. The latter is a set of complex matrices. Under explanation of the usage of the program the I/O data, how to run the program, storing and updating data are shown. Under the heading software solutions, two examples were covered, one on a single circuit bundled conductor line and one on a double circuit line. The program was used to obtain output data in the form of matrices on series phase impedance; series sequence impedance; shunt phase admittance; shunt sequence admittance and conductor surface electric field strength and ground level electric field strength graphically represented. Theory is firstly introduced and then applied in software solutions leading to understanding. The examples chosen are based on actual voltages; line lengths and on practical cables as provided by a cable manufacturer. Also included are five self-evaluation questions.

TABLE 3.4

1.5.4 APPENDIX D

APPENDIX D	
COMPUTER-AIDED STUDY PROGRAMME ON THE BALANCED STEADY-STATE OPERATION OF TRANSMISSION LINES	
HEADINGS	PAGE NUMBERS
1. INTRODUCTION TO THE THEORY OF THE BALANCED STEADY-STATE OPERATION OF TRANSMISSION LINES	2
2. EXPLANATION OF THE USAGE OF THE PACKAGE	40
3. EXAMPLES SOFTWARE SOLUTIONS	53
4. SELF EVALUATION PROBLEMS	70

OVERVIEW

In this write-up I used the same approach as in Appendix C and used the same main headings. This topic covers a fairly wide field of power systems concepts related to the balanced steady-state operation of transmission lines and covers short, medium and long lines. The latter being treated with and without reactive compensation. In order to understand the I/O data, the section on the Introduction to the Theory of Steady-State operation is lengthy and includes 75 mathematical equations on this topic. Under the heading Explanation of the Program I distinguished between input and output data and explained the necessary in regard to compensation techniques. I also related each and every output data result to a mathematical equation as given in the Introduction Section so as to ensure full understanding. Under Software Solution I included 3 examples: one with no compensation and the line having no intermediate substations: one with shunt compensation and no intermediate substations and one with series and shunt compensation and including two intermediate substations. With each example I included a section on Interpretation and Understanding of the output data. I also included five self-evaluation questions covering uncompensated lossy lines: uncompensated lossless lines: lines with shunt and series compensation and lines having intermediate substations.

TABLE 3.5

3.5.5 APPENDIX E

APPENDIX E THE USE OF A COMPUTER FOR EXPERIMENTATION ON THE FORMATION OF A YBUS/ZBUS IN MULTIPOINT POWER SYSTEMS	
HEADINGS	PAGE NUMBERS
1. INTRODUCTION INTO THE THEORY ON THE FORMATION OF Y AND Z BUS MATRICES FOR USE IN MULTINODE REPRESENTATION OF POWER SYSTEMS	2
2. EXPLANATION OF THE USAGE OF THE PROGRAMS:	
a. PROGRAM AUBURN	14
b. PACKAGE GUNGOR	17
(1) PROGRAM ZYBUSB	
(11) PROGRAM ZBUSB	
3. EXPERIMENTATION USING THE PROGRAMS	20
4. SIMULATION INDUSTRIAL APPLICATION	68
5. SELF EXPERIMENTATION	75
6. COMPARISON OF PROGRAMS	77
OVERVIEW	
<p>The laboratory set-up covers the meaning of the Y and Z bus and their importance in power systems. A distinction is drawn between the direct formation of the YBUS and the indirect formation of the ZBUS. The user is also introduced to the direct formation of the ZBUS. Numerical examples are included and the topic approach is used, namely different size networks are applied. How to use each program is explained. Hand calculations are replaced by computer solutions and 6 computer based experiments are described followed by a simulated industrial application. Positive and zero sequence Y and Z bus are also computed. A Table comparing the Auburn and Gungor Packages is also included.</p>	

TABLE 3.6



3.5.6 APPENDIX F

APPENDIX F THE USE OF GUNGOR'S COMPUTER PROGRAMS ACPF1B, ACPF2B AND DCPFB FOR EXPERIMENTATION ON LOAD FLOW ON MULTIPOINT POWER SYSTEMS	
HEADINGS	PAGE NUMBERS
1. INTRODUCTION	1
2. EXPLANATION OF THE USAGE OF THE PROGRAMS:	4
a. AC POWER FLOW GAUSS-SEIDEL (ACPF1B)	4
b. AC POWER FLOW NEWTON-RAPHSON (ACPF2B)	17
c. DC POWER FLOW (DCPFB)	33
3. EXPERIMENTATION USING THE PROGRAMS:	41
a. ACPF1B	41
b. ACPF2B	54
c. DCPFB	74
4. EXPERIMENTATION FOR SELF EVALUATION	82
5. COMPARISON OF PROGRAMS	84

OVERVIEW
<p>This laboratory set-up is used to introduce the user to load flow studies, to the Gauss-Seidel and Newton-Raphson iterative methods and to D.C. Power flow. MW and MVAR line flows and system totals are computed, numerical hand calculated examples are included which are also computed. The topic approach is used and a number of different size power systems are analysed. The Jacobian and its inverse matrix are introduced and computed. Both ACPF1B and ACPF2B are used to compute the load flow solution for the same network showing that both iterative methods give comparable results. The DC flow method is introduced and computed showing its usefulness for rapid calculations of real power flows as no iterations are used. In this set-up 9 PC based experiments are demonstrated and two are self grading. No tap-changing transformers are accomodated by the programs.</p>

TABLE 3.7

3.5.7 APPENDIX G

APPENDIX G	
THE USE OF A COMPUTER TO ANALYSE A 16 BUS 3 GENERATOR POWER SYSTEM WITH REGARDS TO LOAD FLOW FAULT STUDIES, TRANSIENT STABILITY AND ECONOMIC DISPATCH	
HEADINGS	PAGE NUMBERS
1. INTRODUCTION	1
2. CHAPTER ONE - LOAD FLOW ANALYSIS	5
a. EXPLANATION OF USAGE OF THE PROGRAMS:	
(i) "POWERFLOW"	5
(ii) "LOADFLOW"	14
b. EXPERIMENTATION USING THESE PROGRAMS:	22
c. SELF EVALUATION	53
d. COMPARATIVE STUDY OF PROGRAMS USED	54
3. CHAPTER TWO - FAULT STUDY ANALYSIS	56
a. EXPERIMENTATION OF USAGE OF THE PROGRAMS:	57
(i) "SYMMETRICAL SHORT CIRCUITS"	57
(ii) "SHORT CIRCUITS"	62
b. EXPERIMENTATION USING THESE PROGRAMS:	67
c. SELF EVALUATION	81
4. CHAPTER THREE - TRANSIENT STABILITY ANALYSIS	83
a. EXPLANATION OF USAGE OF THE PROGRAM:	86
(i) "TRANSIENT STABILITY"	
b. EXPERIMENTATION USING THE PROGRAM USING OUTPUT DATA FROM CH.1 a(i) AND b.	102
c. SELF EVALUATION	111
5. CHAPTER FOUR - ECONOMIC DISPATCH ANALYSIS	115
a. EXPLANATION OF USAGE OF THE PROGRAM:	136
(i) "ECONOMIC DISPATCH"	
b. EXPERIMENTATION USING THE PROGRAM USING OUTPUT DATA FROM CH. 1 a(ii) AND b.	146
c. SELF EVALUATION	150
OVERVIEW	
<p>The one line diagram and tables of data received are given in Chapter One. This data simulates a real life example. Data is converted by hand to pu values. Usage of each of the programs is demonstrated and the network approach (one single network) is applied but it is subjected to load flow, fault study, transient stability and economic dispatch analyses. The "POWERFLOW" program includes fixed and automatic tap-changing transformers but only uses the Newton-Raphson method whereas the "LOADFLOW" uses both Gauss-Seidel and Newton-Raphson methods. Both symmetrical and assymetrical faults are computed as well as pu ZBUS (+, -, 0). To compute the transient stability the "POWERFLOW" must first be run and its output data is used by the "Transient Stability" program. The reactive compensation technique is also introduced to the user. The program can handle 3 disturbances. The theory behind economic dispatch is firstly introduced and essential concepts are defined/explained. The LaGrange Multiplier is applied. Numerical and computed examples are included. The effect of inequality constraints and transmission losses are described. Tables v polynomials (cost curves) are discussed and the lambda search method is applied. Usage of the program is demonstrated to obtain the economic dispatch solution and self evaluation is included.</p>	

TABLE 3.8

### 3.6. SPECIAL FEATURES OF DEVELOPED LABORATORY SET-UPS

#### 3.6.1 DEVELOPED FROM SCRATCH

The laboratory set-ups written are not cut versions of existing manuals but are derived from scratch. They do include some aspects from existing sources. (Glover,1987)(Gungor,1988).

The laboratory set-ups, except for Appendices A and B, have a similar layout format, namely:

LAYOUT FORMAT	
a	THEORY
b	EXPLANATION OF THE USAGE OF THE PROGRAMS
c	PC EXPERIMENTATION
d	SELF EVALUATION

TABLE 3.9

The format used for the laboratory set-ups is unique.

#### 3.6.2 MATCH THEORY TO SOFTWARE PROGRAMS

The author had to first find out what the software programs could do before knowing how to apply them. Each program in a laboratory set-up was first assessed to determine those aspects of the program needing to be clarified so that persons lacking background would understand the program parameters.

FOR EXAMPLE: On page 6 of Appendix F a major shortcoming of the program is that it fails to define, for example the meaning of the iteration headings: QC, DQ, DE, DF. It was necessary to run a computer experiment first, then compare its results to a hand calculated example, and in this way determine the definition and meaning of these program symbols.

To meet this clarification need, the author chose the laboratory set-up layout format given in Table 3.9 above.

It was found that it was necessary to provide introductory theory and to match this theory to the program. This was one of the biggest obstacles which had to be overcome.

The theory or background provided as introductory material matches what is needed to understand each program. The author attempts to anticipate user questions and answer them beforehand. The theory provided also provides a user with the vocabulary and the relationships needed to follow the newly introduced material. A user is more enthusiastic about computer-aided instruction if it addresses unasked questions beforehand so that when encountered, the difficulty would already have been overcome. (Reid, 1990).

The principal idea is to implement the essential concepts in a clear meaningful manner so that its basic nature can be readily grasped.

FOR EXAMPLE: See pages 117 to 135 in Appendix G where fossil-fuel units are introduced.

### 3.6.3 USAGE

Besides providing matching theory it was essential to investigate problems linked with the chosen software resources in regards to each programs capabilities and limitations. Each program has features inherent to its programmers style. It thus became necessary to differentiate between the strengths and weaknesses of the algorithms and to determine each programs range of options and then explain them to a user before using a program.

This is achieved under the heading "EXPLANATION OF THE USAGE OF THE PROGRAM" in each laboratory set-up and forms the second main part of a laboratory set-up.

The sub-headings under this section are usually:

- (1) INPUT DATA
- (2) OUTPUT DATA
- (3) RUNNING THE PROGRAM
- (4) STORING
- (5) UPDATING
- (6) PRINTING

FOR EXAMPLE: See pages 14 - 19 of Appendix E

Under Input and Output data the parameters and their meanings are explained, highlighting each programs capabilities and limitations. The other sub-headings explain how to run the program, store, update and print data.

### 3.6.4 PC EXPERIMENTATION AND A TABLE LISTING THE NUMBER OF SIMULATION EXPERIMENTS COVERED

This section of a laboratory set-up is the simulation section and the user is introduced to PC solutions of typical power systems problems.

All told 62 Simulations Experiments have been included:

NUMBER OF SIMULATION EXPERIMENTS			
APPENDIX	TOPIC	NUMBER OF SIMULATION EXPERIMENTS	PAGES
A	SYMMETRICAL COMPONENTS	EXPERIMENTS 1, 2, 3, 4, 5, 6, 7	1-12
B	SYMMETRICAL COMPONENTS AND MATRIX OPERATIONS	EXPERIMENTS 1 2 3 4	2-5 8-11 11-13 14-24
C	TRANSMISSION LINE CONSTANTS	EXPERIMENTS 1 2 3 4 5 6 7	20-31 32-38 42 43 44 46 48
D	STEADY-STATE OPERATION OF TRANSMISSION LINES	EXPERIMENTS 1 2 3 4 5 6 7 8	54-57 58-63 64-69 70 70 71 71 72-73
E	YBUS AND ZBUS MATRIX FORMATION	EXPERIMENTS 1 2 3 4 5 6 7 8	20-25 26-33 34-52 53-60 60-64 65-67 68-74 75-76
F	LOAD FLOW	EXPERIMENTS 1 2 3 4 5 6 7 8 9 10 11	41-46 47-50 51-53 54-61 62-64 65-73 74-76 77-79 80-81 82 83
G	16 BUS 3 GENERATOR POWER SYSTEM	EXPERIMENTS LOADFLOW 1, 2, 3, 4 FAULTS 1, 2, 3, 4, 5 STABILITY 1, 2, 3, 4, 5 ECONOMIC DISPATCH 1, 2, 3	22-53 67-82 102-114  143-152
THE TOTAL NUMBER OF SIMULATION EXPERIMENTS =			62

TABLE 3.10

The experiments included are systematically chosen to cover many of the most common power systems topics. In some set-ups hand calculations are firstly introduced and then solved by software.

FOR EXAMPLE: See pages 9 - 16 and pages 41 - 46 of Appendix F. Here a 3 bus power system is firstly hand calculated and then computed.

This proves the **"accuracy"** of programs and allows a user to develop **"confidence"** in software program solutions.

The use of a digital computer for analysis has resulted in obtaining more precise results. The accuracy of a solution depends entirely on the realistic and accurate specification of the input data. (Symond,1986).

By varying the input a user can watch the output results obtained. In this way a user develops **"intuitive skills"** just as he would in a real life situation.

FOR EXAMPLE: See pages 108-114 of Appendix G. Here the transient stability of the 16 bus power system is subjected to different disturbances and different output results are obtained. If the output results could be graphically represented so much the better as it would provide a concrete picture. (See page 101 of Appendix G and page 43-47 of Appendix C).

During this section of each set-up the author has attempted to **"exploit the capabilities"** of each program by providing a number of different experiments.

FOR EXAMPLE: See page 1 of Appendix D and the index pages of Appendices E, F and G.

### 3.6.5 SELF PACING

The variety of experiments improves **"learner control"**. Each laboratory set-up has the feature that a learner can direct the flow of instruction. He can follow along with the prepared lessons or can direct it to respond to his own exploratory and experimental needs. This is a highly desirable feature and the author through his chosen structures attempted to achieve a high degree of learner control.

### 3.6.6 DIVERSE BACKGROUNDS

The author has also attempted to provide for a diversity of user backgrounds. With the sub-headings chosen the laboratory set-ups are presented in a manner so that better prepared students need only quick review and will not be bored or slowed down. If a user is fully acquainted with theory of the topic in question he can proceed directly to the section explaining the usage of the programs. If familiar with this, he can proceed directly to the experimentation section and can apply his knowledge immediately. Or once the course has been completed, he could re-fresh himself and also apply what has been learnt to his own experimentation.

### 3.6.7 MODULAR LABORATORY SET-UPS

To further enhance the feature of catering for a diversity of backgrounds the author has prepared a series of laboratory set-ups (Appendices A to G) in modular form. Each set-up stands on its own which means a user can start with any of the appendices depending upon his background. Some can even be skipped out or they can be followed in random order which is ideal for more experienced users.

Even in Appendix G the chapters can be followed individually, except for Chapter Three on transient stability which requires inputs from the "POWERFLOW" program.

### 3.6.8 SELF GRADING

A leading feature of the set-ups is that each provides for self grading.

In the experimentation section users are taken through a number of experiments and provided input data is correctly entered the correct answers will be obtained. Should a correct answer not be obtained then the user immediately receives feedback that something is wrong or something is not understood.

Included in each set-up are self evaluation problems with results. Here the student must apply what has been learnt. These self evaluating problems are all "simulation tutorials"

FOR EXAMPLE: See pages 22,23,53,67,81,102,103,111,112, 113,114,146 and 150 of Appendix G.

### 3.6.9 MODELLING

Power system simulation plays an important role in the planning, operation and investigation activities of supply authorities. Different models of plant such as generators, lines and loads are applied according to the type of simulation performed. This course provides an overview of the requirements and limitations of the models used.

FOR EXAMPLE: See Appendix D, pages 14 and 21 for lossless versus lossy lines, pages 33 to 39 for with and without reactive compensation.

A model is any means of describing a real life system or object. Typical passive elements are lines, transformers, reactors and capacitors whereas active elements are motors, generators, synchronous capacitors and thyristor drives.

The manner in which these elements are modelled can affect the results of an analysis. The software programs chosen are bridging programs and many assumptions are made for the algorithms in question. This means the results obtained will not accurately agree with what is actually found in industry. In industrial grade programs far less assumptions are made and the results obtained more accurately agree with that found in practice.

FOR EXAMPLE: See Appendix G, Chapter Two page 57, where for symmetrical fault studies the following assumptions are made:

1. Transformers are used as leakage reactances only. Winding resistances, shunt admittances and D-Y phase shifts are neglected.
2. Lines are represented by their positive sequence equivalent series reactances. Series resistances and shunt admittances are neglected.
3. Synchronous machines are taken as constant voltage sources behind sub-transient reactances. Resistances, saliency and saturation are neglected.
4. All non-rotating loads are neglected.
5. Induction motors are treated as synchronous machines or neglected.

It must be remembered that the programs selected are inexpensive and are aimed at providing an introduction into the practical real world.

Typical industrial grade software costs in the region of \$25000 (R90000) to \$150000 (R550000) and are much more sophisticated with their modelling.

#### 3.6.10 ALTERNATIVE PROGRAMS

As the task becomes larger and more complicated and where hand calculations would take forever and one would not be sure of the accuracy of the solutions obtained a software program to compute solutions should be used.

However even when using a program one is not sure that what has been entered is correct nor can one be sure of the results. To ensure the user and to give confidence, the author has used alternative programs for some applications in order to check the solutions.

FOR EXAMPLE: See Appendix F pages 62,63 and 64. Here the ACPF1B and ACPF2B programs were used and their solutions compared. Also see Appendix G, Chapter One, pages 22 and 23 where the "POWERFLOW" and "LOADFLOW" programs are used and compared.

It must however be remembered that programs have certain capabilities and a user can only work within these constraints. When capabilities are lacking it is necessary to turn to alternative programs (if available) which do not have these limitations. (Boylestad,1990).

#### 3.6.11 INTERPRETATION OF OUTPUT DATA

Some of the laboratory set-ups also demonstrate how to interpret output data.



FOR EXAMPLE: See pages 57 of Appendix D and Figures(App.F) 4 (p16), 8(p40), 10(p44), 11(p50), 12(p52), 14(p59),16(p77), 17(p79), and 18(p81) which are derived one line diagrams of load flow solutions. These having to be interpreted from output results as one line diagrams are not drawn by the programs in question. See also Appendix G, Chapter Three on transient stability where the user has to interpret whether or not the 16 bus power system is stable or not. (See pages 101,110,111,112,113, and 114).

### 3.6.12 COMPARING FUNCTIONS AND FEATURES

Some of the set-ups provide comparative tables of the capabilities and limitations of the programs used.

FOR EXAMPLE: See pages 77 of Appendix E, page 84 of Appendix F and pages 54 and 55 of Appendix G.

This feature enables a user to obtain an overview of the set-up used and for quick reference at any time subsequent thereto.

NB! For a detailed knowledge of the capabilities and limitations of each set-up the user must work through each set-up and draw his own conclusions.

### 3.6.13 TECHNICAL SOPHISTICATION

One of the aims of this thesis is to gear this programme at Technologists or to persons having similar backgrounds.

The set-ups are particularly suited to 5th and 6th semester Technikon students preparing themselves as Technologists for industry.

The topics covered and the level of the tasks which have to be completed relate to the Power Systems Curriculum at Technikons and would be an ideal supplement to such a course or could very easily be integrated into such a course.

### 3.6.14 USER FRIENDLINESS

The manner in which the set-ups have been structured and the manner in which the above special features have been integrated make, in the author's opinion, a very user friendly PC based course.

## CHAPTER FOUR

### 4. CONCLUSIONS AND RECOMMENDATIONS

#### 4.1 CONCLUSIONS

a. A programme for using software in power systems simulation has been designed and developed and can now be used with a degree of confidence to enhance understanding of power systems.

b. The programme developed is based on traditional topics currently forming the core of modern conventional power systems courses.

c. The research covered mostly an investigation of academic type software and partially industrially related software packages.

d. The structure chosen includes a "Topic" and "Network" approach. The "Topic" approach uses different size electrical networks and covers different topics and serves as introductory background. The "Network" approach uses one electrical network and covers different topics and serves as the application stage of the course.

e. The laboratory set-ups developed are task orientated rather than product orientated. Product orientation describes the general capabilities of packages without applying them. Task orientation assesses the capabilities of a package and then applies them to industrially related problems. A major research finding is the lack of task orientated manuals. Those that are available, are limited in their content.

f. The author developed 7 laboratory set-ups wherein 18 programs have been applied in a task orientated manner. All told 62 simulation experiments are covered in the programme. The laboratory set-ups form the appendices to the dissertation.

g. The author found that the format for the layout of laboratory set-ups is best served by the headings:

1. Theory.
2. Explanation of the Usage of the program
3. PC based experimentation
4. PC based Self Evaluation

h. The programme comprises three basic essential components, namely:

1. Hardware (PC)
2. Software programs
3. Task orientated laboratory set-ups

Together they form a training simulator.

- i. The programme developed is easily implementable. It is modular, supported by high-quality textbooks and is written in a step-by-step approach making the course very user friendly.
- j. The programme is geared at Technologists and at persons with similar backgrounds. The developed set-ups will greatly improve the education of users.
- k. The PC is introduced from an early start and is used throughout the course.
- l. The advantages of computer simulation become impressively evident as networks become more complex.
- m. The programme provides hands-on involvement making the course meaningful.
- n. Traditional hand calculations are shown and replaced with PC based solutions.
- o. The integrated programme, once mastered by a user, becomes a powerful and useful tool which can be used for own experimentation and exploration.
- p. The developed programme provides an example of how computers are used in industry.

#### 4.2 RECOMMENDATIONS

The author recommends that:

- a. The developed PC based programme be integrated into the power system courses at Technikons.
- b. The developed programme be offered as a short course (workshop) to industry, within a comprehensive continuing engineering education programme.
- c. The current programme to be expanded to include more advanced simulations and to include topics not covered by this course. That further task orientated laboratory set-ups/manuals to be developed.
- d. Research be conducted to ascertain the most effective manner that should be used for task orientated documentation.
- e. A further study of more industrially orientated programs be undertaken and that PC based task orientated laboratory set-ups be developed and written to save future users time and to enable them to move quickly towards applying them in industry.
- f. Research be conducted in the usage/comparison of industrial-grade packages.

#### 4.3 THE WAY AHEAD .

PC based industrial grade training courses in power systems should now be developed. The following is proposed:

a. The "ETAP" package be used and industrially related task orientated laboratory set-ups be developed. Its Load Scheduling program, in particular, should be used for system modelling followed by an analysis done under starting, steady-state and fault conditions.

b. The TC Curve protective co-ordination program which accompanies "ETAP" should be used and industrially related task orientated laboratory set-ups should be developed. This program and its library of relay curves should also be used as an extension for the ETAP analyses done in "a".

c. That task orientated programmes be developed for other PC based industrial grade packages currently being applied by industry in the RSA. The author is aware of other software packages for power systems simulation existent in the RSA (e.g. at the University of Cape Town/Eskom/Cape Town Municipality etc).

- - - END - - -

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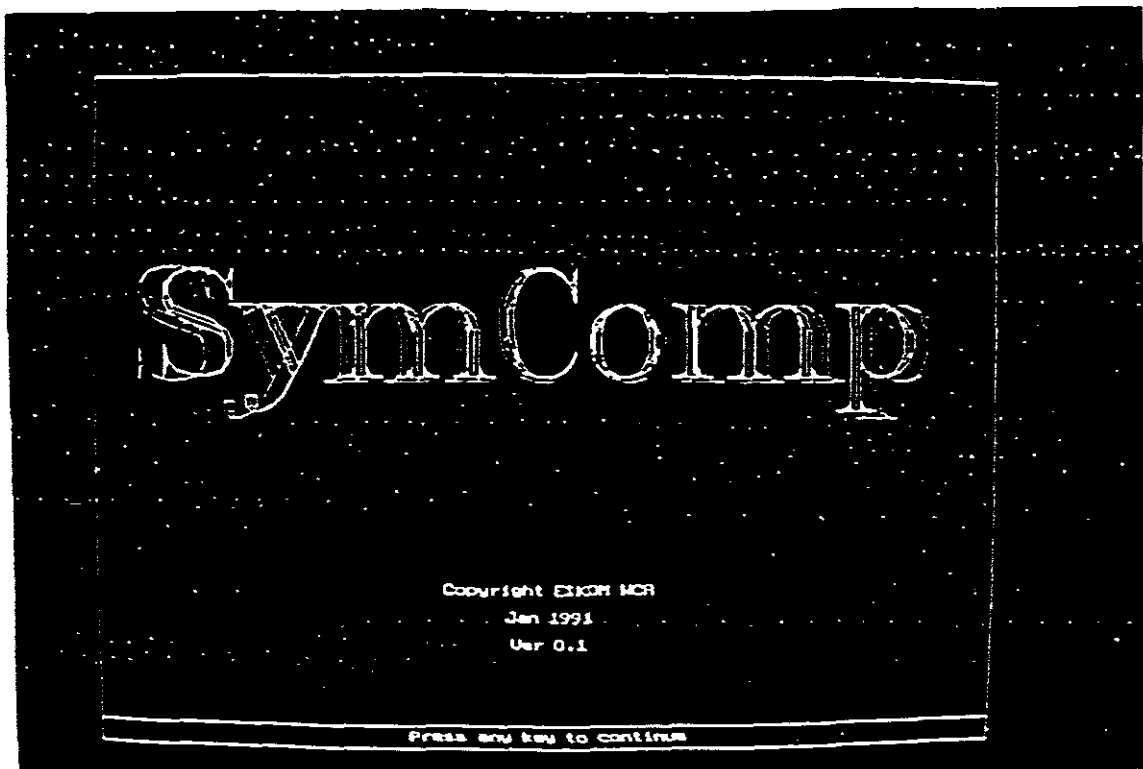
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COMPUTER-AIDED LABORATORY SESSION

ON

SYMMETRICAL COMPONENTS



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10-02-1992

SYMMETRICAL COMPONENTS

C:\> cd SYMCOMP

Press enter

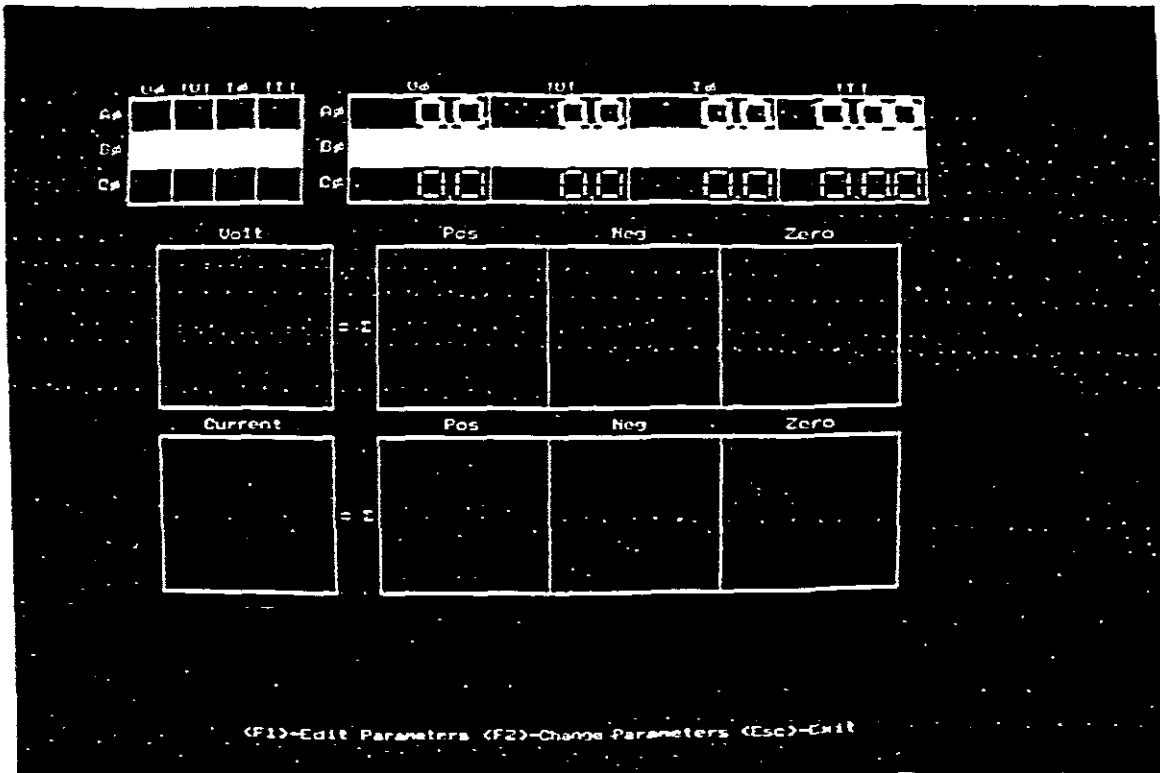
C:\ SYMCOMP>

C:\SYMCOMP>SYMCOMP

Press enter (access obtained)

Press any key to continue,make sure "Num Lock" is on.

Screen shows



<F1>-Edit Parameters <F2> Change Parameters <Esc>-Exit

Press <F1>

VφAφ red block is highlighted and the command line to:

↑↓←→-Select Field <a.z.or A.Z.>-Label<Keyboard>-Change Field  
<ENTER>-Accept<F3>Toggle Channel On-Off.



Use ↓ to move field select downwards from  $V\phi A\phi$  red block to  $V\phi B\phi$  yellow.  
Use → to move field select to the right from  $V\phi B\phi$  yellow block to  $|V|B\phi$  yellow block.  
Use → and move field select to the right from  $|V|B\phi$  yellow block to  $|I|B\phi$  yellow block.  
Use ↓ to move field select downwards from  $|I|B\phi$  yellow block to  $|I|C\phi$  blue block.  
Use ← to move field select to the left from  $|I|C\phi$  blue block to  $V\phi C\phi$  blue block.  
Use ↑ to move field select upwards from  $V\phi C\phi$  blue block to  $V\phi A\phi$  red block.

Label  $V\phi A\phi$  by pressing key a , use relevant arrow keys and

"  $|V|A\phi$  " " " b ,  
"  $I\phi A\phi$  " " " c ,  
"  $|I|A\phi$  " " " d ,  
"  $V\phi B\phi$  " " " e , etc until  $|I|C\phi$  has been  
labelled " " " l .

#### EXPERIMENT.1

Select a and press 7 on numeric keypad and increase angle  $V\phi$  from  $0^\circ$  to  $360^\circ(0^\circ)$ . Press 7 key and select an angle of  $40^\circ$  for the label a.

Select b and press 7 key and increase the magnitude of the voltage  $|V|$  from 0V to 100V(maximum), press 1 key to decrease the magnitude  $|V|$  back to 0V. Select 50V for the magnitude of label b. Press 8 key to increase magnitude in steps of 1V, increase the value of b to 55V. Press 2 key to decrease magnitude in steps of 1V, decrease magnitude to 52V. Leave b = 52V.

Select e and increase its value to  $250^\circ$ .

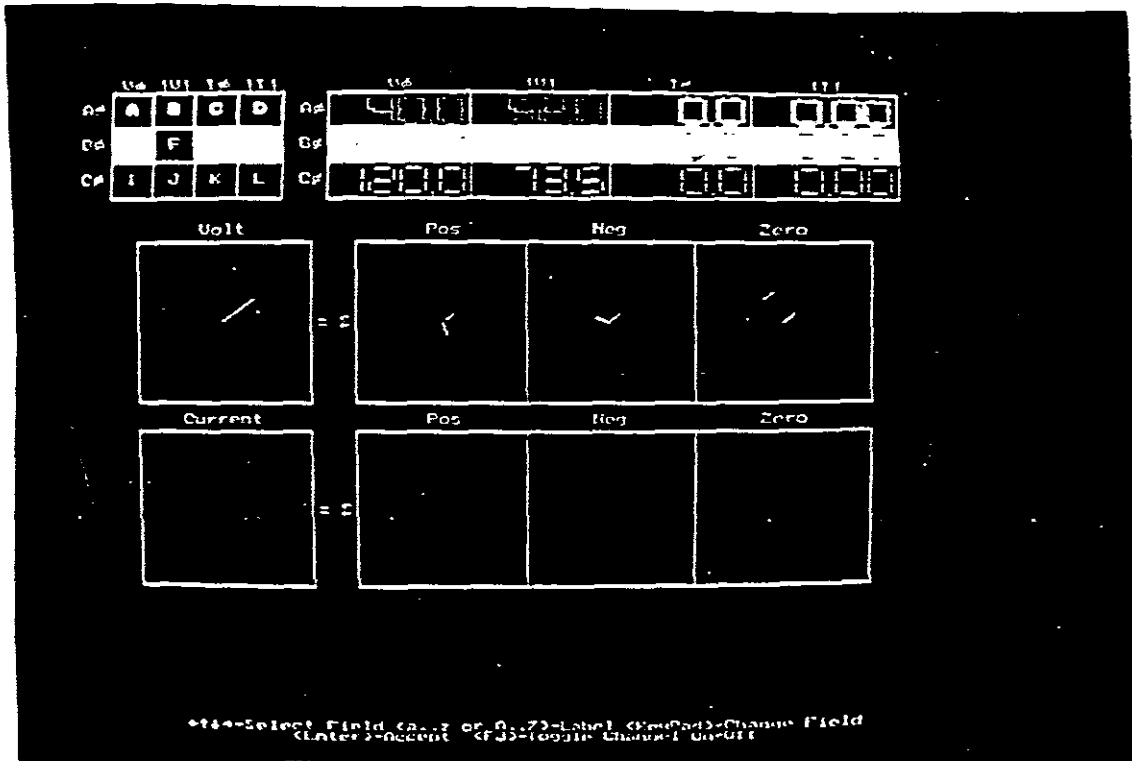
Select f and increase its value to 100V.

Select i and increase its value to  $120^\circ$ .

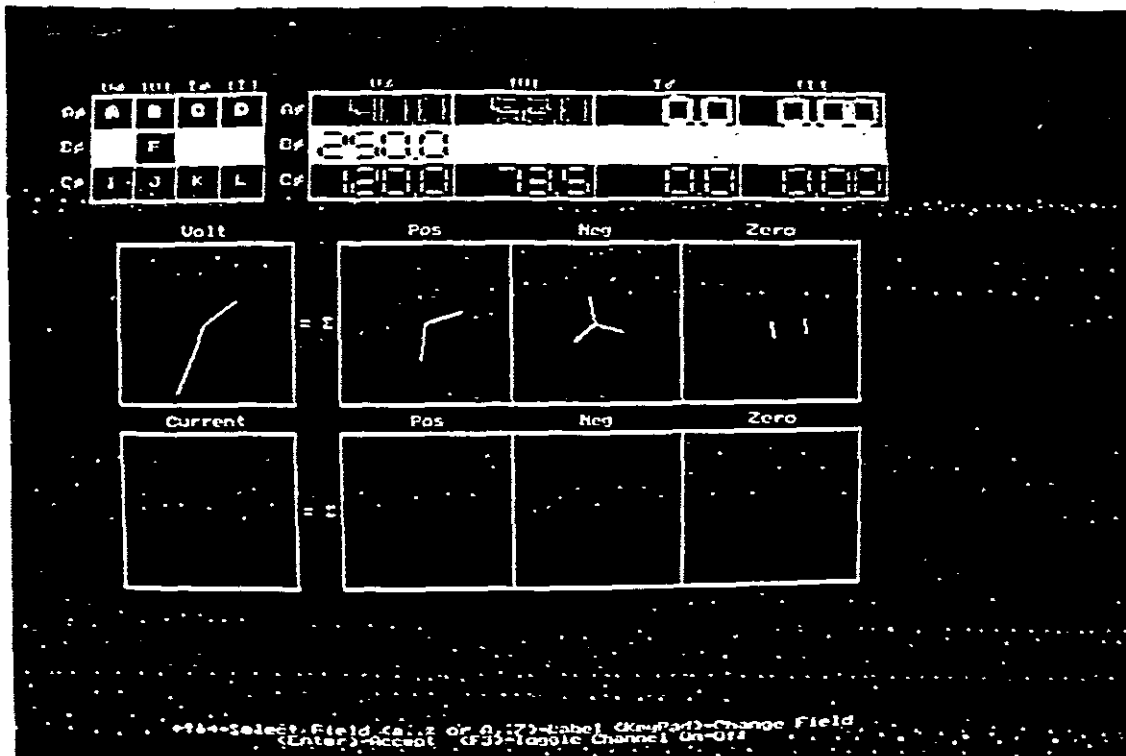
Select j and increase its value to 73V. Using 9 key increase the magnitude to 73,9V. Using 3 key decrease magnitude to 73,5V.

Select a by using relevant cursor arrows to return to the red phase.

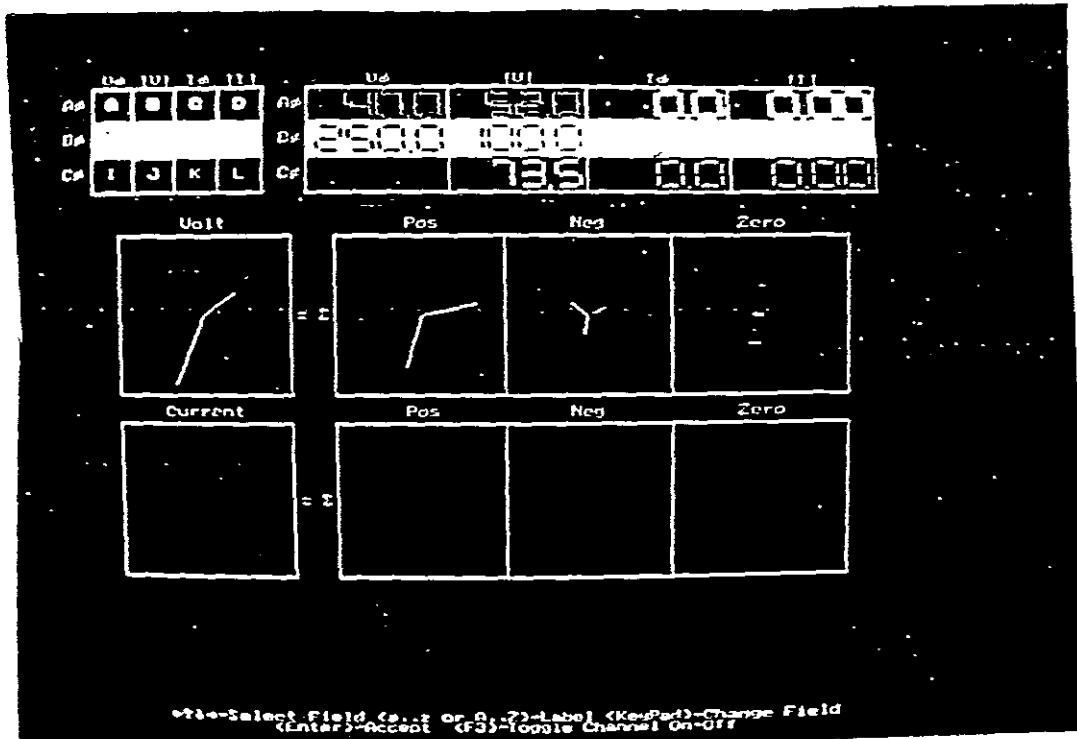
Press F3 and the screen will be indicating the following:



Select e and press F3 and the screen will be indicating the following:



Select i and press F3 and the screen will indicate the following:



With i selected and by pressing F3 ,the blue phase will be removed from the screen. Remove the blue phase by pressing F3. By pressing F3 again the blue phase will be returned.

With e selected and F3 pressed , the yellow phase is removed and can likewise be returned by pressing F3 again.

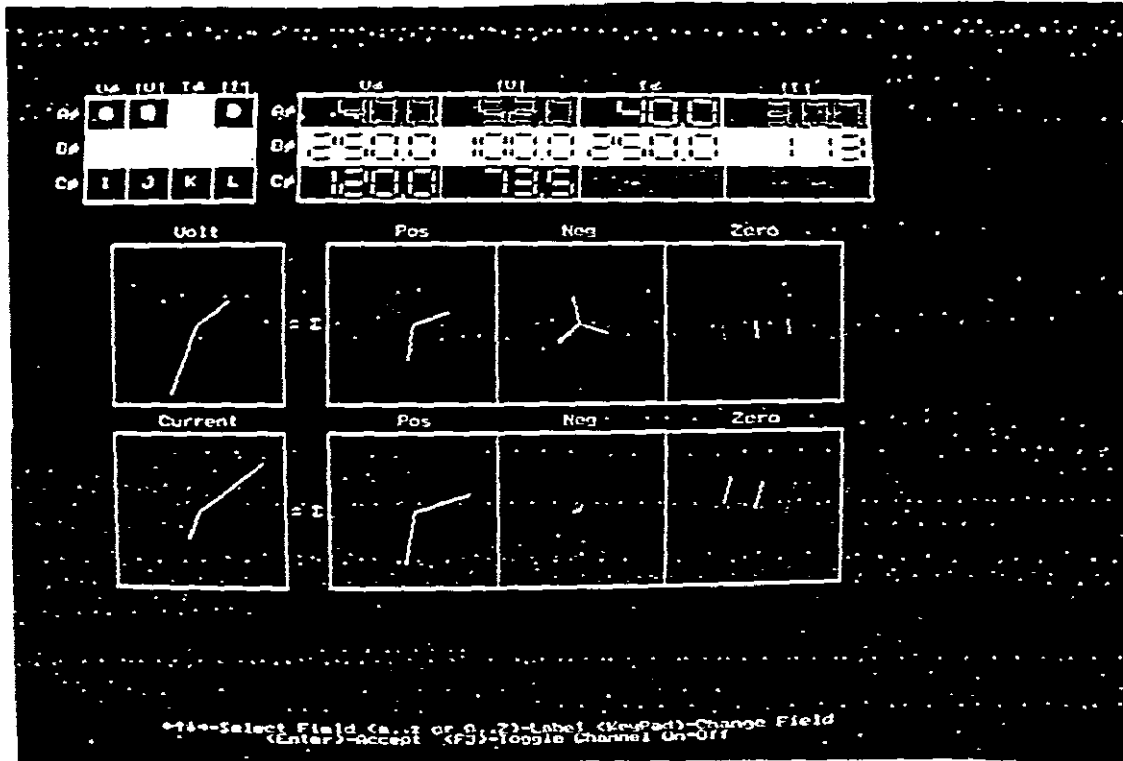
With a selected and F3 pressed a similar effect can be achieved for the red phase.

By pressing F3 return all three phases back to the screen.

Let  $c = 40^\circ$  and  $d = 3A$ (maximum). Select c and press F3, and screen indicates the red phase for the current and its symmetrical components.

Add the yellow phase by letting  $g = 250^\circ$  and  $h = 2,56A$ . Press F3 and screen indicates the red and yellow phases for the current and their symmetrical components.

Add the blue phase by letting  $k = 120^\circ$  and  $l = 1,13A$ . Press F3 and screen indicates the red, yellow and blue phases as follows:



Calculations are now done to determine if the values of the positive, negative and zero sequences as shown on the screen are correct:

### VOLTAGE CALCULATIONS

The voltages from above are:

$$\begin{aligned}
 V_a &= 52 \angle 40^\circ \\
 V_b &= 100 \angle 250^\circ \\
 V_c &= 73,5 \angle 120^\circ
 \end{aligned}$$

$$\begin{aligned}
 V_{a0} &= 1/3 ( V_a + V_b + V_c ) \\
 &= 1/3 ( 52 \angle 40^\circ + 100 \angle 250^\circ + 73,5 \angle 120^\circ ) \\
 &= 10,42 \angle 174,3^\circ \text{ volts} \\
 &= V_{b0} = V_{c0} \text{ (red, yellow and blue phases zero sequence)}
 \end{aligned}$$

$$\begin{aligned} V_{a1} &= 1/3 ( V_a + \alpha V_b + \alpha^2 V_c ) \\ &= 1/3 ( 52 \angle 40^\circ + 1 \angle 120^\circ 100 \angle 250^\circ + 1 \angle -120^\circ 73,5 \angle 120^\circ ) \\ &= 72,6 \angle 13,5^\circ \text{volts (red phase positive sequence )} \end{aligned}$$

$$\begin{aligned} V_{a2} &= 1/3 ( V_a + \alpha^2 V_b + \alpha V_c ) \\ &= 1/3 ( 52 \angle 40^\circ + 1 \angle -120^\circ 100 \angle 250^\circ + 1 \angle 120^\circ 73,5 \angle 120^\circ ) \\ &= 25,6 \angle 143^\circ \text{volts (red phase negative sequence )} \end{aligned}$$

$$V_{b1} = \alpha^2 V_{a1} = 72,6 \angle -106,5^\circ \text{volts (yellow phase positive sequence)}$$

$$V_{b2} = \alpha V_{a2} = 25,6 \angle 263^\circ \text{volts (yellow phase negative sequence)}$$

$$V_{c1} = \alpha V_{a1} = 72,6 \angle 133,5^\circ \text{volts (blue phase positive sequence)}$$

$$V_{c2} = \alpha^2 V_{a2} = 25,6 \angle 23^\circ \text{volts (blue phase negative sequence )}$$

#### CURRENT CALCULATIONS

$$\begin{aligned} I_a &= 3 \angle 40^\circ \text{A} \\ I_b &= 2,56 \angle 250^\circ \text{A} \\ I_c &= 1,13 \angle 120^\circ \text{A} \end{aligned}$$

$$\begin{aligned} I_{a0} &= 1/3 ( I_a + I_b + I_c ) \\ &= 1/3 ( 3 \angle 40^\circ \text{A} + 2,56 \angle 250^\circ \text{A} + 1,13 \angle 120^\circ \text{A} ) \\ &= 0,33 \angle 30,8^\circ \text{A} \\ &= I_{b0} = I_{c0} \text{ ( red, yellow and blue phases )} \end{aligned}$$

$$\begin{aligned} I_{a1} &= 1/3 ( I_a + \alpha I_b + \alpha^2 I_c ) \\ &= 1/3 ( 3 \angle 40^\circ + 1 \angle 120^\circ 2,56 \angle 250^\circ + 1 \angle -120^\circ 1,13 \angle 120^\circ ) \\ &= 2,13 \angle 21,75^\circ \text{A (red phase positive sequence )} \end{aligned}$$

$$\begin{aligned} I_{a2} &= 1/3 ( I_a + \alpha^2 I_b + \alpha I_c ) \\ &= 1/3 ( 3 \angle 40^\circ + 1 \angle -120^\circ 2,56 \angle 250^\circ + 1 \angle 120^\circ 1,13 \angle 120^\circ ) \\ &= 0,97 \angle 88,6^\circ \text{A (red phase negative sequence )} \end{aligned}$$

$$I_{b1} = \alpha^2 I_{a1} = 1 \angle -120^\circ 2,13 \angle 21,75^\circ = 2,13 \angle 261,75^\circ \text{A (yellow phase positive sequence)}$$

$$I_{b2} = \alpha I_{a2} = 1 \angle 120^\circ 0,97 \angle 88,6^\circ = 0,97 \angle 208,6^\circ \text{A ( yellow phase negative sequence)}$$

$$I_{c1} = \alpha I_{a1} = 1 \angle 120^\circ 2,13 \angle 21,75^\circ = 2,13 \angle 141,75^\circ \text{A ( blue phase positive sequence)}$$

$$I_{c2} = \alpha^2 I_{a2} = 1 \angle -120^\circ 0,97 \angle 88,6^\circ = 0,97 \angle 328,6^\circ \text{A (blue phase negative sequence)}$$

## VERIFICATION OF RESULTS

Use a set of dividers and measure the 100V and 3A phasors in mm on your screen. ( e.g. 100V = 20mm or 5V = 1mm and 3A = 21mm or 0,143A = 1mm ). Use your scale and measure the magnitude of each of the phasors of the positive, negative and zero sequence components. Likewise use a protractor to measure angles. Check your results against that calculated to verify that what this software has produced on the screen is approximately true.

## CHANGING PARAMETERS

### METHOD 1.

Select a by using the relevant arrow keys. Decrease its value to 0°.  
Select b and increase its value to 65V.  
Select e and alter to 240°.  
Select j and decrease to 48,5V.

[ NB! In a similar manner any other parameter can be changed. ]

### METHOD 2.

Press enter

Press F2

Command line changes to :

<Label>-Select Field(s)<Keypad>-Change Field(s)<Enter>-Exit

Press a and alter its value back to 40°

Press b " " " " " " 52V

Press e " " " " " " 250°

Press j " " " " " " 73,5V

Press enter

[ NB! In a similar manner any other parameter can be changed ]

Command line changes to :

<F1>-Edit Parameter<F2>-Change Parameter<Esc>-Exit

Press F1

EXPERIMENT.2

EXISTENCE OF SYMMETRICAL COMPONENTS

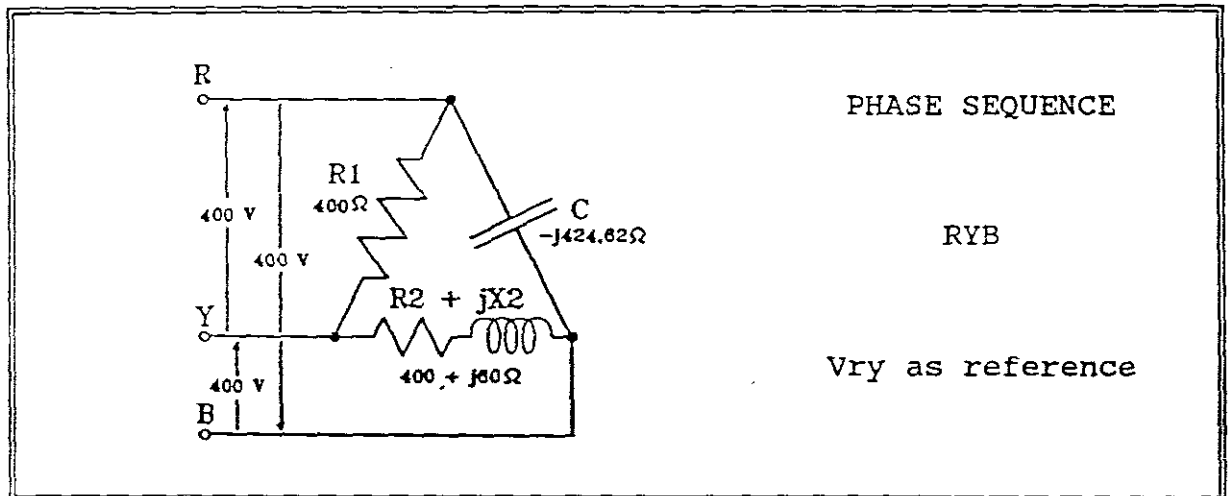
The currents to a 3 phase 3 wire star connected unbalanced load can have no zero sequence component, since the sum of the three line currents is zero. The zero sequence component is one third of the sum of the line currents, therefore it must be zero.

Let the three line currents flowing in such a 3 wire system be  $I_a = 2,68 \angle 15^\circ \text{A}$ ,  $I_b = 2,68 \angle 165^\circ \text{A}$  and  $I_c = 1,39 \angle -90^\circ \text{A}$ .

Change the current parameters on your screen to these values given and show that there are no zero sequence components.

The three line currents that supply a delta connected load have no zero sequence component, because the sum of the line currents  $I_a + I_b + I_c = 0$ . However for an unbalanced delta load the sum of the phase currents is not equal to zero and a zero sequence current will circulate in the delta. It circulates around the delta, but never gets out of the the delta since it is merely a component of each phase.

Let such a circuit be:



From which the phase currents are:

$$I_1 = 1 \angle 0^\circ \text{A} , \quad I_2 = 0,98 \angle 231,5^\circ \text{A} \quad \text{and} \quad I_3 = 0,94 \angle 210^\circ \text{A}$$

Now  $I_1 + I_2 + I_3 = 1,3 \angle 252,1^\circ \text{A}$   
( It does not equal zero )

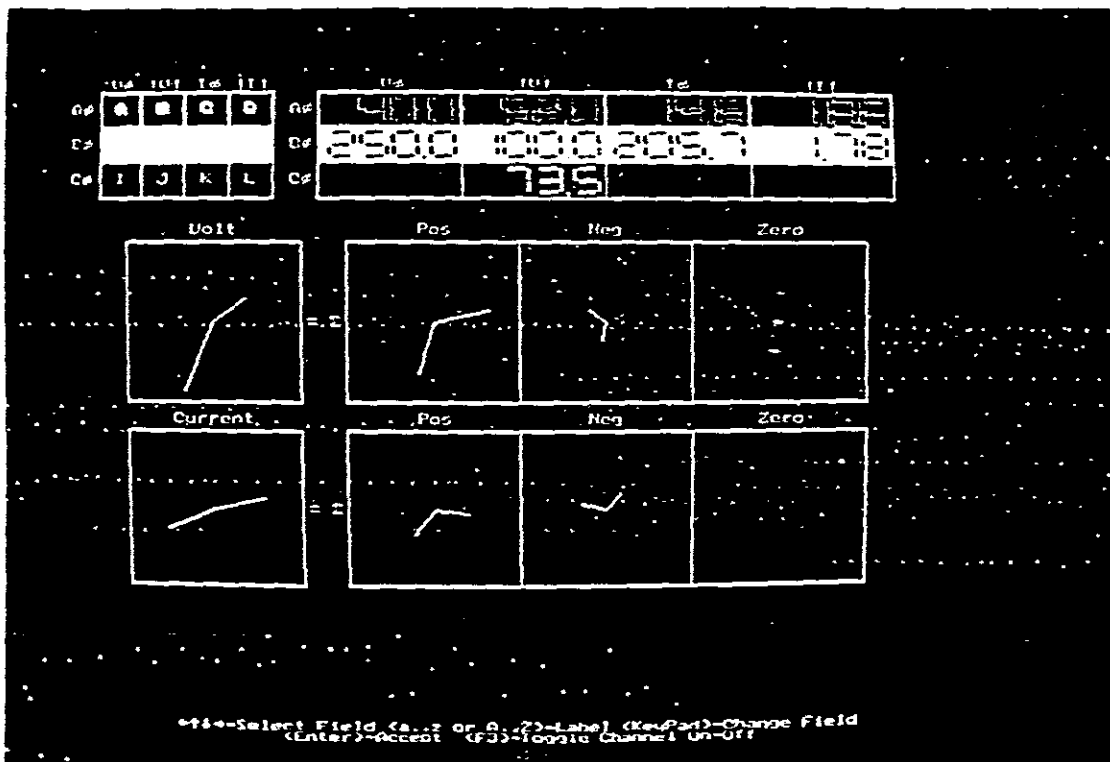
Enter these three currents onto your screen and see that zero sequence components are present.

Now calculating the three line currents from the phase currents:

$$I_a = 1,86 \angle 14,63^\circ \text{A} , I_b = 1,78 \angle 205,7^\circ \text{A} \text{ and } I_c = 0,36 \angle 123,7^\circ \text{A}$$

Enter these three line currents onto your screen and show that there are no zero sequence components.

YOUR SCREEN SHOULD LOOK AS FOLLOWS:



Another general relationship is that there are no zero sequence voltages in a balanced three phase system because the sum of the three balanced phasors is zero. This can be seen from the equation:

$$V_0 = 1/3( V_a + V_b + V_c )$$

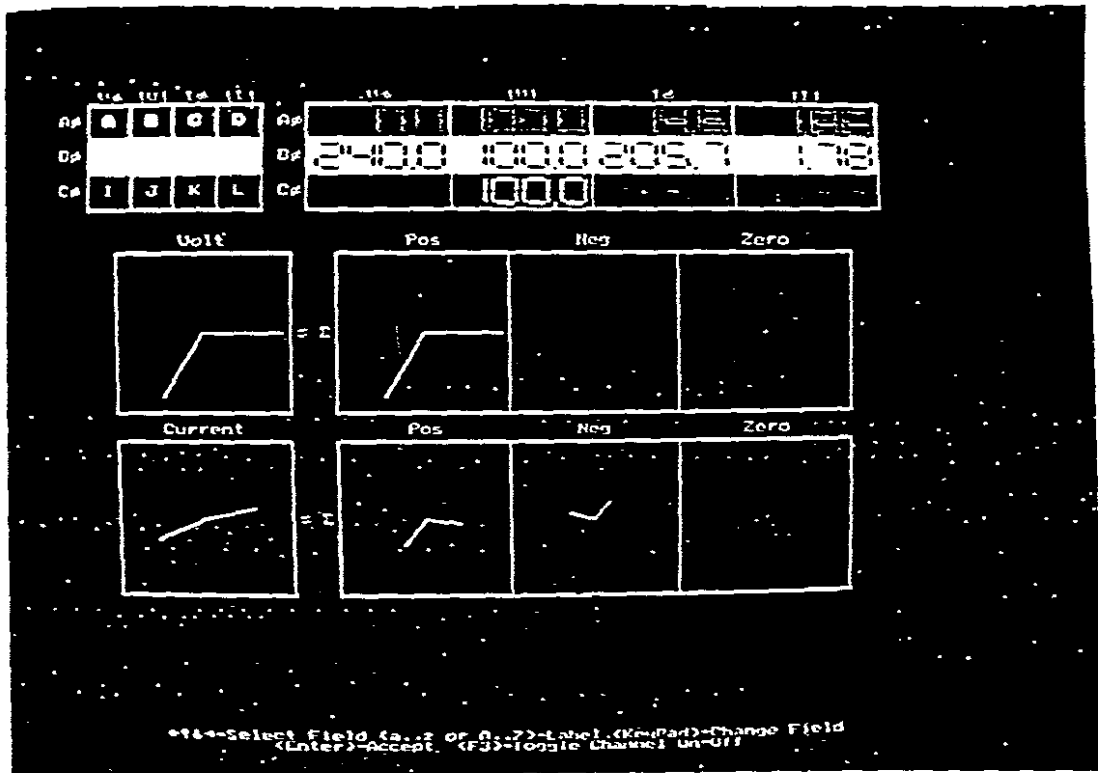
Where  $V_0$  = zero sequence component of the voltage.

Alter the voltage values on your screen to :

$$a = 0^\circ , b = 100\text{V} , e = 240^\circ , f = 100\text{V} , i = 120^\circ \text{ and } j = 100\text{V}$$



The screen now shows:



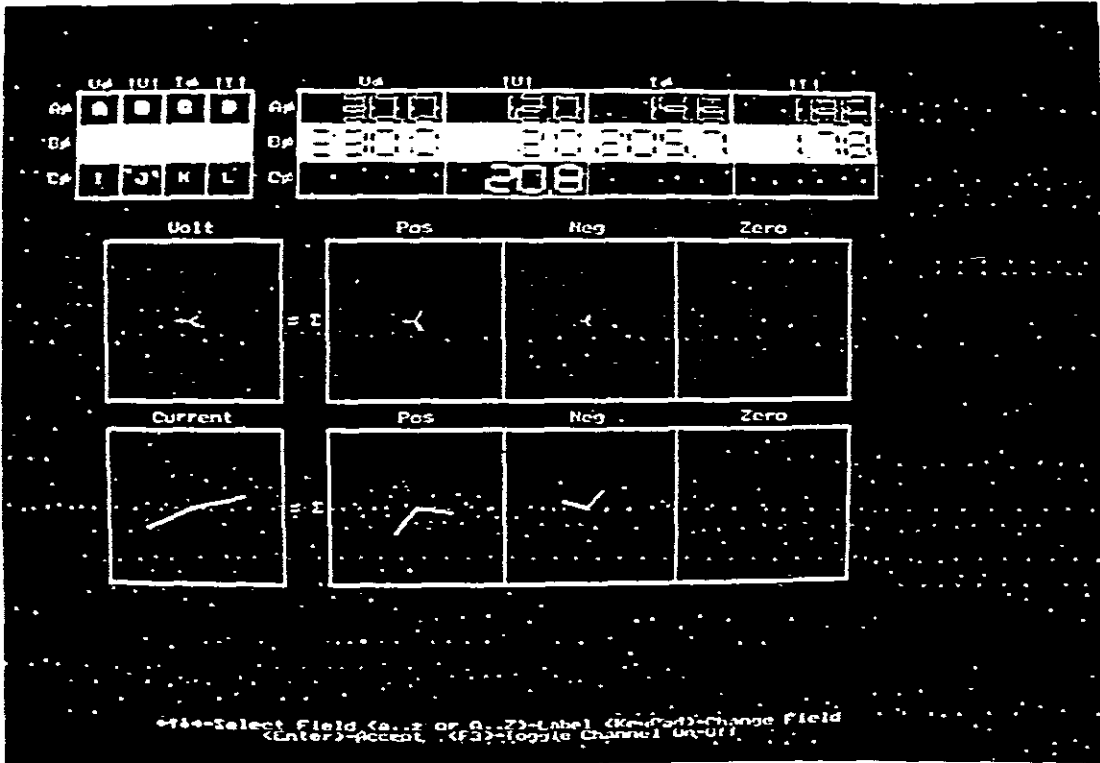
This example illustrates the fact that balanced three phase systems have no zero sequence or negative sequence components.

Line-to-line voltages never have a zero sequence component, since by Kirchoff's Voltage Law their sum is always zero. This is also true for unbalanced line-to-line voltages.

Alter the voltage values on your screen to:

a = 30°, b = 12V , e = 330° , f = 12V , i = 180° and j = 20,8V

The screen now shows:



#### LIMITATIONS OF PACKAGE

- a. Only voltages up to a maximum of 100V and currents to a maximum of 3A can be used.
- b. Printing of screen is not possible due to the colours and any printing comes out black. This makes measurement of the sequence components difficult.

SELF EVALUATION PROBLEMS

1. When one of the correctly connected 50V phases of a star connected 3 wire generator is reversed , the values of the assymetrical line voltages are  $86,6 \angle 30^\circ \text{V}$  ,  $50 \angle 180^\circ \text{V}$  and  $50 \angle 240^\circ \text{V}$  respectively. The phase sequence was RYB and  $V_{rn}$  was used as reference. Enter these values onto your screen and determine the symmetrical components produced. Give reasons for your findings.
2. Three  $40\mu\text{F}$  capacitors are star connected across a 100V 50Hz 3 wire supply. If the capacitor in the blue-to-neutral branch is short circuited, it is found that the line currents are  $I_r = 1,256 \angle 30^\circ \text{A}$  ,  $I_y = 1,256 \angle -30^\circ \text{A}$  and  $I_b = 2,175 \angle 180^\circ \text{A}$ . The phase sequence was RYB and  $V_{ry}$  was taken as reference. Enter these values onto your screen and determine the symmetrical components produced. Give reasons for your findings.
3. Show on your screen the sequence components of the following balanced line-to-neutral voltages with abc sequence:

$$V_{an} = 27,7 \angle 0^\circ \text{V} , V_{bn} = 27,7 \angle -120^\circ \text{V} \text{ and } V_{cn} = 27,7 \angle 120^\circ \text{V}$$

What does this example seek to illustrate? (See Glover p53)

4. A star connected load has balanced currents with ACB sequence of  $I_a = 1 \angle 0^\circ \text{A}$  ,  $I_b = 1 \angle 120^\circ \text{A}$  and  $I_c = 1 \angle -120^\circ \text{A}$ . Show on your screen the sequence components and explain what this example seeks to illustrate. (See Glover p54)
5. A three phase line feeding a balanced-Y load has one of its phases(phase b) open. The load neutral is grounded, and the the unbalanced line currents are:

$$I_a = 1 \angle 0^\circ \text{A} , I_b = 0 \text{A} \text{ and } I_c = 1 \angle 120^\circ \text{A}$$

Show on your screen the sequence components. What does this example seek to illustrate? What is the value of the neutral current and what is its relationship to the zero sequence component?

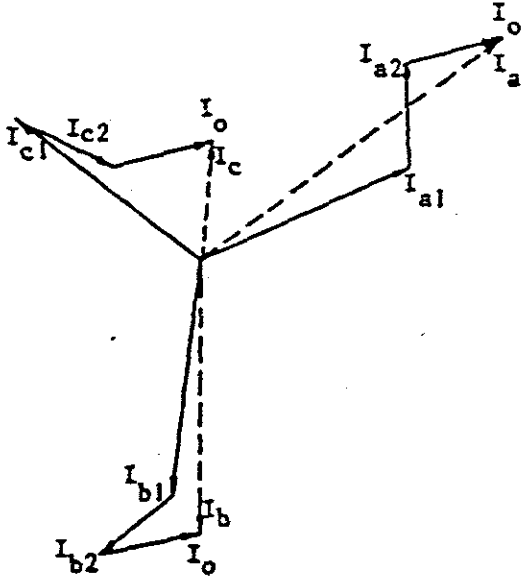
COMPUTER-AIDED LABORATORY SESSION

ON

SYMMETRICAL COMPONENTS

AND

THE USE OF MATRIX OPERATIONS



## SYMMETRICAL COMPONENTS

### USE OF MATRIX OPERATIONS

C:\> cd POWER  
Press Enter  
C:\POWER>  
C:\POWER>CHAP2  
Press enter (access obtained)

Screen shows

#### MATRIX OPERATIONS

REFERENCE: J.D.GLOVER AND M.SARMA.  
POWER SYSTEM ANALYSIS AND DESIGN  
WITH PERSONAL COMPUTER APPLICATIONS  
PWS PUBLISHERS, BOSTON, 1987  
CHAPTER TWO

Before proceeding, the following must be understood:

This programme contains the following nine subroutines:

- (1) RMA - computes the matrix sum  $C = A+B$  of the two  $N * M$  real matrices A and B.
- (2) CMA - computes the matrix sum  $C = A+B$  of the two  $N * M$  complex matrices A and B.
- (3) RMM - computes the matrix product  $C = A * B$  of the  $N * M$  real matrix A and the  $M * P$  real matrix B.
- (4) CMM - computes the matrix product  $C = A * B$  of the  $N * M$  complex matrix A and the  $M * P$  complex matrix B.
- (5) RMI - computes the matrix inverse  $A^{-1}$  of the  $N * N$  real matrix A whose determinant is assumed to be non zero.
- (6) CMI - computes the matrix inverse  $A^{-1}$  of the  $N * N$  complex matrix A whose determinant is assumed to be non zero.
- (7) RMT - computes the matrix transpose  $A^T$  of the real matrix A.
- (8) CMT - computes the matrix transpose  $A^T$  of the  $N * M$  complex matrix A.
- (9) CMC - computes the complex conjugate  $A^*$  of the  $N * M$  complex matrix A.

The maximum dimension (N, M, or P) of any matrix you enter is 30. You can enter the elements of complex matrices in either rectangular or polar form. The input/output data can be displayed on the monitor and the printer. Also, you can display the input/output data in either exponential format (similar to scientific notation) or fixed-point format (numbers with decimal points).

Let A be the 3 \* 3 symmetrical components transformation matrix:

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

The inverse of matrix A is :

$$A^{-1} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

This can be rewritten as follows :

$$A^{-1} = \begin{bmatrix} 1/3/0^\circ & 1/3/0^\circ & 1/3/0^\circ \\ 1/3/0^\circ & 1/3/120^\circ & 1/3/240^\circ \\ 1/3/0^\circ & 1/3/240^\circ & 1/3/120^\circ \end{bmatrix}$$

and which can be represented in exponential format (scientific notation) as follows:

$$A^{-1} = \begin{bmatrix} 3.33E-01 & 0.00E+00D & 3.33E-01 & 0.00E+00D & 3.33E-01 & 0.00E+00D \\ 3.33E-01 & 0.00E+00D & 3.33E-01 & 1.20E+02D & 3.33E-01 & 2.40E+02D \\ 3.33E-01 & 0.00E+00D & 3.33E-01 & 2.40E+02D & 3.33E-01 & 1.20E+02D \end{bmatrix}$$

### EXPERIMENT.1

To use this package to invert the 3 \* 3 symmetrical components transformation matrix A and to show that its solution is as above, we need to use the CMI subroutine, that is number (6) from the list of nine subroutines given:

Press return (enter) to continue

The screen shows:

THIS PROGRAM CONTAINS THE FOLLOWING NINE SUBROUTINES

- 1.SUBROUTINE RMA (REAL MATRIX ADD)
- 2.SUBROUTINE CMA (COMPLEX MATRIX ADD)
- 3.SUBROUTINE RMM (REAL MATRIX MULTIPLY)
- 4.SUBROUTINE CMM (COMPLEX MATRIX MULTIPLY)
- 5.SUBROUTINE RMI (REAL MATRIX INVERSE)
- 6.SUBROUTINE CMI (COMPLEX MATRIX INVERSE)
- 7.SUBROUTINE RMT (REAL MATRIX TRANSPOSE)
- 8.SUBROUTINE CMT (COMPLEX MATRIX TRANSPOSE)
- 9.SUBROUTINE CMC (COMPLEX MATRIX CONJUGATE)

THE MAXIMUM DIMENSION OF ANY MATRIX YOU ENTER MUST BE 30 \* 30 OR LESS

TO USE ONE OF THE ABOVE SUBROUTINES ENTER AN INTEGER FROM 1 TO 9 OR ENTER THE INTEGER 10 TO EXIT.

WHICH SUBROUTINE (ENTER AN INTEGER FROM 1 TO 10)?

Press 6

Press return and the 6 is added to the screen as well as the following:

INPUT/OUTPUT DATA FOR SUBROUTINE CMI  
WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES(Y OR N)?

Press n and return and answer the next question:

DO YOU WANT THE OUTPUT DATA IN RECTANGULAR COORDINATES(Y OR N)?

Press n and return and answer the next question:

DO YOU WANT THE OUTPUT IN EXPONENTIAL FORMAT (Y OR N)?

Press y and return and answer the next question:

WHAT IS THE DIMENSION N OF THE A MATRIX ?

Press 3 and return and the following appears added to the screen

FOR A COMPLEX MATRIX DENOTED A,  
A = AMAG/AANGLE WHERE AMAG IS THE MAGNITUDE  
AND AANGLE IS THE ANGLE (IN DEGREES) OF A.  
IN OTHER WORDS ENTER A IN POLAR COORDINATES.

ENTER THE FIRST ROW OF THE MATRIX AMAG  
ENTER EACH NUMBER THEN PRESS RETURN.

?

Press 1 and return, 1 and return and 1 and return which adds:

```
? 1 ? 1 ? 1
ENTER NEXT ROW OF THE MATRIX AMAG
?
```

Press 1 and return, 1 and return and 1 and return which adds:

```
? 1 ? 1 ? 1
ENTER THE NEXT ROW OF THE MATRIX AMAG
?
```

Press 1 and return, 1 and return and 1 and return which adds:

```
? 1 ? 1 ? 1
ENTER THE FIRST ROW OF THE MATRIX AANGLE
ENTER EACH NUMBER THEN PRESS RETURN.
?
```

Press 0 and return, 0 and return and 0 and return adding:

```
0 ? 0 ? 0
ENTER THE NEXT ROW OF THE MATRIX AANGLE
?
```

Press 0 and return, 240 and return and 120 and return adding:

```
0 ? 240 ? 120
ENTER THE NEXT ROW OF THE MATRIX AANGLE
?
```

NB:  $a = 120^\circ$ ,  
 $a^2 = 240^\circ$

Press 0 and return, 120 and return and 240 and return adding:

```
0 ? 120 ? 240
USE THE CTRL PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE
RESULTS, PRESS RETURN TO CONTINUE
```

Do not use the Ctrl PRINT SCREEN option at this stage.  
Press return and the screen now shows A and A<sup>-1</sup> in exponential form:

```
THE MATRIX A = AMAG / AANGLE IS
1.000E+00 0.000E+00D 1.000E+00 0.000E+00D 1.000E+00 0.000E+00D
1.000E+00 0.000E+00D 1.000E+00 2.400E+02D 1.000E+00 1.200E+02D
1.000E+00 0.000E+00D 1.000E+00 1.200E+02D 1.000E+00 2.400E+02D

THE MATRIX INVERSE AI = AIMAG / AIANGLE IS
3.333E-01 5.123E-06D 3.333E-01-5.123E-06D 3.333E-01 0.000E+00D
3.333E-01-2.561E-06D 3.333E-01 1.200E+02D 3.333E-01 2.400E+02D
3.333E-01 0.000E+00D 3.333E-01 2.400E+02D 3.333E-01 1.200E+02D

REMOVE Ctrl PRINT SCREEN AND PRESS RETURN TO CONTINUE
```



It can be seen that the AANGLES in Row 1 Column 1, Row 1 Column 2, Row 2 Column 1 tend towards zero and can thus be assumed as zero.

The program thus confirms that the inversion of A is correct.

Press return to continue and the screen shows:

```

THIS PROGRAM CONTAINS THE FOLLOWING NINE SUBROUTINES:

1:SUBROUTINE RMA (REAL MATRIX ADD)
2:SUBROUTINE CMA (COMPLEX MATRIX ADD)
3:SUBROUTINE RMM (REAL MATRIX MULTIPLY)
4:SUBROUTINE CMM (COMPLEX MATRIX MULTIPLY)
5:SUBROUTINE RMI (REAL MATRIX INVERSE)
6:SUBROUTINE CMI (COMPLEX MATRIX INVERSE)
7:SUBROUTINE RMT (REAL MATRIX TRANSPOSE)
8:SUBROUTINE CMT (COMPLEX MATRIX TRANSPOSE)
9:SUBROUTINE CMC (COMPLEX MATRIX CONJUGATE)

THE MAXIMUM DIMENSION OF ANY MATRIX YOU ENTER MUST BE 30*30
OR LESS

TO USE ONE OF THE ABOVE SUBROUTINES ENTER AN INTEGER FROM 1
TO 9. OR ENTER THE INTEGER 10 TO EXIT.

WHICH SUBROUTINE(ENTER AN INTEGER 1 TO 10) ?

```

Should one wish to exit from the program, press 10 and return.

Now before proceeding with the next program we should understand the following:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$

$$V_p = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad V_s = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \quad A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \text{where:}$$

$V_p$  = phase voltages  
 $V_s$  = sequence voltages

or

$$\begin{aligned} V_a &= V_0 + V_1 + V_2 \\ V_b &= V_0 + a^2 V_1 + a V_2 \\ V_c &= V_0 + a V_1 + a^2 V_2 \end{aligned}$$

$$V_p = AV_s$$

and

$$V_s = A^{-1} V_p$$

where:

$$A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

and

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

which can be written as three separate equations:

$$\begin{aligned} V_0 &= \frac{1}{3} (V_a + V_b + V_c) \\ V_1 &= \frac{1}{3} (1 + a)V_b + \frac{1}{3} (1 + a^2)V_c \\ V_2 &= \frac{1}{3} (1 + a^2)V_b + \frac{1}{3} (1 + a)V_c \end{aligned}$$

also

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$
  
$$I_p = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad I_s = \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \quad A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

where:  
I<sub>p</sub> = phase currents  
I<sub>s</sub> = sequence currents

$$I_p = AI_s$$

$$I_s = A^{-1} I_p$$

From which:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

and the phase currents are:

$$\begin{aligned} I_a &= I_0 + I_1 + I_2 \\ I_b &= I_0 + a^2 I_1 + a I_2 \\ I_c &= I_0 + a I_1 + a^2 I_2 \end{aligned}$$

and the sequence currents are:

$$\begin{aligned} I_0 &= \frac{1}{3} (I_a + I_b + I_c) \\ I_1 &= \frac{1}{3} (I_a + a I_b + a^2 I_c) \\ I_2 &= \frac{1}{3} (I_a + a^2 I_b + a I_c) \end{aligned}$$

NB ! The above only applies to the zero, positive and negative sequence components of phase a.

The next program contains the following three symmetrical component subroutines:

- (1) SEQVEC - computes the complex sequence vector  $V_s = A^{-1} V_p$  for any three-phase complex phase vector  $V_p$ .
- (2) PHAVEC - computes the complex phase vector  $V_p = A V_s$  for any three-phase complex sequence vector  $V_s$ .
- (3) SEQIMP - computes the  $3 \times 3$  complex sequence impedance matrix  $Z_s = A^{-1} Z_p A$  for any  $3 \times 3$  complex phase impedance matrix  $Z_p$ .

The V vectors in the above subroutines can be three-phase voltage vectors, three-phase current vectors, or any vectors with three complex components.

Now proceeding

Press 10 and return

C:\>

Enter cd Power and press return

C:\POWER>

Enter CHAP3 and press return twice.

The screen shows:

```
THIS PROGRAM CONTAINS THE FOLLOWING THREE SUBROUTINES:

1: SUBROUTINE SEQVEC (VP, VS)
   SEQVEC COMPUTES THE SEQUENCE VECTOR VS=(AINV)VP
2: SUBROUTINE PHAVEC (VP, VS)
   PHAVEC COMPUTES THE PHASE VECTOR VP=(A)VS
3: SUBROUTINE SEQIMP (ZP, ZS)
   SEQIMP COMPUTES THE SEQUENCE IMPEDANCE MATRIX
   ZS=(AINV)ZP(A)

TO USE ONE OF THE ABOVE SUBROUTINES, ENTER AN INTEGER FROM 1 TO
3 OR ENTER THE INTEGER 4 TO EXIT.

WHICH SUBROUTINE (ENTER AN INTEGER FROM 1 TO 4)?
```

### EXPERIMENT.2

As we wish to compute the sequence components of an unbalance three phase voltage vector, subroutine (1) must be selected.

$$V_p = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 200 / \_0^\circ \\ 190 / \_250^\circ \\ 215 / \_110^\circ \end{bmatrix}$$

Enter 1

Added to the screen is the following:

```
WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES (Y OR N)?
```

Enter N and press return:

```
DO YOU WANT THE OUTPUT IN RECTANGULAR COORDINATES (Y OR N)?
```

Enter N and press return:

DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT (Y OR N)?

Enter N and press return:

INPUT/OUTPUT DATA FOR SUBROUTINE SEQVEC  
THE COMPLEX VECTOR V IS DENOTED  
 $V = VMAG / \_ VANGLE$ , WHERE VMAG IS THE MAGNITUDE AND VANGLE IS  
THE ANGLE (IN DEGREES) OF V.  
IN OTHER WORDS, ENTER V IN POLAR COORDINATES.

ENTER THE FIRST ELEMENT OF THE VECTOR VPMAG  
?

Enter 200, press return:

ENTER THE SECOND ELEMENT OF THE VECTOR VPMAG  
?

Enter 190, press return:

ENTER THE THIRD ELEMENT OF THE VECTOR VPMAG  
?

Enter 215, press return:

THE COMPLEX VECTOR V IS DENOTED  
 $V = VMAG / \_ VANGLE$ , WHERE VMAG IS THE MAGNITUDE AND VANGLE IS  
THE ANGLE (IN DEGREES) OF V.  
IN OTHER WORDS, ENTER V IN POLAR COORDINATES

ENTER THE FIRST ELEMENT OF THE VECTOR VPANGLE  
?

Enter 0, press return:

ENTER THE SECOND ELEMENT OF THE VECTOR VPANGLE  
?

Enter 250, press return:

ENTER THE THIRD ELEMENT OF THE VECTOR VPANGLE  
?

Enter 110, press return:

USE THE Cntrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS  
PRESS RETURN TO CONTINUE

Do not use Cntrl PRINT SCREEN option at this stage.  
Press return

THE MATRIX VP = VPMAG /\_ VPANGLE IS (INPUT DATA = VP)

200 0 DEG  
190 250 DEG  
215 110 DEG

THE MATRIX VS = VSMAG /\_ VSANGLE IS (OUTPUT DATA = VS)

21.93908 20.91195 DEG  
199.621 -.4153456 DEG  
21.09858 197.6118 DEG

WHICH SUBROUTINE (ENTER AN INTEGER FROM 1 TO 4)?

Checking the solution:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} 200 /_{-0^\circ} \\ 190 /_{-250^\circ} \\ 215 /_{-110^\circ} \end{bmatrix} = \boxed{V_s = A^{-1} V_p}$$

$$\begin{aligned} V_0 &= \frac{1}{3}(200/_{-0^\circ} + 190 /_{-250^\circ} + 215 /_{-110^\circ}) \\ &= 21,94 /_{-20,98^\circ} \text{ Volts} \end{aligned}$$

$$\begin{aligned} V_1 &= \frac{1}{3}(200/_{-0^\circ} + 1/_{-120^\circ} * 190/_{-250^\circ} + 1/_{-240^\circ} * 215/_{-110^\circ}) \\ &= 199,62 /_{-0,41^\circ} \text{ Volts} \end{aligned}$$

$$\begin{aligned} V_2 &= \frac{1}{3}(200/_{-0^\circ} + 1/_{-240^\circ} * 190/_{-250^\circ} + 1/_{-120^\circ} * 215/_{-110^\circ}) \\ &= 21,09 /_{-197,7^\circ} \text{ Volts} \end{aligned}$$

Should we wish now to work the problem in reverse, that is:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \boxed{V_p = A V_s}$$

Then:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 21,93908 \ / \_ 20,91195^\circ \\ 199.621 \ / \_ -0,41534^\circ \\ 21,09858 \ / \_ 197,6118^\circ \end{bmatrix}$$

To proceed we must select subroutine (2)

Enter 2

Answer n to the next three questions.

Enter 21.93908 for the first element of vector VSMAG and press return. (NB ! Use a "." not a ",")

Enter 199.621 and press return.

Enter 21.09858 and press return.

Enter 20.91195° for the first element of the vector VSANGLE and press return.

Enter -0.41534° and press return.

Enter 197.6118° and press return.

Do not use Cntrl PRINT SCREEN option at this stage.

Press return to continue.

The Screen shows and confirms the values of Vp.

```

THE MATRIX VS = VSMAG /_ VSANGLE IS (INPUT DATA = VS)
21.93908  20.91195 DEG
199.621  - .41534 DEG
21.09858  197.6118 DEG

THE MATRIX VP = VPMAG /_ VPANGLE IS (OUTPUT DATA = VP)
200.0001  3.005282E-06 DEG
190  250 DEG
215.0001  110 DEG

WHICH SUBROUTINE(ENTER AN INTERGER FROM 1 TO 4)?

```

### EXPERIMENT.3

In a three phase four-wire system the currents in the R, Y, and B lines under abnormal conditions of laoding were as follows

$$I_r = 50 \ / \_ 0^\circ \text{ A}, \ I_y = 60 \ / \_ 60^\circ \text{ A}, \ I_b = 70 \ / \_ -30^\circ \text{ A}$$

Using this program determine the positive,negative and zero sequence currents in the R line.

This is represented as follows:

$$\begin{bmatrix} I_o \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_r \\ I_y \\ I_b \end{bmatrix} = \boxed{I_s = A^{-1} I_p}$$

Now proceeding:

- Enter 1 and press return.
- Enter 50 for the first element of the vector IPMAG, press return.
- Enter 60 for the second element, press return.
- Enter 70 for the third element, press return.
- Enter 0 for the first element of the vector IPANGLE, press return.
- Enter 60 for the second element, press return.
- Enter -30 for the third element, press return.

The screen shows the following results:

```

THE MATRIX IP = IPMAG/_ IPANGLE IS (INPUT DATA = VP)

50   0 DEG
60   60DEG
70  -30DEG

THE MATRIX IS = ISMAG /_ ISANGLE IS (OUTPUT DATA = IS)

47.21367  6.87768DEG
26.273    206.3629DEG
27.33615  12.70661DEG

WHICH SUBROUTINE(ENTER AN INTEGER FROM 1 TO 4)?

```

Now working in reverse:

$$\boxed{IP = A I_s}$$

- Select subroutine (2), press 2 and return.
- Enter n for the next three questions, press return.
- Enter 47.21367 for the first element of vector VSMAG, press return.
- Enter 26.273 for second element, press return.
- Enter 27.33615 for third element, press return.
- Enter 6.87768 for first element of vector VSANGLE, press return.
- Enter 206.3629 for second element, press return.
- Enter 12.70661 for the third element, press return.
- Do not use Ctrl PRINT SCREEN option at this stage.



The screen shows and confirms the values of IP

```

THE MATRIX Is = IsMAG/_IsANGLE IS(INPUT DATA = Is)

47.21367  6.87768DEG
26.273    206.3629DEG
27.33615  12.70661DEG

THE MATRIX IP = IPMAG/_IPANGLE IS(OUTPUT DATA = IP)

49.99999  7.649813E-06DEG
60  59.99999DEG
70 -30DEG

WHICH SUBROUTINE(ENTER AN INTEGER FROM 1 TO 4)?
    
```

(NB! TAKE 49.99999 AS 50, 7.649813e-06 as 0° and 59.99999 as 60°)

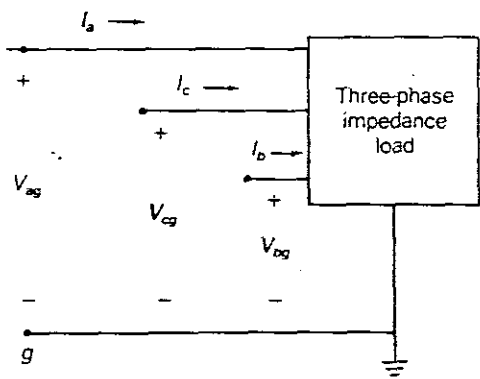
The above sequence component results are only for phase "a".

As the program is unable to produce the sequence components in phases "b" and "c", calculations are needed to determine these values:

$$\begin{aligned}
 I_{a0} &= I_{b0} = I_{c0} = 47.21367 / \underline{6.87768}^\circ \text{A} \\
 I_{b1} &= a^2 I_{a1} = 1 / \underline{240}^\circ * 26.273 / \underline{206.3629}^\circ = 26.273 / \underline{86.369}^\circ \text{A} \\
 I_{b2} &= a I_{a2} = 1 / \underline{120}^\circ * 27.33615 / \underline{12.70661}^\circ = 27.33615 / \underline{132.70661}^\circ \text{A} \\
 I_{c1} &= a I_{a1} = 1 / \underline{120}^\circ * 26.273 / \underline{206.3629}^\circ = 26.273 / \underline{326.3629}^\circ \text{A} \\
 I_{c1} &= a^2 I_{a2} \\
 &= 1 / \underline{240}^\circ * 27.33615 / \underline{12.70661}^\circ = 27.33615 / \underline{252.70661}^\circ \text{A}
 \end{aligned}$$

EXAMPLE (GLOVER PAGE 77)

A THREE PHASE IMPEDANCE LOAD, AS SHOWN IN FIGURE DIRECTLY BELOW, IS REPRESENTED BY THE FOLLOWING PHASE IMPEDANCE MATRIX:



$$Z_P = \begin{bmatrix} (10 + j30) & (5 + j20) & (5 + j20) \\ (5 + j20) & (10 + j30) & (5 + j20) \\ (5 + j20) & (5 + j20) & (10 + j30) \end{bmatrix} \text{ ohms}$$

EXPERIMENT. 4

A STAR CONNECTED SOURCE WITH THE FOLLOWING UNBALANCED LINE TO GROUND VOLTAGES IS APPLIED TO THE LOAD:

$$V_P = \begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} 277/_0^\circ \\ 260/_-120^\circ \\ 295/_115^\circ \end{bmatrix}$$

THE SOURCE NEUTRAL IS SOLIDLY GROUNDED. USE THIS SOFTWARE PACKAGE TO CALCULATE THE FOLLOWING:

- a. Load sequence impedance matrix  $Z_s$ .
- b. Load sequence voltage vector  $V_s$ .
- c. Load sequence current vector  $I_s$ .
- d. Load phase current vector  $I_p$ .
- e. Total complex power delivered to the sequence networks, namely:

$$S_s = V_s^T I_s^*$$

- f. Total complex power delivered to the three phase load, namely:

$$S_p = V_p^T I_p^*$$

SOLUTION USING SOFTWARE PACKAGE

NOW,

a)  $Z_s = A^{-1} Z_p A$

$$Z_s = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} 10+j30 & 5+j20 & 5+j20 \\ 5+j20 & 10+j30 & 5+j20 \\ 5+j20 & 5+j20 & 10+j30 \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

Subroutine (3) of CHAP3 of this package solves for  $Z_s$ . Select subroutine (3) by pressing 3, and answer the questions appearing on your screen as follows:

WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES(Y OR N)? Y

Press return

DO YOU WANT THE OUTPUT IN RECTANGULAR COORDINATES(Y OR N)?Y

Press return

DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT(Y OR N)? Y

Press return

THE COMPLEX MATRIX OF PHASE IMPEDANCES IS DENOTED  
 $ZP = ZPR + jZPI$ , WHERE ZPR IS THE REAL PART AND  
ZPI IS THE IMAGINARY PART.  
IN OTHER WORDS, ENTER ZP IN RECTANGULAR COORDINATES.

ENTER THE FIRST ROW OF THE MATRIX ZPR  
ENTER EACH NUMBER THEN PRESS RETURN  
? 10 ? 5 ? 5

ENTER THE SECOND ROW OF THE MATRIX ZPR  
? 5 ? 10 ? 5

ENTER THE THIRD ROW OF THE MATRIX ZPR  
? 5 ? 5 ? 10

THE COMPLEX MATRIX OF PHASE IMPEDANCES IS DENOTED  
 $ZP = ZPR + jZPI$ , WHERE THE ZPR IS THE REAL PART AND ZPI IS THE  
IMAGINARY PART.  
IN OTHER WORDS, ENTER ZP IN RECTANGULAR COORDINATES.

ENTER THE FIRST ROW OF THE MATRIX ZPI  
ENTER EACH NUMBER THEN PRESS RETURN  
? 30 ? 20 ? 20

ENTER THE SECOND ROW OF THE MATRIX ZPI  
? 20 ? 30 ? 20

ENTER THE THIRD ROW OF THE MATRIX ZPI  
? 20 ? 20 ? 30

USE THE Cntrl PRINT SCREEN OPTION NOW ,BY PRESSING Cntrl PRINT  
SCREEN(IF PRINTER AVAILABLE)  
PRESS RETURN AND A PRINTOUT WILL BE PRODUCED.  
If a printer is not available merely press return

The screen shows the results for Zs:

THE MATRIX  $ZP = ZPR + jZPI$  IS (INPUT DATA = ZP)  
1.000E+01+j3.000E+01 5.000E+00+j2.000E+01 5.000E+00+j2.000E+01  
5.000E+00+j2.000E+01 1.000E+01+j3.000E+01 5.000E+00+j2.000E+01  
5.000E+00+j2.000E+01 5.000E+00+j2.000E+01 1.000E+01+j3.000E+01  
THE MATRIX  $ZS = ZSR + jZSI$  IS (OUTPUT DATA = ZS)  
2.000E+01+j7.000E+01 4.768E-07+j9.537E-07 -1.431E-06+j9.537E-07  
-2.384E-07+j4.768E-07 5.000E+00+j1.000E+01 3.576E-07+j1.192E-07  
7.153E-07+j0.000E+00 1.073E-06+j0.000E+00 5.000E+00+j1.000E+01  
WHICH SUBROUTINE(ENTER AN INTEGER FROM 1 TO 4)?

b) NOW

$$V_s = A^{-1} V_p$$

$$V_s = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} 277/_0^\circ \\ 260/_-120^\circ \\ 295/_115^\circ \end{bmatrix}$$

Subroutine (1) of CHAP3 of this package solves for Vs. Select subroutine (1) by pressing 1, and answer the questions appearing on your screen as follows and thereafter press return:

WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES(Y OR N)? N

DO YOU WANT YHE OUTPUT IN RECTANGULAR COORDINATES (Y OR N)? Y

DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT (Y OR N)? Y

ENTER THE FIRST ELEMENT OF THE VECTOR VPMAG  
 ? 277 PRESS RETURN  
 ENTER THE SECOND ELEMENT OF THE VECTOR VPMAG  
 ? 260 PRESS RETURN  
 ENTER THE THIRD ELEMENT OF THE VECTOR VPMAG  
 ? 295 PRESS RETURN  
 ENTER THE FIRST ELEMENT OF THE VECTOR VPANGLE  
 ? 0 PRESS RETURN  
 ENTER THE SECOND ELEMENT OF THE VECTOR VPANGLE  
 ? -120 PRESS RETURN  
 ENTER THE THIRD ELEMENT OF THE VECTOR VPANGLE  
 ? 115 PRESS RETURN

PRESS RETURN TO CONTINUE or if you wish to obtain a printout of your results, use Cntrl PRINT SCREEN command.

The screen shows the input and output data:

THE VECTOR VP = VPR+jVPI IS (INPUT DATA = VP)  
 2.770E+02+j0.000E+00  
 -1.300E+02-j2.252E+02  
 -1.247E+02+j2.674E+02

THE VECTOR VS = VSR+jVSI IS (OUTPUT DATA = VS)  
 7.443E+00+j1.406E+01  
 2.770E+02-j8.570E+00  
 -7.402E+00-j5.494E+00

WHICH SUBROUTINE (ENTER AN INTEGER FROM 1 TO 4)?

c) NOW

$V_s = Z_s I_s$ $I_s = Z_s^{-1} V_s$
--------------------------------------

Subroutine (6) of CHAP2 of this package inverts a complex matrix, therefore  $Z_s^{-1}$  can be obtained from  $Z_s$ .  
Exit from CHAP3 by entering 4 and press enter.

C:\POWER>

Enter CHAP2 and press return

Press return to continue

Select subroutine (6) by pressing 6, and answer the questions appearing on your screen as follows and thereafter press return:

INPUT/OUTPUT DATA FOR SUBROUTINE CMI

WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES(Y OR N)? Y  
DO YOU WANT THE OUTPUT DATA IN RECTANGULAR COORDINATES(Y OR N)?Y  
DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT(Y OR N)? Y  
WHAT IS THE DIMENSION N OF THE A MATRIX( $Z_s$ )? 3

ENTER THE FIRST ROW OF THE MATRIX AR  
ENTER EACH NUMBER THEN PRESS RETURN  
? 2.000E+01 ? 4.768E-07 ? -1.431E-06  
ENTER THE NEXT ROW OF THE MATRIX AR  
?-2.384E-07 ? 5.000E+00 ? 3.576E-07  
ENTER THE NEXT ROW OF THE MATRIX AR  
? 7.153E-07 ? 1.073E-06 ? 5.000E+00  
ENTER THE FIRST ROW OF THE MATRIX AI  
ENTER EACH NUMBER THEN PRESS RETURN  
? 7.000E+00 ? 9.537E-07 ? 9.537E-07  
ENTER THE NEXT ROW OF THE MATRIX AI  
? 4.768E-07 ? 1.000E+00 ? 1.192E-07  
ENTER THE NEXT ROW OF THE MATRIX AI  
? 0.000E+00 ? 0.000E+00 ? 1.000E+01  
PRESS RETURN TO CONTINUE

The screen shows the input/output data

THE MATRIX A = AR+jAI IS(INPUT DATA =  $Z_s$ )

2.000E+01+j7.000E+01	4.768E-07+j9.537E-07	-1.431E-06+j9.537E-07
-2.348E-07+j4.768E-07	5.000E+00+j1.000E+01	3.576E-07+j1.192E-07
7.153E-07+j0.000E+00	1.073E-06+j0.000E+00	5.000E+00+j1.000E+01

THE MATRIX INVERSE AI = AIR+jAII IS(OUTPUT DATA =  $Z_s^{-1}$ )

3.774E-03_j1.321E-02	-3.599E-10+j1.260E-09	-2.088E-09	-3.243E-10
-6.117E-10+j2.339E-10	4.000E-02-j8.000E-02	9.536E-10+j2.861E-09	
6.478E-10+j5.938E-10	5.150E-09+j6.867E-09	4.000E-02-j8.000E-02	

$Z_s^{-1}$  is a 3 \* 3 matrix which now must be multiplied with  $V_s$  which is a 3 \* 1 matrix. The resultant will be a 3 \* 1 matrix.

Subroutine (4) of CHAP2 of this package multiplies two complex matrices together.

$$\boxed{\begin{bmatrix} I_s \end{bmatrix} = \begin{bmatrix} Z_s^{-1} \end{bmatrix} \cdot \begin{bmatrix} V_s \end{bmatrix}}$$

Select subroutine (4) by pressing 4, and answer the questions appearing on your screen as follows and thereafter press return:-  
INPUT/OUTPUT DATA FOR SUBROUTINE CMM

WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES (Y OR N)? Y  
DO YOU WANT THE OUTPUT DATA IN RECTANGULAR COORDINATES (Y OR N)? Y

HOW MANY ROWS IN THE A MATRIX ? 3

HOW MANY COLUMNS M IN THE A MATRIX ? 3

HOW MANY COLUMNS P IN THE B MATRIX ? 1

ENTER THE FIRST ROW OF THE MATRIX AR

ENTER EACH NUMBER THEN PRESS RETURN.

? 3.774E-03 ? -3.599E-10 ? -2.088E-09

ENTER THE NEXT ROW OF THE MATRIX AR ?

? -6.117E-10 ? 4.000E-02 ? 9.536E-10

ENTER THE NEXT ROW OF THE MATRIX AR

? 6.478E-10 ? 5.150E-09 ? 4.000E-02

ENTER THE FIRST ROW OF THE MATRIX AI

? -1.321E-02 ? 1.260E-09 ? -3.243E-10

ENTER THE NEXT ROW OF THE MATRIX AI

? 2.339E-10 ? -8.000E-02 ? 2.861E-09

ENTER THE NEXT ROW OF THE MATRIX AI

? 5.938E-10 ? 6.867E-09 ? -8.000E-02

ENTER THE FIRST ROW OF THE MATRIX BR

ENTER EACH NUMBER THEN PRESS RETURN

? 7.443E+00

ENTER THE NEXT ROW OF THE MATRIX BR

? 2.770E+02

ENTER THE NEXT ROW OF THE MATRIX BR

? -7.402E+00

ENTER THE FIRST ROW OF THE MATRIX BI

ENTER EACH NUMBER THEN PRESS RETURN

? 1.406E+01

ENTER THE NEXT ROW OF THE MATRIX BI

? -8.570E+00

ENTER THE NEXT ROW OF THE MATRIX BI

? -5.494E+00

USE THE Ctrl PRINT SCREEN OPTION NOW IF YOU WISH TO PRINT THE RESULTS

PRESS RETURN TO CONTINUE

The screen shows

```
THE MATRIX A=AR +jAI Is (INPUT DATA =ZS-1)
3.774E-03-j1.321E-02 -3.599E-10+j1.260E-09 -2.088E-09-j3.243E-10
-6.117E-10+j2.339E-10 4.000E-02-j8.000E-02 9.536E-10+j2.861E-09
6.478E-10+j5.938E-10 5.150E-09+j6.867E-09 4.000E-02-j8.000E-02
THE MATRIX B=BR + jBI Is (INPUT DATA = VS)
7.443E+00 j 1.406E+01
2.770E+02 j-8.570E+00
-7.402E+00 j-5.494E+00
THE MATRIX PRODUCT C=CR + jCI (OUTPUT DATA = Is)
2.138E-01 j-4.526E-02
1.039E+01 j-2.250E+01
-7.356E-01 j 3.724E-01
```

d) Now

$$I_p = A I_s$$

Subroutine (2) of CHAP 3 of this package computes the complex phase vector  $I_p = A I_s$  (or  $V_p = A V_s$ )  
Exit from CHAP 2 by entering 10 and press enter

C:\ Power>

Enter CHAP 3 and press return

Press return to continue

Select subroutine (2) by pressing 2, and answer the questions appearing on your screen as follows and thereafter press return:-

WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES (Y OR N)? Y  
DO YOU WANT THE OUTPUT IN RECTANGULAR COORDINATES (Y OR N)? Y  
DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT (Y OR N)? Y

ENTER THE FIRST ELEMENT TO THE VECTOR  $I_sR$

? 2.138E-01

ENTER THE SECOND ELEMENT OF THE VECTOR  $I_sR$

? 1.039E+01

ENTER THE THIRD ELEMENT OF THE VECTOR  $I_sR$

? -7.356E-01

ENTER THE FIRST ELEMENT OF THE VECTOR  $I_sI$

? -4.526E-02

ENTER THE SECOND ELEMENT OF THE VECTOR  $I_sI$

? -2.250E+01

ENTER THE THIRD ELEMENT OF THE VECTOR  $I_sI$

? 3.724E-01

USE Cntrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS  
PRESS RETURN TO CONTINUE

THE SCREEN SHOWS:-

```
THE VECTOR  $I_s = I_sR + jI_sI$   $I_s$  (INPUT DATA =  $I_s$ )
+2.138E-01 j-4.526E-02
+1.039E+01 j-2.250E+01
-7.356E-01 j+3.724E-01
THE VECTOR  $I_p = I_pR + jI_pI$   $I_s$  (OUTPUT DATA =  $I_p$ )
+9.868E+00 j-2.217E+01
-2.442E+01 j+1.383E+01
+1.519E+01 j+2.065E+01
WHICH SUBROUTINE (ENTER AN INTERGER FROM 1 TO 4) ?
```

WHERE:

$$I_s = \begin{bmatrix} 2.138E-01 & j-4.526E-02 \\ 1.039E+01 & j-2.250E+01 \\ -7.356E-01 & j+3.724E-01 \end{bmatrix} = \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$I_p = \begin{bmatrix} 9.868E+00 & j-2.217E+01 \\ -2.442E+01 & j1.383E+00 \\ 1.519E+01 & j2.065E+01 \end{bmatrix} = \begin{bmatrix} I_a \\ I_a \\ I_c \end{bmatrix}$$

Press 4 and exit from CHAP3.

e) Now,

The power delivered to a three phase network can be determined from the power delivered to the sequence networks. Let  $S_s$  be the total power delivered to the sequence networks, namely:

$$S_s = V_s^T * I_s^*$$

where: T denotes transpose and \* denotes complex conjugate.

Therefore to determine  $S_s$  we must first find the transpose of  $V_s$  and the complex conjugate of  $I_s$  and then multiply the two together.

Subroutine (8) of CHAP2 of this package computes the matrix transpose  $A^T$  of a  $N * M$  complex matrix. (Subroutine CMT).

Subroutine (9) of CHAP2 of this package computes the complex conjugate  $A^*$  of a  $N * M$  complex matrix  $A$ . (Subroutine CMC).

Subroutine (4) of CHAP2 of this package computes the matrix product. (Subroutine CMM).

Select subroutine (8) of CHAP2 by pressing 8, and answer the questions appearing on your screen as follows and thereafter press return:

```

INPUT/OUTPUT DATA FOR SUBROUTINE CMT
WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES(Y OR N)?Y
DO YOU WANT THE OUTPUT DATA IN RECTANGULAR COORDINATES(Y OR N)?Y
DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT(Y OR N)?Y
HOW MANY ROWS N IN THE A MATRIX ? 3 (Vs matrix)
HOW MANY COLUMNS M IN THE A MATRIX ? 1

```



ENTER THE FIRST ROW OF THE MATRIX AR  
ENTER EACH NUMBER THEN PRESS RETURN  
? 7.443E+00  
ENTER THE NEXT ROW OF THE MATRIX AR  
? 2.770E+02  
ENTER THE NEXT ROW OF THE MATRIX AR  
? -7.402E+00  
ENTER THE FIRST ROW OF THE MATRIX AI  
ENTER EACH NUMBER THEN PRESS RETURN  
? 1.406E+01  
ENTER THE NEXT ROW OF THE MATRIX AI  
? -8.570E+00  
ENTER THE NEXT ROW OF THE MATRIX AI  
? -5.494E+00  
PRESS RETURN TO CONTINUE

The screen shows:

```
THE MATRIX A = AR+jAI Is (INPUT DATA = Vs)
7.443E+00   j 1.406E+01
2.770E+02   j-8.570E+00           [ 3 * 1 matrix ]
-7.402E+00   j-5.494E+00

THE MATRIX TRANSPOSE AT = ATR+jATI Is (OUTPUT DATA = VsT)
7.443E+00 j1.406E+01 2.770E+02 j-8.570E+00 -7.402E+00 j-5.494E+00
           [ 1 * 3 matrix ]
```

Press return to continue  
Select subroutine (9) of chap2 BY PRESSING 9, AND ANSWER THE  
QUESTIONS APPEARING ON YOUR SCREEN As follows and thereafter press  
return:

```
INPUT/OUTPUT DATA FOR SUBROUTINE CMC
WILL YOU ENTER THE INPUT DATA IN RECTANGULAR COORDINATES
(Y OR N)? Y
DO YOU WANT THE OUTPUT DATA IN RECTANGULAR COORDINATES
(Y OR N)? Y
DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT (Y OR N)? Y
HOW MANY ROWS N IN THE A MATRIX? 3 (Is matrix)
HOW MANY COLUMNS M IN THE A MATRIX ? 1
```

ENTER THE FIRST ROW OF THE MATRIX AR  
ENTER EACH NUMBER THEN PRESS RETURN.  
? 2.138E-01  
ENTER THE NEXT ROW OF THE MATRIX AR  
?1.039E+01  
ENTER THE NEXT ROW OF THE MATRIX AR  
?-7.356E-01  
ENTER THE FIRST ROW OF THE MATRIX AI  
ENTER EACH NUMBER THEN PRESS RETURN  
?-4.526E-02  
ENTER THE NEXT ROW OF THE MATRIX AI  
?-2.250E+01  
ENTER THE NEXT ROW OF THE MATRIX AI  
? 3.724E-01  
PRESS RETURN TO CONTINUE

The screen shows:

```
THE MATRIX A = AR+jAI Is (INPUT DATA = Is)

2.138E-01  j4.526E-02
1.039E+01  j-2.250E+01
-7.356E-01 j3.724E-01

THE MATRIX CONJUGATE AC = ACR+jACI Is (OUTPUT DATA = Is*)

2.138E-01  j-4.526E-02
1.039E+01  j2.250E+01      [ 3 * 1 matrix ]
-7.356E-01 j-3.724E-01
```

PRESS RETURN TO CONTINUE

We must now multiply the two matrices together, namely a (1\*3) matrix ( $V_s^T$ ) times a (3\*1) matrix ( $I_s^*$ ).

Select subroutine (4) of CHAP2 by pressing 4, and answer the questions appearing on your screen as follows and thereafter press return:

```
INPUT/OUTPUT DATA FOR SUBROUTINE CMM
WILL YOU ENTER THE DATA IN RECTANGULAR COORDINATES(Y OR N)? Y
DO YOU WANT THE OUTPUT DATA IN RECTANGULAR COORDINATES(Y OR N)?Y
DO YOU WANT THE OUTPUT DATA IN EXPONENTIAL FORMAT(Y OR N)? Y
HOW MANY ROWS N IN THR A MATRIX? 1 (VsT matrix)
HOW MANY COLUMNS M IN THE A MATRIX? 3
HOW MANY COLUMNS P IN THE B MATRIX? 1
```

```
ENTER THE FIRST ROW OF THE MATRIX AR
ENTER EACH NUMBER THEN PRESS RETURN
? 7.443E+00 ? 2,770E+02 ? -7.402E+00
ENTER THE FIRST ROW OF THE MATRIX BR
ENTER EACH NUMBER THEN PRESS RETURN
?2.138E-01
ENTER THE NEXT ROW OF THE MATRIX BR
1.039E+01
ENTER THE NEXT ROW OF THE MATRIX BR
? -7.356E-01
ENTER THE FIRST ROW OF THE MATRIX BI
ENTER EACH NUMBER THEN PRESS RETURN
? -4.526E-02
ENTER THE NEXT ROW OF THE MATRIX BI
? 2.250E+01
ENTER THE NEXT ROW OF THE MATRIX BI
? -3.724E-01
PRESS RETURN TO CONTINUE
```

The screen shows:

```
THE MATRIX A = AR+jAI Is (INPUT DATA = VsT)
7.443E+00 j1.406E+01 2.770E+02 j-8.570E+0 -7.402E+0 j-5.494E+00
THE MATRIX B = BR+jBI Is (INPUT DATA = Is*)
2.138E-01 j-4.526E-02
1.039E+01 j2.250E+01
-7.356E-01 j-3.724E-01
THE MATRIX PRODUCT C = CR+jCI Is (OUTPUT DATA = Ss = VsT * Is*)
3.076E+03 j6.153E+03
```

PRESS RETURN TO CONTINUE

f) Now

The total complex power delivered to a three phase load is:

$$S_p = V_{ag}I_{a^*} + V_{bg}I_{b^*} + V_{cg}I_{c^*}$$

which in matrix form is:

$$S_p = [V_{ag} + V_{bg} + V_{cg}] \cdot \begin{bmatrix} I_{a^*} \\ I_{b^*} \\ I_{c^*} \end{bmatrix}$$

$$S_p = V_p^T \cdot I_p^*$$

$$S_p = (AV_s)^T \cdot (A I_s)^*$$

$$S_p = V_s^T [A^T \cdot A^*] I_s^*$$

where :  $A^T \cdot A^* = 3$

Therefore

$$S_p = 3 V_s^T * I_s^*$$

$$S_p = 3 \begin{bmatrix} V_0 + V_1 + V_2 \end{bmatrix} \cdot \begin{bmatrix} I_0^* \\ I_1^* \\ I_2^* \end{bmatrix}$$

$$S_p = 3 (V_0 I_0^* + V_1 I_1^* + V_2 I_2^*)$$

$$S_p = 3 S_s$$

Thus the total complex power  $S_p$  delivered to a three phase network equals three times the total complex power  $S_s$  delivered to the sequence networks.

Therefore

$$\begin{aligned} S_p &= 3 * ( 3.076E+03 + j6.153E+03 ) \\ &= 9.228E+03 + j18.459E+03 \\ &= 9.228E+03 + j1.846E+04 \end{aligned}$$

ALTERNATIVELY  $S_p$  can be found by using the software package, namely:

$$S_p = V_p^T * I_p^*$$

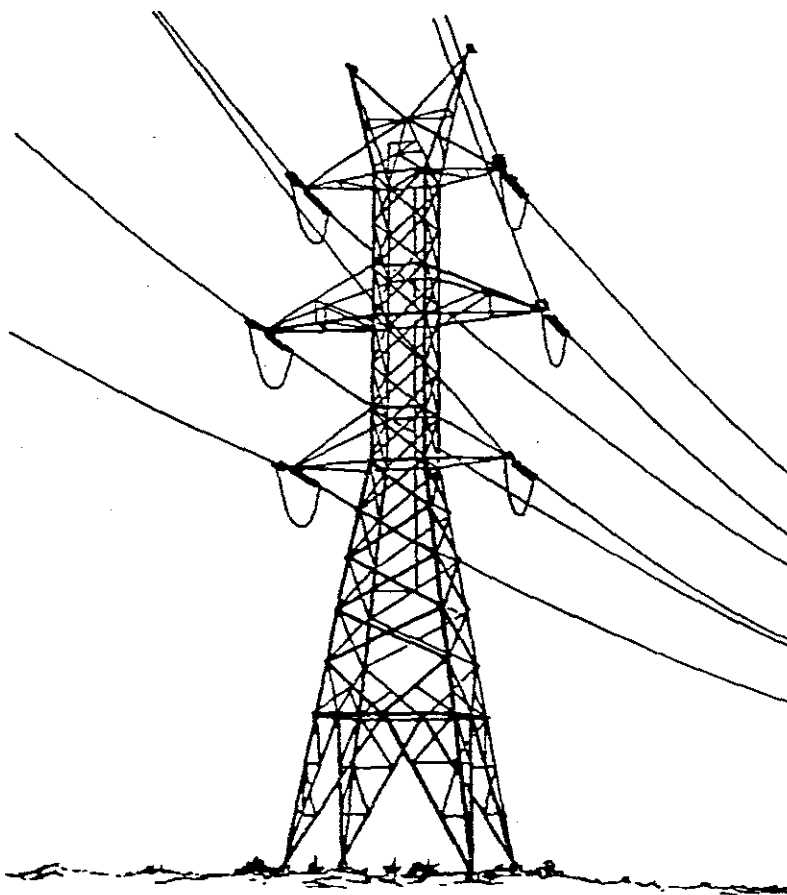
EXERCISE:

USE THE SOFTWARE PACKAGE AND SHOW THAT THE RESULT OBTAINED BY MULTIPLYING THE TRANSPOSE OF  $V_p$  WITH THE CONJUGATE OF  $I_p$  IS THE SAME AS THAT OBTAINED ABOVE.

COMPUTER-AIDED LABORATORY SESSION

ON

TRANSMISSION LINE CONSTANTS



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26-05-1992

TRANSMISSION LINE PARAMETERS

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(The details of the following questions and their answers appear towards the end of this publication.)

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---	----

5. REFERENCES

- (a) Power Systems - B.R. Gungor.
- (b) Elements of Power Systems Analysis - W.D. Stevenson.
- (c) Power System Analysis and Design - J.D. Glover/M. Sarma.

SECTION ONE  
INTRODUCTION TO THEORY OF LINE CONSTANTS

1. TRANSMISSION LINE DESIGN CONSIDERATIONS.

a. CONDUCTORS

Aluminium as against copper is now the most common conductor material for overhead transmission. The most common type is Aluminium conductor, Steel Reinforced (ASCR). Another type is Aluminium Clad Steel conductor (Alumoweld). EHV lines often have more than one conductor per phase, called a bundle. Bundle conductors have a lower electric field strength at the conductor surface, thereby reducing corona.

Shield wires are located above phase conductors for protection against lightning and are grounded to the towers. Some transmission lines have two shield wires. Conductor spacings, types and sizes determine series impedances and shunt admittances, the latter causing charging currents (capacitive) which injects reactive power into the power system.

b. RESISTANCE.

The dc resistance of a conductor at a specified temperature is:

$$R = \rho l / a \text{ ohms}$$

where:

- p = conductor resistivity
- l = length
- a = cross - sectional area

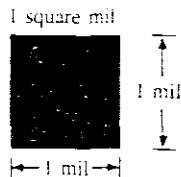
Two sets of units are commonly used, SI and English units. In English units "a" is expressed in circular mils (cmil), whereas in SI it is metres (  $m^2$  ).

Now:

$$1 \text{ mil} = 1/1000 \text{ inches} = 0.001 \text{ in}$$

$$\text{i.e. } 1000 \text{ mils} = 1 \text{ in}$$

A square mil is as follows:



By definition a wire that has a diameter of 1mil, has an area of 1 circular mil (CM):



One square mil is superimposed on the 1-CM area to show that the square mil has a larger surface area than the circular mil.

Now if  $d = 1\text{mil}$

$$A = \pi d^2 / 4, A = \pi/4 \text{ sq mils} = 1 \text{ CM}$$

or

$$1 \text{ sq mil} = 4/\pi \text{ CM}$$

Therefore to find an area in CM, a diameter must first be converted to mils if it is given in inches, for example

$$0.123 \text{ inches} = 123.0 \text{ mils}$$

also circular mils is expressed in kmils, for example

$$1113 \text{ kmils} = 1113000 \text{ mils}$$

EXAMPLE: What is the resistance of a 100ft length of copper wire with a diameter of 0.020 in at 20 degrees celsius, if the resistivity is 10.37 CM - ohms/ft?

$$p = 10.37 \quad d = 0.020\text{in} = 20\text{mils} \quad A = 20^2 = 400$$

$$R = (10.37)(100)/400 = 2.59 \text{ ohms}$$

EXAMPLE: If  $l = 100\text{m}$ ,  $p = 0.018 \text{ micro - ohm metre}$  and  $A = 40\text{EXP-6 metre squared}$ , find R in ohms?

$$R = (0.018\text{EXP-6})(100)/40\text{EXP-6} = 0.045 \text{ ohms}$$

Resistance depends upon:

1. Spiralling makes strands 1 or 2% longer, therefore stranded conductors have a dc resistance of 1 or 2% higher than that calculated above. If 2% is used then the above must be multiplied by 1.02.

2. Due to the skin effect the resistance in AC is higher than that in DC. For these values, manufacturers provide tables. TABLE A.4 which is attached is an example of such a TABLE.

For example: The "Finch" cable is aluminium 1113kmil having a dc resistance at 25 degrees of 0.0839 ohms per mile whereas it has an ac resistance of 0.0844 ohms per mile at 60Hz.



3. Current magnitude - magnetic conductors A magnetic conductor such as steel used for shield wires, depends on current magnitude. TABLE A.4 lists resistance at two different current levels.

For example: The "Cardinal" cable is aluminium 954kmil having a resistance of 0.0981 at small currents and a resistance of 0.1118 at 75% capacity at 50Hz.

4. Temperature The variation of resistance with temperature of metallic conductors is practically linear over the range of operation.

For example: The "Canary" cable has a resistance at 25 degrees of 0.104 and at 50 degrees of 0.1175 at 50Hz.

### C. INDUCTANCE.

1. Single conductor.

The total inductance due to both internal and external flux linkages is: (See Gungor pages 110 to 113 for the derivation).

$$L = 2 \text{EXP-7} * \ln(D/r') \text{ H/m}$$

where: the radius  $r'$  is that of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor of radius  $r$ .

$$r' = 0.7788r \text{ (See Stevenson page 49).}$$

and  $D$  is a point at a distance from the conductor.

2. Single Phase Two Wire Line. (See Gungor pages 113 to 114).

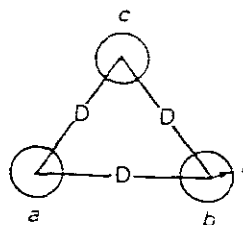
$$L = 4 \text{EXP-7} * \ln(D/r') \text{ H/m (Loop Inductance)}$$

where:  $D$  is the distance between the two lines.

3. Three Phase 3 Wire Line With Equal Phase Spacing " $D$ ".

$$L_1 = L_2 = 2 \text{EXP-7} * \ln(D/r') \text{ H/m}$$

where:  $L_1$  is the positive sequence inductance and  $L_2$  is the negative sequence inductance.



A Composite conductor consists of two or more solid cylindrical subconductors in parallel (e.g. stranded conductors).

When dealing with composite conductors it's GMR, i.e. it's Geometric Mean Radius must be used.

It is seldom necessary to calculate the GMR as Tables are usually provided by manufacturers which include it, but occasions do arise where the GMR must be calculated.

For example: The "Finch" cable has a GMR of 0.0435 ft at 60Hz. (See TABLE A.4.)

If stranded conductors are used instead of solid conductors and equal spacing is used,  $r'$  in the above formula is replaced by the GMR( $D_s$ ), therefore:

$$L_1 = L_2 = 2 \text{EXP-7} * \ln (D/D_s) \text{ H/m}$$

NB!  $D$  and  $D_s$  must be in the same unit, inches/feet/metres

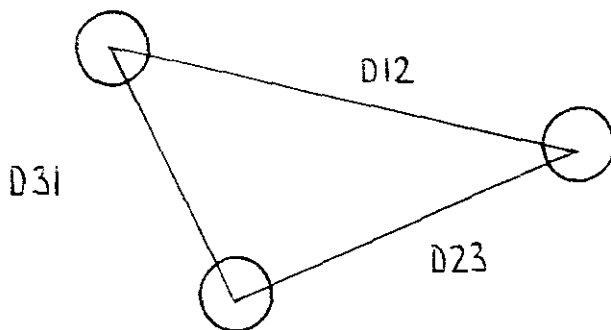
#### 4. THREE PHASE 3 WIRE LINE WITH UNEQUAL PHASE SPACINGS.

If spacings are unequal, the phase inductances are unequal.

Balance can be restored by transposition, which is an arrangement which ensures that each phase occupies a third of a line length averaging the inductance of each phase, resulting in:

$$L_a = L_b = L_c = L_1 = L_2 = 2 \text{EXP-7} * \ln (D_{eq}/D_s) \text{ H/m}$$

where:  $L_a$ ,  $L_b$  and  $L_c$  is the inductance/phase and  $L_1$  is the positive and  $L_2$  is the negative sequence inductance.



and

$$D_{eq} = (D_{12} * D_{23} * D_{31}) \text{EXP } 1/3$$

which is the GMD (Geometric Mean Distance) between phases and  $D_{12}$  is the distance between phase 1 and phase 2,  $D_{23}$  the distance between phases 2 and 3 and  $D_{31}$  between phases 3 and 1.

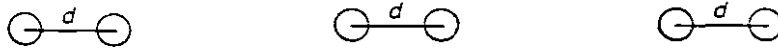
$D_s = \text{GMR}$ , but if the conductors are solid  $D_s$  is replaced by  $r'$ .

5. THREE PHASE BUNDLED CONDUCTOR LINES.

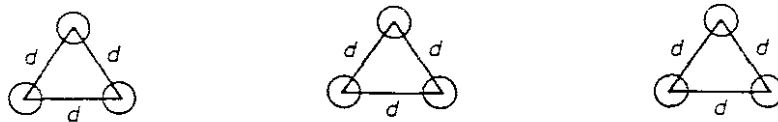
It is common practise for EHV lines to use more than one conductor per phase, a practise called bundling.

Bundling reduces the electric field strength at the conductor surface, reducing corona, decreasing an undesirable power loss, reducing communication interference and audible noise. It also reduces the series reactance of the line by increasing the GMR of the bundle.

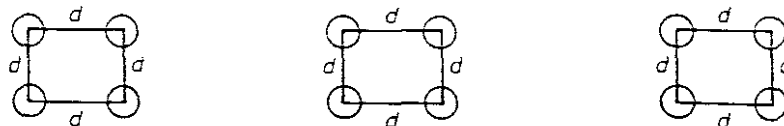
Two conductors per bundle:



Three conductors per bundle:



Four conductors per bundle:



With bundling the  $D_s$  is replaced by the GMR of the bundle  $D_{s1}$ , where:

Two conductor bundle

$$D_{s1} = (D_s * d) \text{EXP } 1/2$$

Three conductor bundle

$$D_{s1} = (D_s * d^2) \text{EXP } 1/3$$

Four conductor bundle

$$D_{s1} = 1.091 [(D_s * d^3) \text{EXP } 1/4]$$

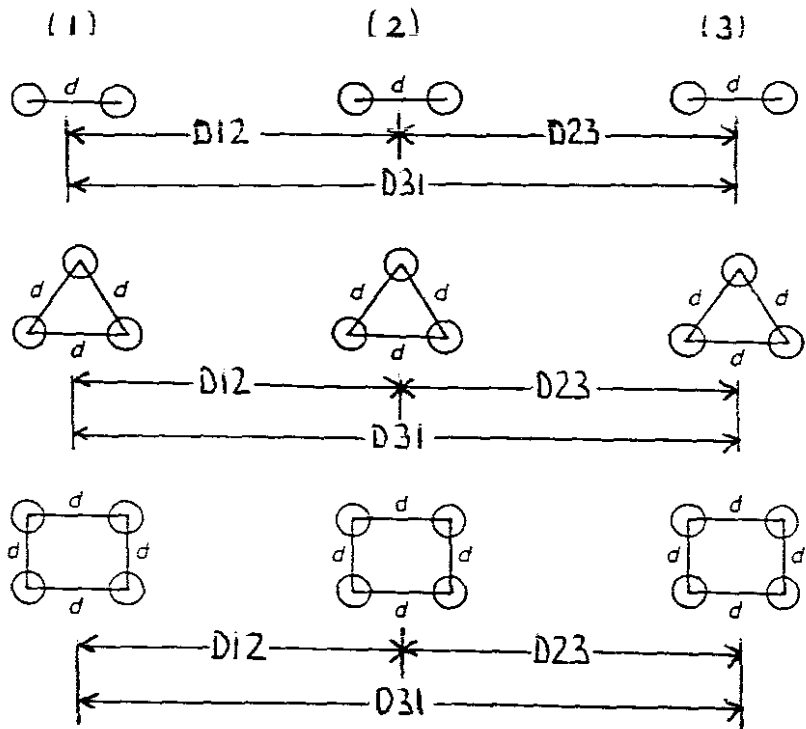
wherefrom:

$$L_1 = L_2 = 2 \text{EXP } -7 * \ln (D_{eq}/D_{s1}) \text{ H/m}$$

and  $L_1$  and  $L_2$  are the positive and negative sequence inductances.

NB! If the phase spacings are large compared to bundle spacings, then sufficient accuracy for  $D_{eq}$  is obtained by using the distances between bundle centres.

For example:



$$D_{eq} = (D_{12} * D_{21} * D_{31}) \text{EXP } 1/3$$

d. CAPACITANCE.

1. Single Phase Two Wire Line.

If the two wire line is fed from a transformer with a grounded centre tap, then the voltage between each conductor and ground is one half of the line-to-line voltage.

If  $C_x = C_y$  are the capacitances between any line and ground and ground is neutral then  $C_x = C_y = C_n$ , and

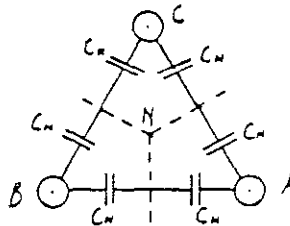
$$C_n = 2\pi\epsilon \div \ln(D/r) \text{ F/m line-to-neutral}$$

where:  $\epsilon_0 = 8.85 \text{EXP-12}$ ,  $D$  = distance between lines and  $r$  = the radius of a conductor.

If the line-to-line capacitance is required, then as  $C_n$  is twice in series the total capacitance will be  $C_n/2$ , therefore:

$$C_T = 1/2 * 2\pi\epsilon \div \ln(D/r) = \pi\epsilon \div \ln(D/r) \text{ F/m line-to-line}$$

2. THREE PHASE LINE WITH EQUAL SPACING.



The capacitance-to-neutral, neglecting the effect of earth and neutral conductors is:

$$C_n = 2\pi\epsilon \div \ln(D/r) \text{ F/m line-to-neutral}$$

which is the positive sequence capacitance and equals the negative sequence capacitance, therefore:

$$C_1 = C_2 = 2\pi\epsilon \div \ln(D/r) \text{ F/m line-to-neutral}$$

### 3. THREE PHASE UNEQUAL SPACING OF CONDUCTORS.

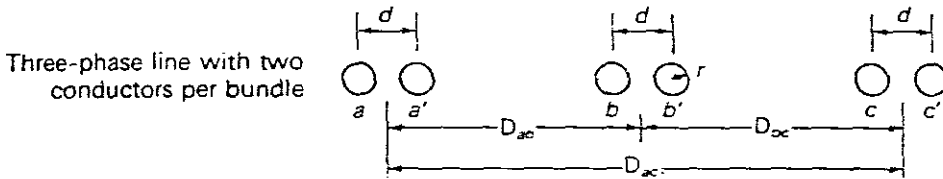
The phase-to-neutral capacitances are unequal but balance can be restored by transposing the line such that each phase occupies each position for one third of the line length. The resulting positive and negative sequence capacitance becomes:

$$C_1 = C_2 = 2\pi\epsilon \div \ln(\text{Deq}/r) \text{ F/m line-to-neutral}$$

where:

$$\text{Deq} = (\text{Dab} * \text{Dbc} * \text{Dca}) \text{EXP } 1/3$$

### 4. THREE PHASE UNEQUAL SPACING OF BUNDLED CONDUCTORS.



The figure shows a bundled conductor line with two conductors per bundle. If the line is transposed the positive and negative sequence capacitance will be:

$$C_1 = C_2 = 2\pi\epsilon \div \ln(\text{Deq}/\text{Dsc}) \text{ F/m line-to-neutral}$$

where:

$$\begin{aligned} \text{Dsc} &= (rd) \text{EXP } 1/2 \text{ for a two bundled conductor} \\ \text{Dsc} &= (rd^2) \text{EXP } 1/3 \text{ for a three bundled conductor} \\ \text{Dsc} &= 1.091(rd^3) \text{EXP } 1/4 \text{ for a four bundled conductor} \end{aligned}$$

and

$$\text{Deq} = (\text{Dab} * \text{Dbc} * \text{Dca}) \text{EXP } 1/3$$

"Deq" is the geometric mean of the distances between phases.

"Dsc" is analogous to Dsl for inductance except the conductor outside radius "r" replaces the conductor GMR "Ds".

The current supplied to the transmission line capacitance is called charging current. Capacitors deliver reactive power and are represented as parallel components (shunt admittances) whereas resistances and inductances are series components (series impedances) in networks.

e. THREE PHASE WITH NEUTRAL CONDUCTORS AND EARTH RETURN.

1. SERIES IMPEDANCE

a. The series impedance includes series resistance and series inductance. In the above mention was made only of positive and negative sequence inductances. Zero sequence inductance was ignored. To determine  $L_0$ , the return paths including neutral conductors and earth return must be considered. We will now include equations which can be used to determine the series impedance and the series sequence impedances for more general three phase lines and which contain neutral conductors and earth returns, thereby including zero sequence impedance.

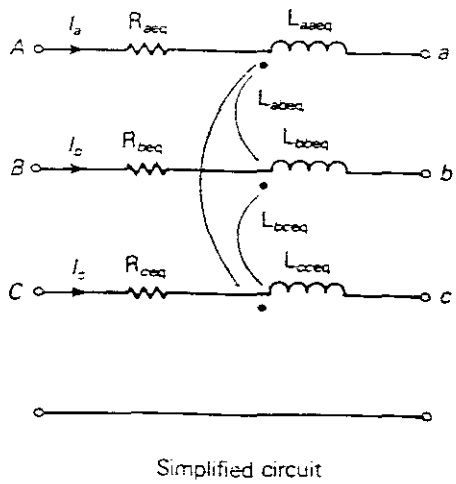
b. Now:

$$E_p = Z_p I_p \quad \text{----- (1)}$$

where  $E_p$  relates the phase conductor voltage drops (including neutral voltage drop) to the phase currents.  $Z_p$  is the series phase impedance, but is a  $3 \times 3$  matrix whose elements are denoted as follows:

$$Z_p = \begin{bmatrix} Z_{aaeq} & Z_{abeq} & Z_{aceq} \\ Z_{abeq} & Z_{bbeq} & Z_{bceq} \\ Z_{aceq} & Z_{bceq} & Z_{cceq} \end{bmatrix} \text{ ohms/m} \quad \text{----- (2)}$$

this having been derived from the simplified circuit of a three phase line with neutral conductors and an earth return represented as follows:



However if the line is completely transposed, the series phase impedance becomes: (See Glover page 165):

$$\hat{Z}_{\text{phat}} = \begin{bmatrix} Z_{aaeq} & Z_{abeq} & Z_{abeq} \\ Z_{abeq} & Z_{bbeq} & Z_{abeq} \\ Z_{abeq} & Z_{abeq} & Z_{ccee} \end{bmatrix} \text{ ohms/m} \quad \text{----- (3)}$$

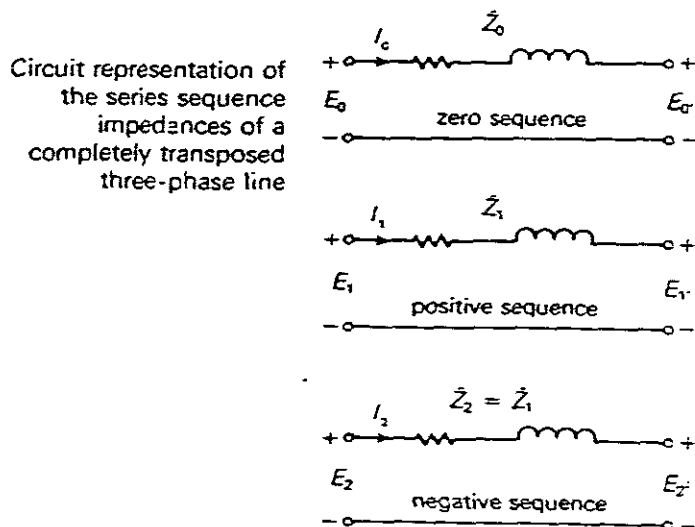
which can be transformed to the sequence domain to obtain the series sequence impedances whose elements are:

$$Z_s = \begin{bmatrix} Z_0 & Z_{01} & Z_{02} \\ Z_{10} & Z_1 & Z_{12} \\ Z_{20} & Z_{21} & Z_2 \end{bmatrix} \text{ ohms/m} \quad \text{----- (4)}$$

However if the the line is completely transposed it resolves to:

$$\hat{Z}_{\text{shat}} = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \text{ ohms/m} \quad \text{----- (5)}$$

from which a circuit representation of the series sequence impedances of a completely transposed three phase line is:





and,

$$\begin{bmatrix} E_{00}' \\ E_{11}' \\ E_{22}' \end{bmatrix} = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} * \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \quad \text{----- (6)}$$

wherefrom the phase voltdrops are:

$E_{00}' = Z_0 I_0$	----- (7)
$E_{11}' = Z_1 I_1$	----- (8)
$E_{22}' = Z_2 I_2$	----- (9)

2. SHUNT ADMITTANCES

a. For a three phase line with neutral conductors the shunt phase admittance matrix is given:

$$Y_p = j\omega C_p = j(2\pi f) C_p \text{ S/m} \quad \text{----- (10)}$$

or for a completely transposed line:

$$Y_{phat} = j\omega C_p = j(2\pi f) C_p \text{ S/m} \quad \text{----- (11)}$$

where:

$$C_p = \begin{bmatrix} C_{aa} & C_{ab} & C_{ac} \\ C_{ab} & C_{bb} & C_{bc} \\ C_{ac} & C_{bc} & C_{cc} \end{bmatrix} \text{ F/m} \quad \text{----- (12)}$$

however if the line is completely transposed the shunt capacitance becomes: (See Glover page 180):

$$C_p = \begin{bmatrix} C_{aa} & C_{ab} & C_{ab} \\ C_{ab} & C_{bb} & C_{ab} \\ C_{ab} & C_{ab} & C_{cc} \end{bmatrix} \text{ F/m} \quad \text{----- (13)}$$

The equations for  $Y_p$  and  $Y_{phat}$  can also be transformed to the sequence domain to obtain the shunt sequence admittance matrix:

$$Y_s = G_s + j(2\pi f)C_s \quad S/m \quad \text{-----(14)}$$

where:

$$C_s = \begin{bmatrix} C_o & C_{o1} & C_{o2} \\ C_{1o} & C_1 & C_{12} \\ C_{2o} & C_{21} & C_2 \end{bmatrix} \quad F/m \quad \text{-----(15)}$$

and  $G_s$  is also a  $3 \times 3$  matrix, therefore:

$$Y_s = \begin{bmatrix} 3 \times 3 \\ G_s \text{ matrix} \end{bmatrix} + j(2\pi f) \begin{bmatrix} C_o & C_{o1} & C_{o2} \\ C_{1o} & C_1 & C_{12} \\ C_{2o} & C_{21} & C_2 \end{bmatrix} \quad \text{-----(16)}$$

$$Y_s = \begin{bmatrix} 3 \times 3 \\ G_s \text{ matrix} \end{bmatrix} + \begin{bmatrix} j2\pi f C_o & j2\pi f C_{o1} & j2\pi f C_{o2} \\ j2\pi f C_{1o} & j2\pi f C_1 & j2\pi f C_{12} \\ j2\pi f C_{2o} & j2\pi f C_{21} & j2\pi f C_2 \end{bmatrix} \quad \text{-----(17)}$$

$$Y_s = \begin{bmatrix} G_{so}+j\omega C_o & G_{so1}+j\omega C_{o1} & G_{so2}+j\omega C_{o2} \\ G_{s1o}+j\omega C_{1o} & G_{s1}+j\omega C_1 & G_{s12}+j\omega C_{12} \\ G_{s2o}+j\omega C_{2o} & G_{s21}+j\omega C_{21} & G_{s2}+j\omega C_2 \end{bmatrix} \quad S/m \quad \text{---(18)}$$

However in general  $C_s$  is not diagonal but if the line is completely transposed and if  $G_s$  is neglected:

$$Y_{shat} = j(2\pi f) \begin{bmatrix} C_o & 0 & 0 \\ 0 & C_1 & 0 \\ 0 & 0 & C_2 \end{bmatrix} \quad S/m \quad \text{---(19)}$$

which is the shunt sequence admittance matrix.  $C_o$  being for the zero sequence,  $C_1$  for the positive sequence and  $C_2$  for the negative sequence.

f. ELECTRIC FIELD STRENGTH AT CONDUCTOR SURFACES AND AT GROUND LEVEL

1. AT CONDUCTOR SURFACES

When the electric field strength at a conductor surface exceeds the breakdown strength of air, current discharges occur. Although breakdown strength depends on many factors, a rough guide is 30kV/cm in a uniform electric field for dry air at atmospheric pressure. Transmission lines are usually designed so that 20kV/cm(rms) is not exceeded.

When line capacitances are determined and conductor voltages are known, the conductor charges can be calculated. The electric field strength at the surface of one phase conductor, neglecting fields due to other charges on other phase conductors and neutral wires is:

Er = q/2πεr V/m -----(20)

where r is conductor outside radius. If however the line is bundled then this formula changes.

2. AT GROUND LEVEL

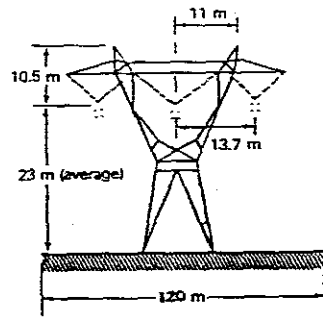
Although the electric field strength at ground level is much less than at surfaces where corona occurs, there is still capacitive coupling effects. Charges are induced on ungrounded equipment such as vehicles with rubber tyres located near a line. If a person contacts the vehicle and ground, a discharge current will flow to ground. Transmission line heights are designed to maintain discharge currents below prescribed levels for any equipment that may be on the right of way(ROW).

The follow TABLE shows examples of maximum ground level electric field strength:

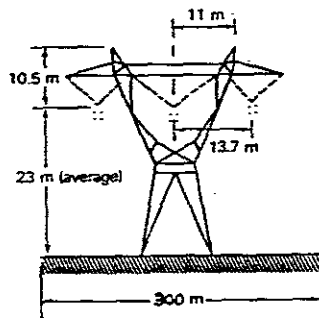
Table with 2 columns: LINE VOLTAGE kVrms and MAXIMUM GROUND-LEVEL ELECTRIC FIELD STRENGTH kVrms/m. Rows include 23(1ph), 23(3ph), 115, 345, 345(double circuit), 500, and 765.

The following are examples of rights of way:

a. ROW = 120m



b. ROW = 300m

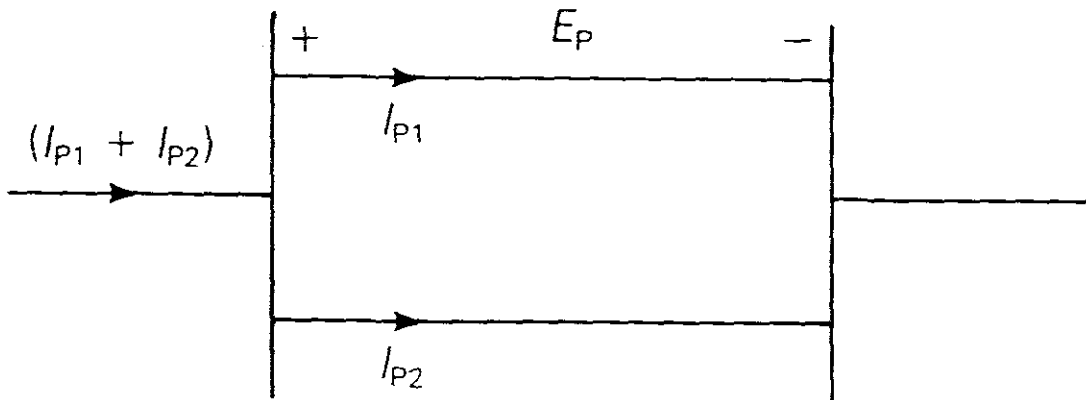


g. PARALLEL CIRCUITS THREE PHASE LINES

1. SERIES PHASE IMPEDANCE FOR DOUBLE CIRCUITS

If two parallel three phase circuits are close together, either on the same tower or on the same ROW, there are mutual inductive and capacitive couplings between the two circuits.

Consider the double circuit line shown as follows:



Since both lines are connected in parallel they have the same voltage drops for each phase. For simplicity the lines are not transposed but do include neutrals and earth returns.

After lumping the neutral voltage drop into the voltage drops across the phase conductors, and eliminating the neutral and earth return currents, it can be shown that:(See Glover page 186):

$$E_p = Z_{peq}(I_{p1} + I_{p2}) \text{-----}(21)$$

where:  $Z_{peq}$  is the equivalent series phase impedance for the double circuit line and is a 3 \* 3 matrix and takes into account the inductive coupling between the two circuits.  $I_{p1}$  and  $I_{p2}$  are the vectors of the phase currents for lines 1 and 2.  $E_p$  is the vector of the phase conductor voltage drops including the neutral voltage drop.

2. SHUNT ADMITTANCE DOUBLE CIRCUIT.

After eliminating the neutral wire charges, it can be shown that:(See Glover page 186):

$$(q_{p1} + q_{p2}) = C_{peq} V_p \text{-----}(22)$$

where:  $V_p$  is the vector of the phase-to-neutral voltages and  $q_{p1}$  and  $q_{p2}$  are the vectors of the phase-conductor charges for lines 1 and 2.  $C_{peq}$  is the equivalent shunt admittance.

Also that:(See Glover page 187):

$$Y_{peq} = j\omega C_{peq} \text{-----}(23)$$

where  $Y_{peq}$  is the equivalent 3 \* 3 matrix of the double circuit line and takes into account the capacitive coupling between the two circuits.

The corresponding sequence matrices of the double-circuit are computed in the same manner as for the single-circuit line.

NB!  $Z_{peq}$  and  $Y_{peq}$  are for the phase domain and can be transformed to the sequence domain from which  $Z_s$  and  $Y_s$  for the double circuit line is obtained. See software solutions which follow.

A PERSONAL COMPUTER PROGRAM IS TO FOLLOW WHICH WILL BE USED TO COMPUTE VALUES FOR THREE PHASE LINES WITH NEUTRAL CONDUCTORS AND EARTH RETURNS.-----

SECTION TWO  
EXPLANATION OF THE PACKAGE

The software package is entitled "LINE CONSTANTS" and will calculate the series impedance and shunt admittance matrices of single and double circuit three phase transmission lines. The program also calculates electric field strength at the surface of the phase conductors and a lateral profile (graphical representation) of ground level electric field strength can be obtained if your computer has graphics capability.

INPUT DATA

Input data for the program consists of: (1) line voltage (2) frequency (3) earth resistivity (4) ROW width and for each circuit (5) outside radius, GMR, and resistance of each phase conductor and each neutral wire (6) number of phase conductors in a bundle and bundle spacing and, (7) horizontal and vertical position of each phase and of each neutral wire. Resistance and GMR data are given for a specified temperature, frequency and current. TABLE A.4 will also be used to explain how certain values for the input data are obtained.

OUTPUT DATA

The output data consists of: the series phase impedance  $Z_p$ (eq.2)&(eq.3); the series sequence impedance matrix  $Z_s$ (eq.4)&(eq.5); the shunt phase admittance matrix  $Y_p$ (eq.10)&(eq.11) in matrix form; the shunt sequence admittance matrix  $Y_s$ (eq.18)&(eq.19); the conductor surface electric field strength  $E$ (eq.20) for each phase and the program will adapt it for two, three or four conductor bundles; and the ground level electric field strength from the centre of a ROW, which will be graphically represented. The output data will provide for a double circuit the sequence impedances and shunt sequence admittances for completely transposed lines and these values having been derived from (eq.23)&(eq.25).

RUNNING THE PROGRAM

When the program is run, the user selects one of the following: load the input data, update the input data, save the input data, run the program, display the output, and exit.

STORING

The user can store the input data for up to five separate cases in data files called LCI.DAT, LC2.DAT, LC3.DAT, LC4.DAT and LC5.DAT. When load or save is selected, the user is asked to enter an integer from one to five. The program then loads the input data from or saves input data to the input file that is selected.

UPDATING

When the user selects update, the input data is displayed on the monitor as follows:

The top row of the input data consists of:

- a. The number of circuits NC, where NC = 1 for a single circuit and NC = 2 for a double circuit.
- b. The earth resistivity RHO in ohm-metres.
- c. The rated line voltage, kV line-to-line.
- d. The frequency F(hz).
- e. The right-of-way ROW in metres.
- f. The number of neutral wires N1 for circuit 1 and N2 for circuit 2, where N1 and N2 can be 0 or 1 or 2.

The next consists of headings only

- a. Conductor resistance R in ohms/km.
- b. Conductor GMR in cm.
- c. Conductor outside diameter D in cm.
- d. Horizontal position X from the centre of the ROW and the vertical position in metres.
- e. Number of bundled conductors Nb, where Nb = 1, 2, 3, or 4.
- f. The bundle spacing d in cm.

The subsequent rows consists of:

After the row of headings there are rows for inputting data under each of the headings for each phase and for each neutral and this is provided for Circuit 1 and Circuit 2.

For example:

INPUT DATA TABLE LC1.DAT							
NC =	RHO =	V =	F =	ROW =	N1 =	N2 =	
	R	GMR	D	X	Y	Nb	d
CIRCUIT 1							
Phase a							
Phase b							
Phase c							
NEUTRAL 1							
NEUTRAL 2							
CIRCUIT 2							
Phase a							
Phase b							
Phase c							
NEUTRAL 1							
NEUTRAL 2							

When  $NC = 1$  for a single circuit, the input data for circuit 2 is not used when the program is run. Also, when  $N1$  or  $N2 = 0$  for no neutral wires, the input data for NEUTRAL 1 and NEUTRAL 2 are not used when the program is run. Similarly, when  $N1$  or  $N2 = 1$ , the input data for NEUTRAL 2 is not used.

CHANGING DATA

To make a data change, select update. The program will then display the input data and ask the user "are these correct (Y/N)?" The user should respond by pressing N for no. Next press either the up, down, left, or right cursor on the keyboard until the cursor is positioned under the number to be changed. Then press the space bar, type the new number and press return. Repeat this procedure for each number to be changed. After all changes are made, press the ESC key. The user can then save this data, run the program, and display the outputs.

OBTAINING OUTPUT DATA

Select run and the program completes its computations, then select display to obtain the output data.

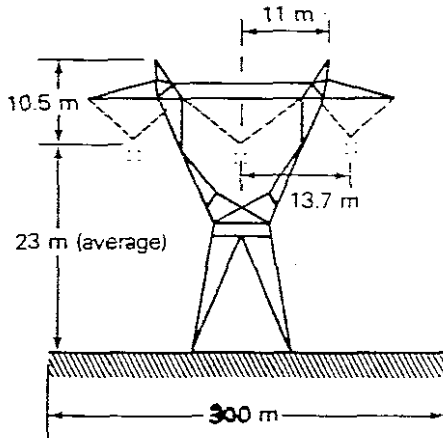


SECTION THREE  
EXAMPLES - SOFTWARE SOLUTIONS

EXAMPLE A.  
A 765kV, 4 Bundled conductor transmission line  
Three phase ACSR 954 kcmil 54/7

INFORMATION AVAILABLE:

The line is a 765kV, 60Hz, single circuit three phase line having four ACSR 954 kcmil conductors per bundle, with 45.7cm between conductors in the bundle. The line has flat horizontal phase spacing with 13.7m between adjacent phases and 23m average line height. There are two Alumoweld 7 no.8 neutral wires located 10.5m vertically above and 11m horizontally from the centre phase. The earth resistivity is 100 ohm-metres and the right-of-way width is 300m. It is represented by a diagram as follows:



Neutrals:

2-Alumoweld 7 no.8

Radius = 0.489cm

GMR = 0.0636cm

Resistance = 1.52ohms/km

Phase conductors:

4-ACSR 954 kcmil, 54/7

Radius = 1.519cm

GMR = 1.229cm

Resistance = 0.0701

ohms/km

Bundle spacing = 45.7cm

Earth resistivity = 100

ohm-m

Frequency = 60Hz

Voltage = 765kV

FIGURE 1.

The information given on the right hand side of the figure gives the Radius = 1.519cm, the GMR = 1.229cm and the Resistance = 0.0701 ohms per km. To obtain these values, TABLE A.4 is used, followed by the necessary conversion from imperial units to metric units. These values which are needed as input data are determined as follows:

a. OUTSIDE DIAMETER "D":

PHASE CONDUCTORS

The outside diameter as input data for this program must be in cm, where:

$$D = 2 * \text{radius (cm)}$$

It can be seen from TABLE A.4 that the 954 kcmil 54/7 is the "Cardinal" cable, having an outside diameter = 1.196 inches. Now:

$$\begin{aligned} \text{radius} &= 1.196 \div 2 = 0.598 \text{ inches} \\ &= 0.598 \div 12 = 0.04983 \text{ feet} \end{aligned}$$

$$\text{as 1ft} = 0.3048\text{m}$$

$$\begin{aligned} 0.04983\text{ft} &= 0.04983 * 0.3048\text{m} \\ &= 0.015189\text{m} \\ &= 0.015189 * 100\text{cm} \\ &= 1.519\text{cm} \end{aligned}$$

therefore:

$$\text{radius} = 1.519\text{cm as given above}$$

and

$$D = 2 * 1.519 = 3.308\text{cm}$$

NEUTRAL CONDUCTORS

The outside diameter as input data for this program must be in cm. As an Alumoweld cable table is not available we use the information given in Figure 1, namely:

$$D = 2 * \text{radius (cm)}$$

that is:

$$D = 2 * 0.489$$

$$D = 0.978\text{cm}$$

b. GEOMETRICAL MEAN RADIUS (GMR):

PHASE CONDUCTORS

The GMR as input data for this program must be in "cm".

The "Cardinal" cable gives the GMR = 0.0403ft at 60Hz.

Now: ...

$$\begin{aligned} 1\text{m} &= 39.37\text{inches} \\ &= 39.37 \div 12 \\ &= 3.2808\text{ft} \end{aligned}$$

$$\begin{aligned} 1\text{ft} &= 1 \div 3.208 \\ &= 0.3048\text{m} \end{aligned}$$

$$\begin{aligned} 0.0403\text{ft} &= 0.0403 * 0.3048 \\ &= 0.01228\text{m} \\ &= 0.01228 * 100\text{cm} \\ &= 1.229\text{cm} \end{aligned}$$

therefore:

$$\text{GMR} = 1.229\text{cm as given above}$$

NEUTRAL CONDUCTORS

The GMR as input data for this program must be in "cm".

From Figure 1 this value = 0.0636cm

therefore:

$$\text{GMR} = 0.0636\text{cm}$$

c. RESISTANCE PER CONDUCTOR (R):

PHASE CONDUCTORS

The resistance per conductor for this program must be in ohms per kilometre.

The "Cardinal" cable gives the resistance = 0.1128 ohms per conductor per mile at 50 degrees celsius at 75% current capacity.

Now:

1m = 39.37inches  
1km = 1000 \* 39.37  
= 39370inches  
= 39370 ÷ 36  
= 1093.611yards

1mile = 1760yards  
1km = 1093.611 ÷ 1760  
1km = 0.6211miles  
= 0.1128 \* 0.6211  
= 0.0701 ohms/km

therefore:

Resistance = 0.0701 ohms/km/conductor

NOTE !!!!!

The 4 bundle conductors make up one phase and are in parallel. The program only requires ohms/km/conductor as it works out the resultant total resistance when it runs.

NEUTRAL CONDUCTORS

The resistance per conductor for this program must be in ohms per km.

From Figure 1. this value = 1.52

therefore:

Resistance = 1.52 ohms/km/conductor

d. HORIZONTAL POSITION (X):

From Figure 1:

Phase a = -13.7m from centre of ROW  
Phase b = 0m as is on centre of ROW  
Phase c = 13.7m from centre of ROW  
Neutral 1 = -11m from centre of ROW  
Neutral 2 = 11m from centre of ROW

e. VERTICAL POSITION (Y):

From Figure 1:

Phase a	=	23m from ground level
Phase b	=	23m from ground level
Phase c	=	23m from ground level
Neutral 1	=	33.5m from ground level
Neutral 2	=	33.5m from ground level

f. NUMBER OF BUNDLED CONDUCTORS (NB):

From Figure 1:

Phase a = Phase b = Phase c = 4 bundled conductors/phase
Neutral 1 = Neutral 2 = 1 conductor

g. BUNDLE SPACING (d):

From Figure 1:

Phase a = Phase b = Phase c = 45.7cm
Neutral 1 = Neutral 2 = 0

h.

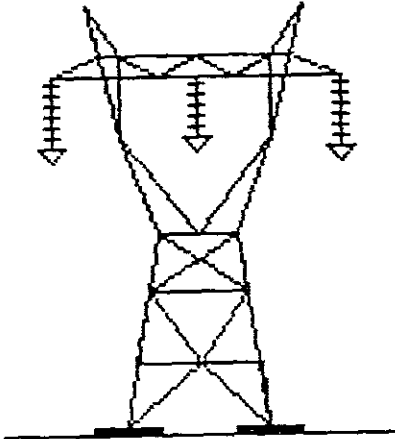
INPUT DATA

INPUT DATA TABLE LC1.DAT							
NC = 1 RHO = 100 V = 765 F = 60 ROW = 300 N1 = 2 N2 =							
	R	GMR	D	X	Y	Nb	d
CIRCUIT 1		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0701	1.229	3.038	-13.7	23	4	45.7
Phase b	.0701	1.229	3.038	0	23	4	45.7
Phase c	.0701	1.229	3.038	13.7	23	4	45.7
NEUTRAL 1	1.52	.0636	.978	-11	33.5	1	0
NEUTRAL 2	1.52	.0636	.978	11	33.5	1	0
CIRCUIT 2							
Phase a							
Phase b							
Phase c							
NEUTRAL 1							
NEUTRAL 2							

i. **RUNNING THE LINE CONSTANTS PROGRAM**

C:\>cd\Power, press return  
C:\Power>CHAP5, press return  
The following sketch is displayed:

**POWER SYSTEM ANALYSIS  
AND DESIGN SERIES**



**LINE CONSTANTS**

**WRITTEN BY:  
JALIL ELMERNISSI  
BOSTON 1987**

**Press any key to continue**

Press any key to continue, and again  
The screen shows:

INPUT DATA TABLE LC1.DAT						
NC =	RHO =	V =	F =	ROW =	N1 =	N2 =
R	GMR	D	X	Y	Nb	d
CIRCUIT 1						
Phase a						
Phase b						
Phase c						
NEUTRAL 1						
NEUTRAL 2						
CIRCUIT 2						
Phase a						
Phase b						
Phase c						
NEUTRAL 1						
NEUTRAL 2						

INPUT DATA TABLE # FROM 1 TO 5 [LC1.DAT]?

Press 1 (this selects LC1.DAT 1), press return  
The screen now shows:

MAIN MENU	
L	oad input data
U	update input data
S	ave input data from disk
R	un the program
D	isplay the output
E	xit
Enter Function:< >	

Press U,  
The screen shows:

INPUT DATA TABLE LC1.DAT							
-----							
NC = 1 RHO = 100 V = 765 F = 60 ROW = 120 N1 = 2 N2 = 2							
-----							
	R	GMR	D	X	Y	Nb	d
-----							
CIRCUIT 1		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0701	1.229	3.038	-13.7	23	4	45.7
Phase b	.0701	1.229	3.038	0	23	4	45.7
Phase c	.0701	1.229	3.038	13.7	23	4	45.7
NEUTRAL 1	1.52	.0636	.978	-11	33.5	1	0
NEUTRAL 2	1.52	.0636	.978	11	33.5	1	0
-----							
CIRCUIT 2							
Phase a	.0701	1.228	3.38	5	20	3	40
Phase b	.0701	1.228	3.38	15	20	3	40
Phase c	.0701	1.228	3.38	25	20	3	40
NEUTRAL 1	3.75	.0636	.978	8	29	1	0
NEUTRAL 2	3.75	.0636	.978	22	29	1	0

ARE THESE CORRECT (Y/N)?

The data shown above may partially agree with your input data and partially it may not. If it does, follow the STEP "R" below, if not the TABLE has to be updated. Proceed as follows:

Press N and return

The screen remains the same except instructions are given at the bottom of the TABLE on how to update, namely:

"USE UP,DOWN,LEFT,RIGHT,PRESS SPACE,ENTER NUMBER,PRESS RETURN AFTER MAKING ALL CHANGES,PRESS ESC TO EXIT"
---

If your top row has incorrect data, move cursor to this data, press space bar, enter corrected data, press return. If your Circuit.1 data is correct your cursor to Circuit.2 for deletion of all data given should it contain data irrelevant to this example.

To "DELETE" data:

Place cursor under incorrect data, press space bar then press return and the incorrect data changes to 0. Repeat this for each incorrect data that appears. It will be noticed that after return is pressed the cursor moves automatically to the next horizontal data position until the end of a row and then to the next row.

The screen should now be the same as the input TABLE above, namely:

INPUT DATA TABLE LC1.DAT							
-----							
NC = 1	RHO = 100	V = 765	F = 60	ROW = 300	N1 = 2	N2 =	
-----							
	R	GMR	D	X	Y	Nb	d
-----							
CIRCUIT 1		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0701	1.229	3.038	-13.7	23	4	45.7
Phase b	.0701	1.229	3.038	0	23	4	45.7
Phase c	.0701	1.229	3.038	13.7	23	4	45.7
NEUTRAL 1	1.52	.0636	.978	-11	33.5	1	0
NEUTRAL 2	1.52	.0636	.978	11	33.5	1	0
-----							
CIRCUIT 2							
Phase a							
Phase b							
Phase c							
NEUTRAL 1							
NEUTRAL 2							

STEP "R"

Press Esc to exit  
The screen now asks if your input data is correct.  
Press Y, press return  
The screen now returns to the MAIN MENU.  
Press R to run the program  
The program is run and then returns to the MAIN MENU  
Press D to display your results, the screen prompts,  
ENTER YOUR CASE NAME, enter EX.1(any name my be chosen),  
press return



The screen now displays your first result:

SINGLE CIRCUIT		EX.1	
SERIES PHASE IMPEDANCE MATRIX		Zp	EQ --(2) ohms/km
0.2283E+00+j7.189E-01	0.2122E+00+j3.979E-01	0.2084E+00+j3.499E-01	0.2122E+00+j3.979E-01
0.2122E+00+j3.979E-01	0.2323E+00+j7.121E-01	0.2122E+00+j3.979E-01	0.2283E+00+j7.189E-01
0.2084E+00+j3.499E-01	0.2122E+00+j3.979E-01	0.2283E+00+j7.189E-01	

This represents EQ.2, namely:

$$Z_p = \begin{bmatrix} Z_{aaeq} & Z_{abeq} & Z_{aceq} \\ Z_{abeq} & Z_{bbeq} & Z_{bceq} \\ Z_{aceq} & Z_{bceq} & Z_{cceq} \end{bmatrix} \text{ ohms/m} \quad \text{-----(2)}$$

Press space bar for next result:

SINGLE CIRCUIT		EX.1	
Zp FOR A COMPLETELY TRANSPOSED LINE		Zphat	EQ --(3) ohms/km
0.2296E+00+j7.166E-01	0.2109E+00+j3.819E-01	0.2109E+00+j3.819E-01	0.2109E+00+j3.819E-01
0.2109E+00+j3.819E-01	0.2296E+00+j7.166E-01	0.2109E+00+j3.819E-01	0.2109E+00+j3.819E-01
0.2109E+00+j3.819E-01	0.2109E+00+j3.819E-01	0.2296E+00+j7.166E-01	

This represents EQ.3, namely:

$$Z_{phat} = \begin{bmatrix} Z_{aaeq} & Z_{abeq} & Z_{abeq} \\ Z_{abeq} & Z_{bbeq} & Z_{abeq} \\ Z_{abeq} & Z_{abeq} & Z_{cceq} \end{bmatrix} \text{ ohms/m} \quad \text{-----(3)}$$

Press space bar for next result:

SINGLE CIRCUIT		EX.1	
SERIES SEQUENCE IMPEDANCE MATRIX		Zs	EQ --(4) ohms/km
0.6514E+00+j1.480E+00	0.1060E-01-j9.113E-03	-.1319E-01-j4.620E-03	0.1875E-01+j3.348E-01
-.1319E-01-j4.620E-03	0.1875E-01+j3.348E-01	-.2904E-01+j1.815E-02	0.3024E-01+j1.608E-02
0.1060E-01-j9.113E-03	0.3024E-01+j1.608E-02	0.1875E-01+j3.348E-01	

This represents EQ.4, namely:

$$Z_s = \begin{bmatrix} Z_o & Z_{o1} & Z_{o2} \\ Z_{1o} & Z_1 & Z_{12} \\ Z_{2o} & Z_{21} & Z_2 \end{bmatrix} \text{ ohms/m} \quad \text{----- (4)}$$

Press space bar for next result:

SINGLE CIRCUIT		EX.1
Zs FOR A COMPLETELY TRANSPOSED LINE	Zshat	EQ --(5) ohms/km
0.6514E+00+j1.480E+00	0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.1875E-01+j3.348E-01	0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	0.1875E-01+j3.348E-01

This represents EQ.5, namely:

$$Z_{shat} = \begin{bmatrix} Z_o & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \text{ ohms/m} \quad \text{----- (5)}$$

From the result it can be seen that  $Z_1 = Z_2$ .

Press space bar for next result:

SINGLE CIRCUIT		EX.1
SHUNT PHASE ADMITTANCE MATRIX	Yp	EQ --(10) s/km
+j4.898E-06	-j9.777E-07	-j2.541E-07
-j9.777E-07	+j5.083E-06	-j9.777E-07
-j2.541E-07	-j9.777E-07	+j4.898E-06

This represents EQ.10, which includes EQ.12 namely:

$$Y_p = j\omega C_p = j(2\pi f) C_p \text{ S/m} \quad \text{----- (10)}$$

$$C_p = \begin{bmatrix} C_{aa} & C_{ab} & C_{ac} \\ C_{ab} & C_{bb} & C_{bc} \\ C_{ac} & C_{bc} & C_{cc} \end{bmatrix} \text{ F/m} \quad \text{----- (12)}$$

Press space bar for next result:

SINGLE CIRCUIT		EX.1
Yp FOR A COMPLETELY TRANSPOSED LINE		Yphat EQ --(11) s/km
+j4.960E-06	-j7.365E-07	-j7.365E-07
-j7.365E-07	+j4.960E-06	-j7.365E-07
-j7.365E-07	-j7.365E-07	+j4.960E-06

This represents EQ.11, which includes EQ.13 namely:

$$Y_{phat} = j\omega C_p = j(2\pi f) C_p \text{ S/m} \quad \text{-----(11)}$$

$$C_p = \begin{bmatrix} C_{aa} & C_{ab} & C_{ab} \\ C_{ab} & C_{bb} & C_{ab} \\ C_{ab} & C_{ab} & C_{cc} \end{bmatrix} \text{ F/m} \quad \text{-----(13)}$$

Press space bar for next result:

SINGLE CIRCUIT		EX.1
SHUNT SEQUENCE ADMITTANCE MATRIX		Ys EQ --(18) s/km
0.0000E+00+j3.487E-06	-.1555E-06+j8.977E-08	0.1555E-06+j8.977E-08
0.1555E-06+j8.977E-13	0.7802E-13+j5.696E-06	0.4711E-06-j2.720E-07
-.1555E-06+j8.977E-08	-.4711E-06-j2.720E-07	-.7802E-13+j5.696E-06

This represents EQ.18, namely:

$$Y_s = \begin{bmatrix} G_{s0}+j\omega C_0 & G_{s01}+j\omega C_{01} & G_{s02}+j\omega C_{02} \\ G_{s10}+j\omega C_{10} & G_{s1}+j\omega C_1 & G_{s12}+j\omega C_{12} \\ G_{s20}+j\omega C_{20} & G_{s21}+j\omega C_{21} & G_{s2}+j\omega C_2 \end{bmatrix} \text{ S/m} \quad \text{---(18)}$$

Press space bar for next result:

SINGLE CIRCUIT		EX.1
Ys FOR A COMPLETELY TRANSPOSED LINE		Yshat EQ --(19) s/km
0.0000E+00+j3.487E-06	0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.0000E+00+j5.696E-06	0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	0.0000E+00+j5.696E-06

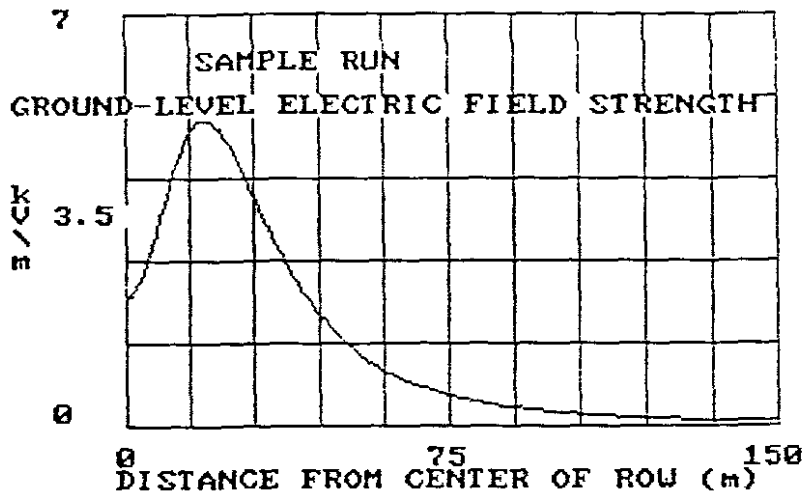
This represents EQ.19, namely:

$$\hat{Y} = j(2\pi f) \begin{bmatrix} C_0 & 0 & 0 \\ 0 & C_1 & 0 \\ 0 & 0 & C_2 \end{bmatrix} \text{ S/m} \quad \text{---(19)}$$

Press space bar for next result:

```
CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH  
  
PHASE: 1      20.61891 kV/cm  
PHASE: 2      22.5181 kV/cm  
PHASE: 3      20.61891 kV/cm  
  
MAXIMUM ELECTRIC FIELD STRENGTH IS:  22.5181 kV/cm
```

Press space bar to plot the "lateral profile" of the Ground Electric Field Strength:



Press space bar to return to the MAIN MENU, Select E to exit from the program.

Should you wish to print your output data use "PRINT SCREEN".

EXAMPLE B.

A 345kV, transmission line, double circuit

Three phase ACSR 2515 kcmil 76/19

INFORMATION AVAILABLE:

Using the LINE CONSTANTS program, calculate the equivalent series sequence impedance matrix and the equivalent shunt sequence admittance matrix for the double-circuit, three phase line shown in Figure.2: [PHASE ARRANGEMENT 1]

Phase conductors:  
1-ACSR 2515 kcmil, 76/19  
Radius = 2.388cm  
GMR = 1.893cm  
Resistance = 0.0280 ohms/km

Neutral conductors:  
2-Alumoweld 7 no.8  
Radius = 0.489cm  
GMR = 0.0636cm  
Resistance = 1.52 ohms/km

Earth Resistivity = 100 ohm-m  
Frequency = 60Hz  
Voltage = 345kV

Assume a ROW = 70m

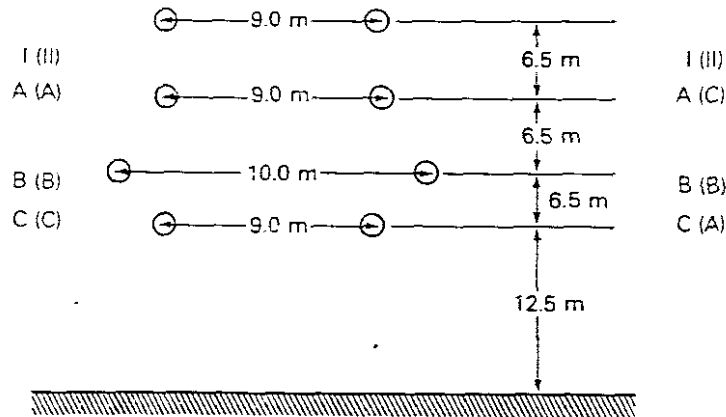
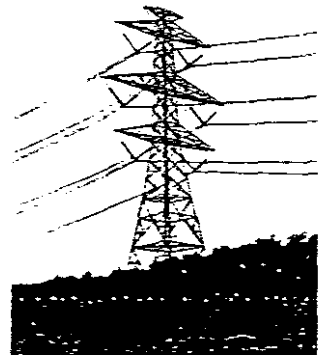


FIGURE. 2

A 345 kV double-circuit transmission line with self-supporting lattice steel towers

(Courtesy of Boston Edison Company)



The information given on above the figure gives the Radius = 2.388cm, the GMR = 1.893cm and the Resistance = 0.0280 ohms per km. To obtain these values, TABLE A.4 is used, followed by the necessary conversion from imperial units to metric units. These values which are needed as input data are determined as follows:

a. OUTSIDE DIAMETER "D":

PHASE CONDUCTORS

The outside diameter as input data for this program must be in cm, where:

$$D = 2 * \text{radius (cm)}$$

It can be seen from TABLE A.4 that the 2515 kcmil 76/19 is the "Joree" cable, having an outside diameter = 1.880 inches.

Now:

radius = 1.880 ÷ 2 = 0.940 inches  
          = 0.940 ÷ 12 = 0.07833 feet  
  
as 1ft = 0.3048m  
  
0.07833ft = 0.07833 \* 0.3048m  
          = 0.02388m  
          = 0.02388 \* 100cm  
          = 2.388cm  
therefore:  
  
radius = 2.388cm as given above  
  
          and  
  
D = 2 \* 2.388 = 4.780cm

NEUTRAL CONDUCTORS

The outside diameter as input data for this program must be in cm. As an Alumoweld cable table is not available we use the information given in Figure 2, namely:

$$D = 2 * \text{radius (cm)}$$

that is:

$$\begin{aligned} D &= 2 * 0.489 \\ D &= 0.978\text{cm} \end{aligned}$$

b. GEOMETRICAL MEAN RADIUS (GMR):

PHASE CONDUCTORS

The GMR as input data for this program must be in "cm".

The "Joree" cable gives the GMR = 0.0621ft at 60Hz.

Now:

$$\begin{aligned} 1\text{m} &= 39.37\text{inches} \\ &= 39.37 \div 12 \\ &= 3.2808\text{ft} \\ \\ 1\text{ft} &= 1 \div 3.208 \\ &= 0.3048\text{m} \\ \\ 0.0621\text{ft} &= 0.0621 * 0.3048 \\ &= 0.01893\text{m} \\ &= 0.01893 * 100\text{cm} \\ &= 1.893\text{cm} \\ \\ \text{therefore:} \\ \\ \text{GMR} &= 1.893\text{cm as given above} \end{aligned}$$

NEUTRAL CONDUCTORS

The GMR as input data for this program must be in "cm".

From Figure 1 this value = 0.0636cm

therefore:

$$\text{GMR} = 0.0636\text{cm}$$

c. RESISTANCE PER CONDUCTOR (R):

PHASE CONDUCTORS

The resistance per conductor for this program must be in ohms per kilometre.

The "Joree" cable gives the resistance = 0.0450 ohms per conductor per mile at 50 degrees celcius at 75% current capacity.

Now:

1m = 39.37 inches  
1km = 1000 \* 39.37  
= 39370 inches  
= 39370 ÷ 36  
= 1093.611 yards

1mile = 1760 yards  
1km = 1093.611 ÷ 1760  
1km = 0.6211 miles  
= 0.0450 \* 0.6211  
= 0.0280 ohms/km

therefore:

Resistance = 0.0280 ohms/km/conductor

NOTE !!!!!

There is only one conductor per phase. The program only requires ohms/km/conductor as it works out the resultant total when it runs.

NEUTRAL CONDUCTORS

The resistance per conductor for this program must be in ohms per km.

From Figure 1. this value = 1.52

therefore:

Resistance = 1.52 ohms/km/conductor



d. HORIZONTAL POSITION (X):

From Figure 2:

CIRCUIT 1.	
Phase a	= -4.5m from centre of ROW
Phase b	= -5m from centre of ROW
Phase c	= -4.5m from centre of ROW
Neutral 1	= -4.5m from centre of ROW
Neutral 2	= -4.5m from centre of ROW
CIRCUIT 2.	
Phase a	= +4.5m from centre of ROW
Phase b	= +5m from centre of ROW
Phase c	= +4.5m from centre of ROW
Neutral 1	= +4.5m from centre of ROW
Neutral 2	= +4.5m from centre of ROW

e. VERTICAL POSITION (Y):

From Figure 2:

CIRCUIT 1.	
Phase a	= 25.5m from ground level
Phase b	= 19m from ground level
Phase c	= 12.5m from ground level
Neutral 1	= 32m from ground level
Neutral 2	= 32m from ground level
CIRCUIT 2.	
Phase a	= 25.5m from ground level
Phase b	= 19m from ground level
Phase c	= 12.5m from ground level
Neutral 1	= 32m from ground level
Neutral 2	= 32m from ground level

f. NUMBER OF BUNDLED CONDUCTORS (NB):

From Figure 2:

Phase a = Phase b = Phase c = 1 conductors/phase/circuit  
 Neutral 1 = Neutral 2 = 1 conductor

g. BUNDLE SPACING (d):

From Figure 2:

Phase a = Phase b = Phase c = 0cm  
 Neutral 1 = Neutral 2 = 0cm

h. INPUT DATA

INPUT DATA TABLE LC1.DAT							
-----							
NC = 2 RHO = 100 V = 345 F = 60 ROW = 70 N1 = 1 N2 = 1							
-----							
	R	GMR	D	X	Y	Nb	d
-----							
CIRCUIT 1		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0280	1.893	4.780	-4.5	25.5	1	0
Phase b	.0280	1.893	4.780	-5	19	1	0
Phase c	.0280	1.893	4.780	-4.5	12.5	1	0
NEUTRAL 1	1.52	.0636	.978	-4.5	32	1	0
NEUTRAL 2	1.52	.0636	.978	-4.5	32	1	0
-----							
CIRCUIT 2		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0280	1.893	4.780	4.5	25.5	1	0
Phase b	.0280	1.893	4.780	5	19	1	0
Phase c	.0280	1.893	4.780	4.5	12.5	1	0
NEUTRAL 1	1.52	.0636	.978	4.5	32	1	0
NEUTRAL 2	1.52	.0636	.978	4.5	32	1	0

i. RUNNING THE LINE CONSTANTS PROGRAM

```
C:\>cd\Power, press return
C:\Power>CHAP5, press return
```

Run the program and display your results: CASE NAME: EX.2

DOUBLE CIRCUIT		EX.2	
SERIES SEQUENCE IMPEDANCE MATRIX		Zs	EQ --(4) ohms/km
0.6545E+00+j1.490E+00	0.1635E-01-j3.517E-02	0.1579E-01-j2.143E-02	
0.1579E-01-j2.143E-02	0.1449E-01+j2.401E-01	-.2223E-01+j1.319E-02	
0.1635E-01-j3.517E-02	0.2291E-01+j1.284E-02	0.1449E-01+j2.401E-01	

This represents EQ.4, namely:

$$Z_s = \begin{bmatrix} Z_0 & Z_{01} & Z_{02} \\ Z_{10} & Z_1 & Z_{12} \\ Z_{20} & Z_{21} & Z_2 \end{bmatrix} \text{ ohms/m} \quad \text{----- (4)}$$

DOUBLE CIRCUIT		EX.2	
SHUNT SEQUENCE ADMITTANCE MATRIX		Ys	EQ --(18) s/km
0.0000E+00+j3.462E-06	-2.412E-07+j5.478E-08	2.412E-07+j5.478E-08	
2.412E-07+j5.478E-08	0.0000E-00+j7.074E-06	5.633E-07-j3.266E-07	
-2.412E-07+j5.478E-08	-5.633E-07-j3.266E-07	0.000E+00+j7.074E-06	

This represents EQ.18, namely:

$$Y_s = \begin{bmatrix} G_{s0}+j\omega C_0 & G_{s01}+j\omega C_{01} & G_{s02}+j\omega C_{02} \\ G_{s10}+j\omega C_{10} & G_{s1}+j\omega C_1 & G_{s12}+j\omega C_{12} \\ G_{s20}+j\omega C_{20} & G_{s21}+j\omega C_{21} & G_{s2}+j\omega C_2 \end{bmatrix} \text{ S/m} \quad \text{--- (18)}$$

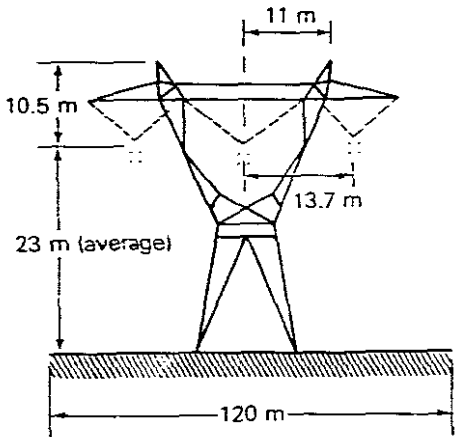
Press space bar to return to the MAIN MENU, Select E to exit from the program.

Should you wish to print your output data use "PRINT SCREEN".

SECTION FOUR  
SELF EVALUATION PROBLEMS

QUESTION ONE

INFORMATION AVAILABLE: [SAME AS EX.1 ABOVE EXCEPT ROW =120M]  
The line is a 765kV, 60Hz, single circuit three phase line having four ACSR 954 kcmil conductors per bundle, with 45.7cm between conductors in the bundle. The line has flat horizontal phase spacing with 13.7m between adjacent phases and 23m average line height. There are two Alumoweld 7 no.8 neutral wires located 10.5m vertically above and 11m horizontally from the centre phase. The earth resistivity is 100 ohm-metres and the right-of-way width is 120m. It is represented by a diagram as follows:

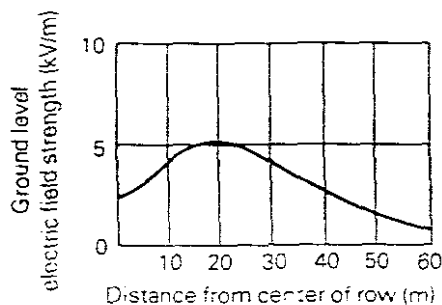


Neutrals:  
2-Alumoweld 7 no.8  
Radius = 0.489cm  
GMR = 0.0636cm  
Resistance = 1.52ohms/km

Phase conductors:  
4-ACSR 954 kcmil, 54/7  
Radius = 1.519cm  
GMR = 1.229cm  
Resistance = 0.0701  
ohms/km  
Bundle spacing = 45.7cm

Obtain a lateral profile of the ground level electric field strength?

ANSWER



QUESTION TWO

If the phase conductors in question one are replaced by 1113 kcmil 54/19 ACSR conductors ("Finch" cable-TABLE A.4), four per bundle, use the LINE CONSTANTS program to compute  $Z_p$ ,  $Z_{phat}$ ,  $Z_s$ ,  $Z_{shat}$ ,  $Y_p$ ,  $Y_{phat}$ ,  $Y_s$ ,  $Y_{shat}$ , conductor surface electric field strength and the ground level electric field strength profile?

Which line, question one or two would have the least corona problems? Give reasons for your answer.

ANSWER

SINGLE CIRCUIT SERIES PHASE IMPEDANCE MATRIX	Q.2 EQ --(2)	ohms/km
0.2257E+00+j7.174E-01	0.2121E+00+j3.978E-01	0.2083E+00+j3.498E-01
0.2121E+00+j3.978E-01	0.2297E+00+j7.106E-01	0.2121E+00+j3.978E-01
0.2083E+00+j3.498E-01	0.2121E+00+j3.978E-01	0.2257E+00+j7.174E-01

SINGLE CIRCUIT $Z_p$ FOR A COMPLETELY TRANSPOSED LINE	Q.2 EQ --(3)	ohms/km
0.2271E+00+j7.151E-01	0.2108E+00+j3.818E-01	0.2108E+00+j3.818E-01
0.2108E+00+j3.818E-01	0.2271E+00+j7.151E-01	0.2108E+00+j3.818E-01
0.2108E+00+j3.818E-01	0.2108E+00+j3.818E-01	0.2271E+00+j7.151E-01

SINGLE CIRCUIT SERIES SEQUENCE IMPEDANCE MATRIX	Q.2 EQ --(4)	ohms/km
0.6487E+00+j1.479E+00	0.1060E-01-j9.113E-03	-.1319E-01-j4.621E-03
-.1319E-01-j4.621E-03	0.1627E-01+j3.333E-01	-.2904E-01+j1.815E-02
0.1060E-01-j9.113E-03	0.3024E-01+j1.608E-02	0.1627E-01+j3.333E-01

SINGLE CIRCUIT $Z_s$ FOR A COMPLETELY TRANSPOSED LINE	Q.2 EQ --(5)	ohms/km
0.6487E+00+j1.479E+00	0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.1627E-01+j3.333E-01	0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	0.1627E-01+j3.333E-01

From the result it can be seen that  $Z_1 = Z_2$ .

SINGLE CIRCUIT SHUNT PHASE ADMITTANCE MATRIX		Yp	Q.2 EQ --(10)	s/km
+j4.921E-06	-j9.869E-07			-j2.558E-07
-j9.869E-07	+j5.109E-06			-j9.869E-07
-j2.558E-07	-j9.869E-07			+j4.921E-06

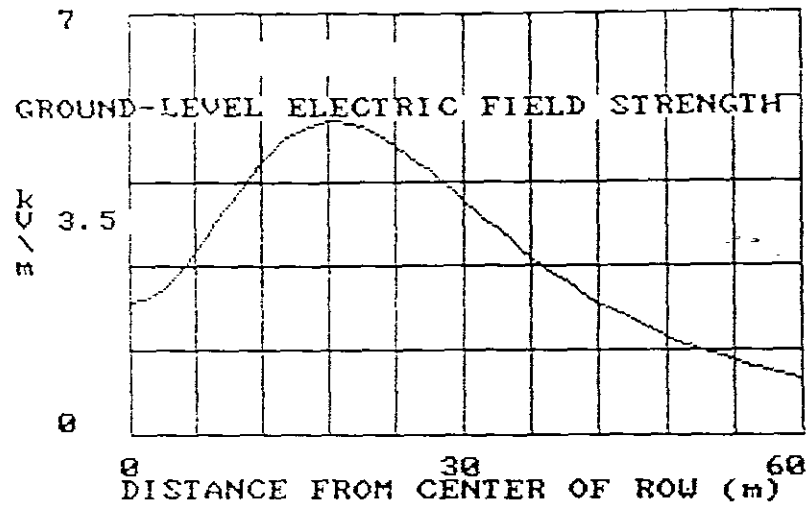
SINGLE CIRCUIT Yp FOR A COMPLETELY TRANSPOSED LINE		Yphat	Q.2 EQ --(11)	s/km
+j4.984E-06	-j7.432E-07			-j7.432E-07
-j7.432E-07	+j4.984E-06			-j7.432E-07
-j7.432E-07	-j7.432E-07			+j4.984E-06

SINGLE CIRCUIT SHUNT SEQUENCE ADMITTANCE MATRIX		Ys	Q.2 EQ --(18)	s/km
0.0000E+00+j3.497E-06	-.1569E-06+j9.059E-08			.1569E-06+j9.059E-08
.1569E-06+j9.059E-08	0.0000E+00+j5.727E-06			.4763E-06-j2.750E-07
-.1569E-06+j9.059E-08	-.4762E-06-j2.750E-07			0.0001E+00+j5.727E-06

SINGLE CIRCUIT Ys FOR A COMPLETELY TRANSPOSED LINE		Yshat	Q.2 EQ --(19)	s/km
0.0000E+00+j3.498E-06	0.0000E+00+j0.000E+00			0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.0000E+00+j5.727E-06			0.0000E+00+j0.000E+00
0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00			0.0000E+00+j5.727E-06

CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH	
PHASE: 1	19.27 kV/cm
PHASE: 2	21.06 kV/cm
PHASE: 3	19.27 kV/cm
MAXIMUM ELECTRIC FIELD STRENGTH IS: 21.06 kV/cm	

GROUND LEVEL PROFILE:



QUESTION THREE

A 230kV 60Hz, three phase completely transposed overhead line has one ACSR 1113 komil conductor per phase and flat horizontal phase spacing, with 7m between adjacent conductors. Using the "LINE CONSTANTS" program, compute the series sequence impedance matrix and obtain therefrom the positive sequence inductive reactance? Assume an average line height of 12m, an earth resistivity of 100 ohm-metre, 60Hz conductor resistances at 50 degrees celcius, and no neutral wires.

ANSWER

SINGLE CIRCUIT		Q.3	
Zs FOR A COMPLETELY TRANSPOSED LINE	Zshat	EQ --(5)	ohms/km
0.3002E+00+j3.046E+00	0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	
0.0000E+00+j0.000E+00	0.2408E+00+j4.901E-01	0.0000E+00+j0.000E+00	
0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	0.2408E+00+j4.901E-01	

$Z1 = 0.2408E+00+j4.901E-01$

therefore: the positive sequence inductive reactance is:

$X1 = 0.49 \text{ ohms/km}$

QUESTION FOUR

PART A

Using the "LINE CONSTANTS" program, compute the shunt sequence admittance matrix for a bundled 500kV, 60Hz, three phase completely transposed overhead line having three ACSR 954 kcmil conductors per bundle, with 45.7cm between conductors in the bundle. The horizontal phase spacings between bundle centres are 10, 10 and 20m. Assume an average line height of 20m and no neutral wires. RHO = 100. Obtain therefrom the positive, negative and zero sequence admittances and then calculate Co, C1 and C2?

ANSWER

SINGLE CIRCUIT		Q.4	
Ys FOR A COMPLETELY TRANSPPOSED LINE		EQ --(19)	s/km
0.0000E+00+j2.614E-06	0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	
0.0000E+00+j0.000E+00	0.0000E+00+j4.815E-06	0.0000E+00+j0.000E+00	
0.0000E+00+j0.000E+00	0.0000E+00+j0.000E+00	0.0000E+00+j4.815E-06	

therefrom:

$Y_{shat}(\text{positive sequence}) = 4.815E-06 \text{ s/km}$   
 $Y_{shat}(\text{negative sequence}) = 4.815E-06 \text{ s/km}$   
 $Y_{shat}(\text{zero sequence}) = 2.614E-06 \text{ s/km}$

$C1 = 12.77\text{nF}$   
 $C2 = 12.77\text{nF}$   
 $C0 = 6.94\text{nF}$

PART B

Rework Part A with two neutral wires located 7m above and 8m to the left and right of the centre of the bundle and find C1, C2 and Co? Use the neutral wire specifications from Q.1.

ANSWER

$C1 = 12.89\text{nF}$   
 $C2 = 12.89\text{nF}$   
 $C0 = 8.13\text{nF}$



PART C

Rework Part B and compute the conductor surface electric field strength and the ground level electric field strength profile if the ROW = 100m?

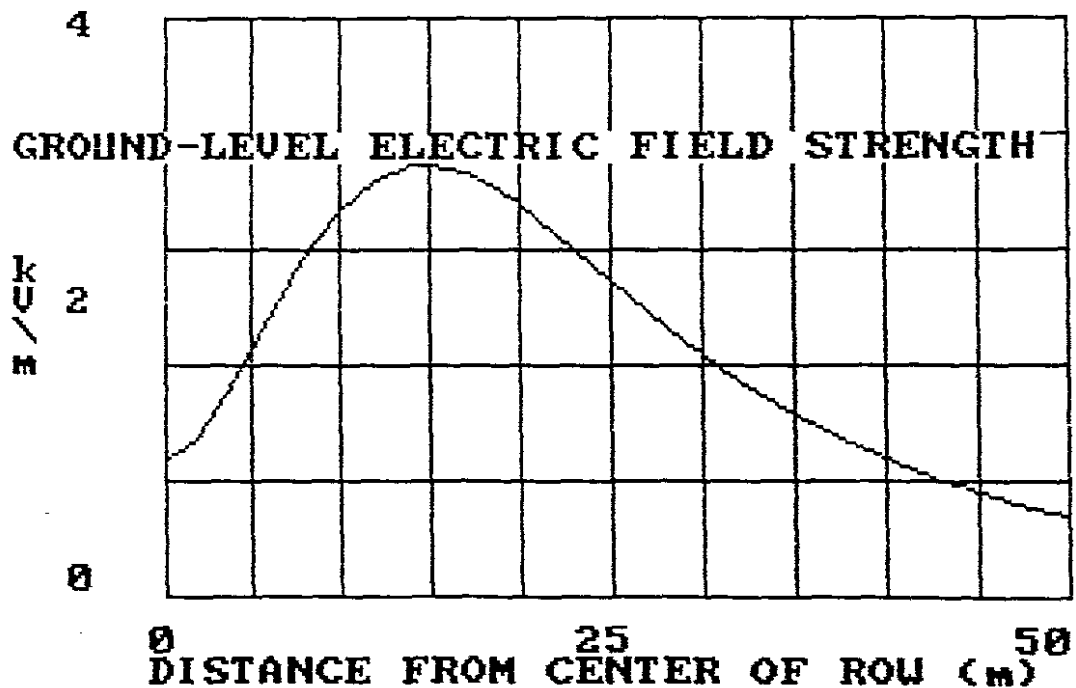
ANSWER

CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH

PHASE: 1      15.20045 kV/cm  
PHASE: 2      16.40931 kV/cm  
PHASE: 3      15.20045 kV/cm

MAXIMUM ELECTRIC FIELD STRENGTH IS: 16.40931 kV/cm

GROUND LEVEL PROFILE:



PART D

Rework Part C and compute the conductor surface electric field strength and the ground level electric field strength profile if the phase spacing is decreased by 10% and if it is increased by 10%?

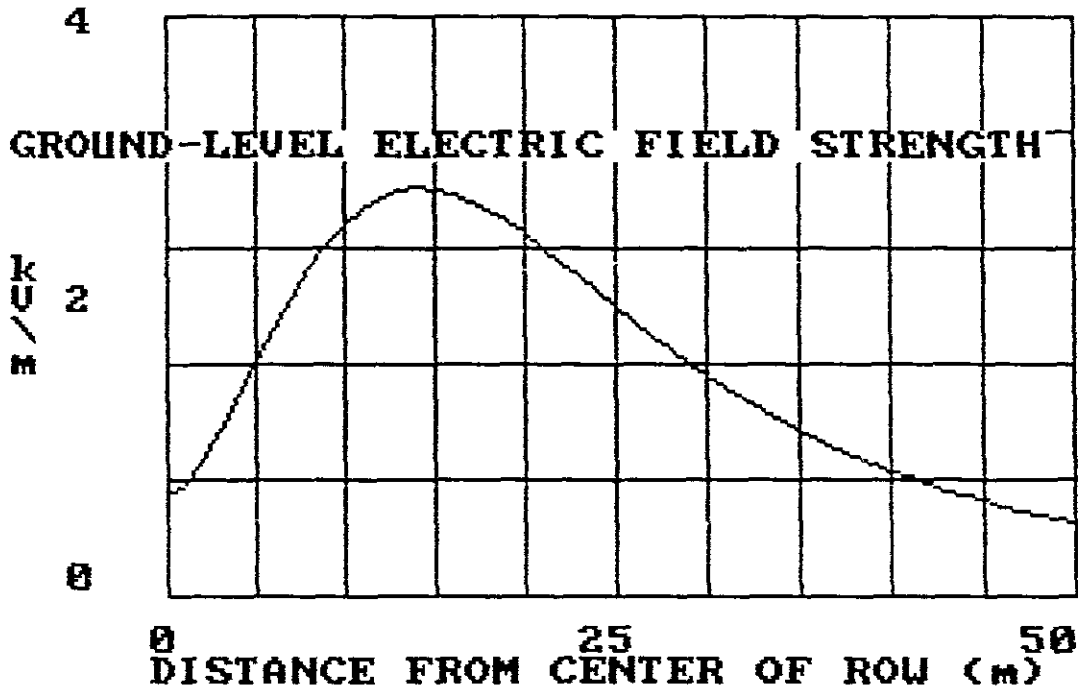
ANSWER

CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH

PHASE: 1	15.53549 kV/cm	Phase Spacing 9, 9, 18 10% decrease
PHASE: 2	16.82957 kV/cm	
PHASE: 3	15.53549 kV/cm	

MAXIMUM ELECTRIC FIELD STRENGTH IS: 16.82957 kV/cm

GROUND LEVEL PROFILE:



ANSWER

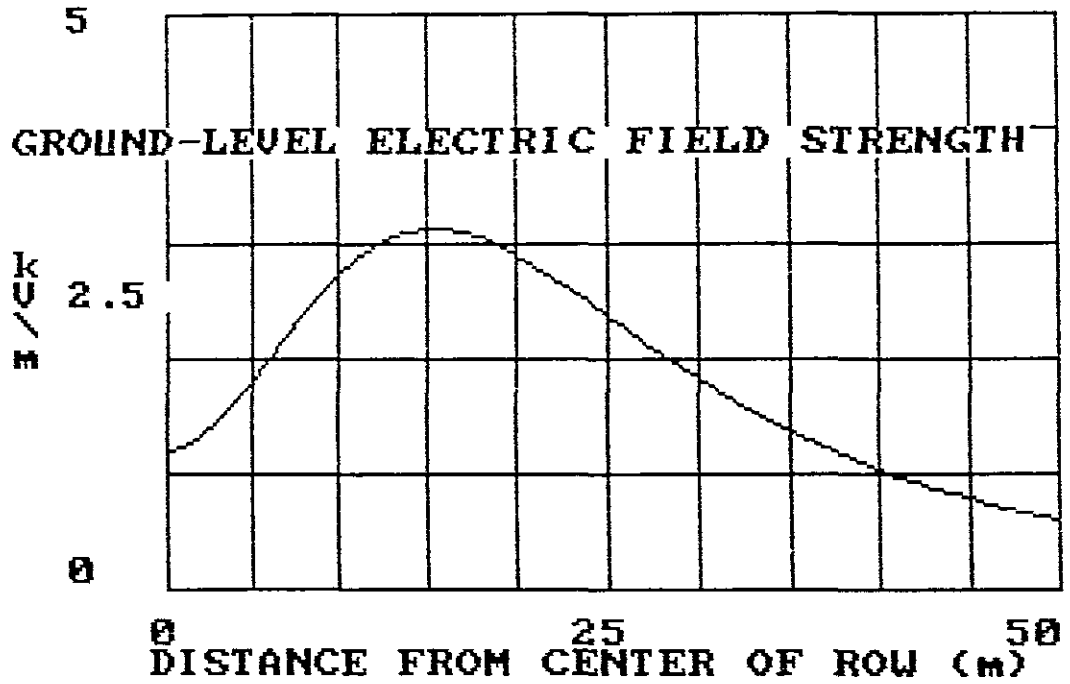
CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH

PHASE: 1      14.90447 kV/cm  
PHASE: 2      16.05954 kV/cm  
PHASE: 3      14.90447 kV/cm

Phase Spacing  
11, 11, 22  
10% increase

MAXIMUM ELECTRIC FIELD STRENGTH IS: 16.05954 kV/cm

GROUND LEVEL PROFILE:



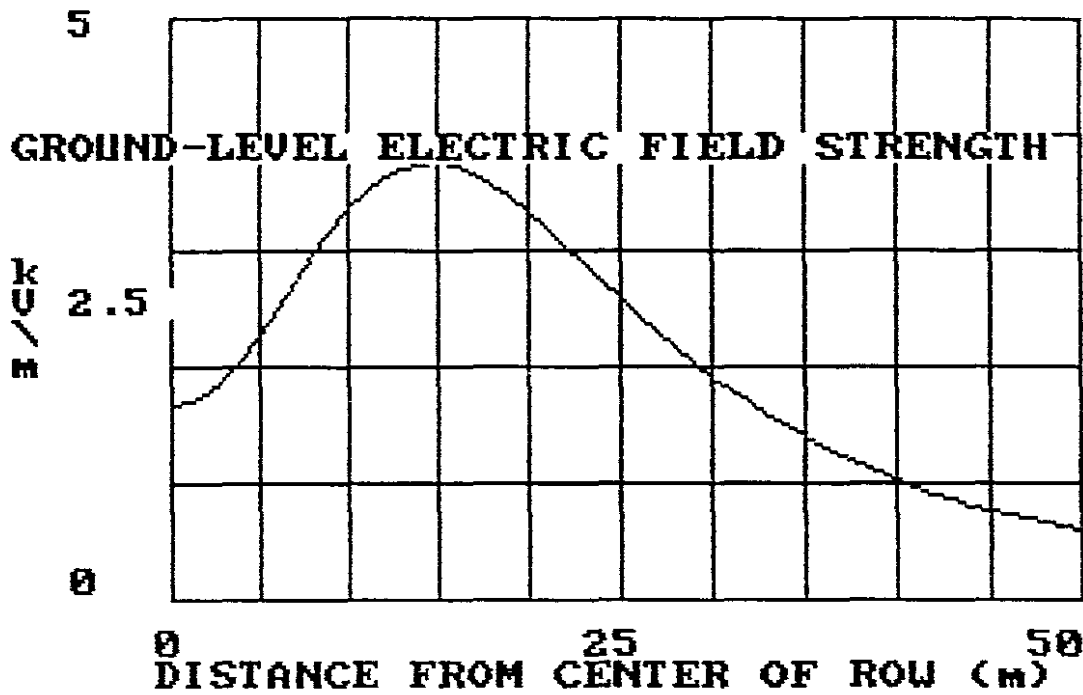
PART E

Rework Part C and compute the conductor surface electric field strength and the ground level electric field strength profile if the average line height is decreased by 10% and if it is increased by 10%?

ANSWER

CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH		
PHASE: 1	15.53549 kV/cm	Line Height 18m 10% decrease
PHASE: 2	16.82957 kV/cm	
PHASE: 3	15.53549 kV/cm	
MAXIMUM ELECTRIC FIELD STRENGTH IS: 16.82957 kV/cm		

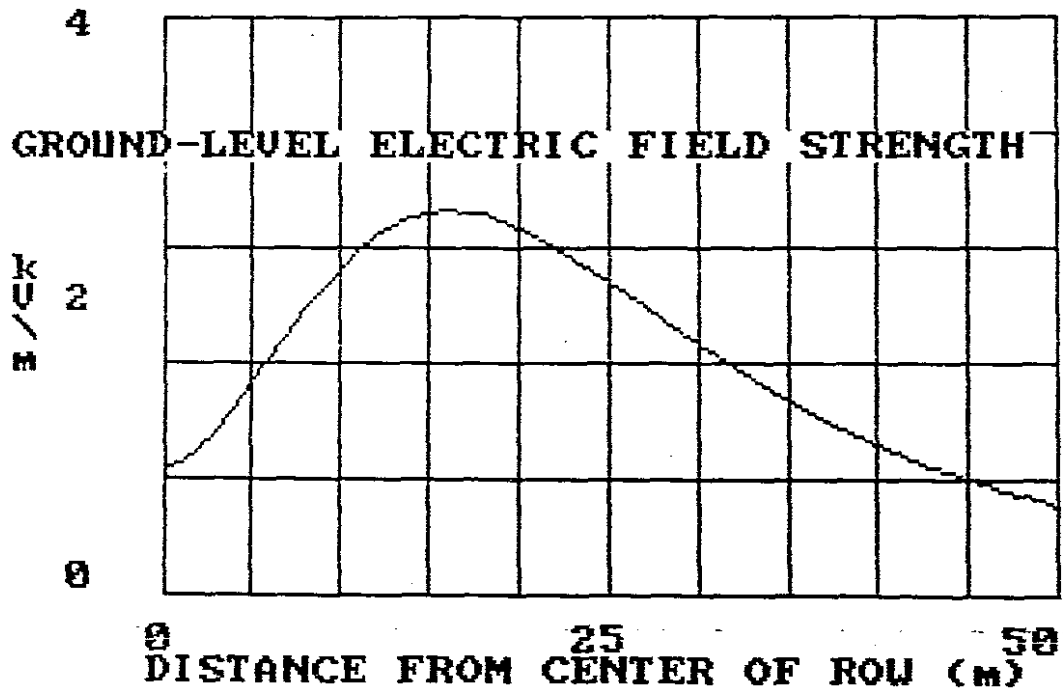
GROUND LEVEL PROFILE:



ANSWER

CONDUCTOR SURFACE ELECTRIC FIELD STRENGTH		
PHASE: 1	14.86343 kV/cm	Line Height 22m 10% increase
PHASE: 2	16.05795 kV/cm	
PHASE: 3	14.86343 kV/cm	
MAXIMUM ELECTRIC FIELD STRENGTH IS: 16.05795 kV/cm		

GROUND LEVEL PROFILE:



QUESTION FIVE

Rework "EXAMPLE B", the 345kV transmission line, double circuit, ACSR 2515 kcmil 76/19 but using the "PHASE ARRANGEMENT 2"?

ANSWER

INPUT DATA TABLE LC1.DAT							
-----							
NC = 2 RHO = 100 V = 345 F = 60 ROW = 70 N1 = 1 N2 = 1							
-----							
	R	GMR	D	X	Y	Nb	d
-----							
CIRCUIT 1		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0280	1.893	4.780	-4.5	25.5	1	0
Phase b	.0280	1.893	4.780	-5	19	1	0
Phase c	.0280	1.893	4.780	-4.5	12.5	1	0
NEUTRAL 1	1.52	.0636	.978	-4.5	32	1	0
NEUTRAL 2	1.52	.0636	.978	-4.5	32	1	0
-----							
CIRCUIT 2		(cm)	(cm)	(m)	(m)		(cm)
Phase a	.0280	1.893	4.780	4.5	?	1	0
Phase b	.0280	1.893	4.780	5	?	1	0
Phase c	.0280	1.893	4.780	4.5	?	1	0
NEUTRAL 1	1.52	.0636	.978	4.5	?	1	0
NEUTRAL 2	1.52	.0636	.978	4.5	?	1	0

DOUBLE CIRCUIT			Q.5	
SERIES SEQUENCE IMPEDANCE MATRIX			Zs	EQ --(4) ohms/km
0.6609E+00+j1.488E+00	0.1352E-01-j5.373E-03	-.1142E-01-j9.026E-03		
-.1142E-01-j9.026E-03	0.1408E-01+j2.196E-01	-.4626E-02+j2.748E-03		
0.1352E-01-j5.373E-03	0.4693E-02+j2.633E-03	0.1408E-01+j2.196E-01		

DOUBLE CIRCUIT			Q.5	
SHUNT SEQUENCE ADMITTANCE MATRIX			Ys	EQ --(18) s/km
0.0000E+00+j3.462E-06	-2.046E-07+j1.181E-07	2.046E-07+j1.181E-07		
2.046E-07+j1.181E-07	-7.802E-14+j7.530E-06	1.691E-07-j9.765E-08		
-2.046E-07+j1.181E-07	-1.691E-07-j9.765E-08	7.802E-14+j7.530E-06		

----- END -----

Table A.4 Characteristics of aluminum cable, steel, reinforced (Aluminum Company of America)

Code Word	Circular Mils Aluminum	Aluminum		Steel		Outside Diameter (Inches)	Copper Equivalent* Circular Mils or A.W.G.	Ultimate Strength (Pounds)	Weight (Pounds per Mile)	Geometric Mean Radius at 60 Hz (Feet)	Approx. Current Carrying Capacity† (Amps)	r <sub>a</sub> Resistance (Ohms per Conductor per Mile)								x <sub>a</sub> Inductive Reactance (Ohms per Mile at 1 Ft Spacing All Currents)	x <sub>c</sub> Shunt Capacitive Reactance (Megohms per Conductor per Mile at 1 Ft Spacing)
			Strand Diameter (Inches)		Strand Diameter (Inches)							25°C (77°F) Small Currents				50°C (122°F) Current Approx. 75% Capacity‡					
												dc	25 Hz	50 Hz	60 Hz	dc	25 Hz	50 Hz	60 Hz		
Joree	2 516 000	76	0.1819	19	0.0849	1.880		61 700		0.0621								0.0450	0.337	0.0755	
Thrasher	2 312 000	76	0.1744	18	0.0814	1.802		57 300		0.0585								0.0482	0.342	0.0767	
Kwei	2 187 000	72	0.1735	7	0.1157	1.735		49 800		0.0670								0.0511	0.346	0.0778	
Bluebird	2 156 000	84	0.1802	19	0.0981	1.762		60 300		0.0588								0.0506	0.344	0.0774	
Chukar	1 781 000	84	0.1456	19	0.0874	1.602		51 000		0.0534								0.0598	0.355	0.0802	
Falcon	1 590 000	54	0.1716	19	0.1030	1.545	1 000 000	56 000	10 777	0.0520	1 380	0.0587	0.0588	0.0590	0.0591	0.0646	0.0658	0.0675	0.0684	0.359	0.0814
Parrot	1 510 500	54	0.1673	18	0.1004	1.506	950 000	53 200	10 237	0.0507	1 340	0.0618	0.0619	0.0621	0.0622	0.0680	0.0690	0.0710	0.0720	0.362	0.0821
Plow	1 431 000	54	0.1628	19	0.0977	1.465	900 000	50 400	9 699	0.0493	1 300	0.0652	0.0653	0.0655	0.0658	0.0718	0.0729	0.0749	0.0760	0.365	0.0830
Martin	1 361 000	54	0.1582	19	0.0949	1.424	850 000	47 600	9 160	0.0479	1 250	0.0691	0.0692	0.0694	0.0695	0.0761	0.0771	0.0792	0.0803	0.369	0.0838
Pheasant	1 272 000	54	0.1535	18	0.0921	1.382	800 000	44 800	8 621	0.0465	1 200	0.0734	0.0735	0.0737	0.0738	0.0808	0.0819	0.0840	0.0851	0.372	0.0847
Grackle	1 192 500	54	0.1486	19	0.0892	1.338	750 000	43 100	8 082	0.0450	1 160	0.0783	0.0784	0.0786	0.0788	0.0862	0.0872	0.0894	0.0906	0.376	0.0857
Finch	1 113 000	54	0.1435	19	0.0862	1.293	700 000	40 200	7 544	0.0435	1 110	0.0839	0.0840	0.0842	0.0844	0.0924	0.0935	0.0957	0.0969	0.380	0.0867
Cuckoo	1 033 500	54	0.1384	7	0.1384	1.248	650 000	37 100	7 019	0.0420	1 060	0.0903	0.0905	0.0908	0.0909	0.0994	0.1005	0.1026	0.1036	0.385	0.0878
Cardinal	954 000	54	0.1329	7	0.1329	1.188	600 000	34 200	6 479	0.0403	1 010	0.0979	0.0980	0.0981	0.0982	0.1078	0.1088	0.1118	0.1128	0.390	0.0890
Canary	900 000	54	0.1291	7	0.1291	1.162	586 000	32 300	6 112	0.0391	970	0.104	0.104	0.104	0.104	0.1146	0.1155	0.1175	0.1185	0.393	0.0898
Crane	874 500	54	0.1273	7	0.1273	1.146	550 000	31 400	5 940	0.0386	950	0.107	0.107	0.107	0.108	0.1178	0.1188	0.1218	0.1228	0.395	0.0903
Condor	785 000	54	0.1214	7	0.1214	1.093	500 000	28 500	5 399	0.0368	900	0.117	0.118	0.118	0.118	0.1288	0.1308	0.1358	0.1378	0.401	0.0917
Drake	795 000	26	0.1749	7	0.1360	1.108	500 000	31 200	5 770	0.0375	900	0.117	0.117	0.117	0.117	0.1288	0.1288	0.1288	0.1288	0.399	0.0912
Mallard	785 000	30	0.1628	18	0.0977	1.140	500 000	38 400	6 517	0.0393	910	0.117	0.117	0.117	0.117	0.1288	0.1288	0.1288	0.1288	0.393	0.0904
Crow	715 500	54	0.1151	7	0.1151	1.036	450 000	28 300	4 659	0.0349	830	0.131	0.131	0.131	0.132	0.1442	0.1452	0.1472	0.1482	0.407	0.0932
Starling	715 500	26	0.1659	7	0.1290	1.051	450 000	28 100	5 193	0.0355	840	0.131	0.131	0.131	0.131	0.1442	0.1442	0.1442	0.1442	0.406	0.0928
Redwing	715 500	30	0.1544	19	0.0926	1.081	450 000	34 600	5 865	0.0372	840	0.131	0.131	0.131	0.131	0.1442	0.1442	0.1442	0.1442	0.399	0.0920
Flamingo	666 600	54	0.1111	7	0.1111	1.000	419 000	24 500	4 527	0.0337	800	0.140	0.140	0.141	0.141	0.1541	0.1571	0.1591	0.1601	0.412	0.0943
Rook	636 000	54	0.1085	7	0.1085	0.977	400 000	23 800	4 316	0.0329	770	0.147	0.147	0.148	0.148	0.1618	0.1638	0.1676	0.1688	0.414	0.0950
Groshawk	636 000	26	0.1584	7	0.1216	0.990	400 000	25 000	4 618	0.0335	780	0.147	0.147	0.147	0.147	0.1618	0.1618	0.1618	0.1618	0.412	0.0946
Egret	636 000	30	0.1456	19	0.0874	1.019	400 000	31 500	5 213	0.0351	780	0.147	0.147	0.147	0.147	0.1618	0.1618	0.1618	0.1618	0.406	0.0937
Pheasant	605 000	54	0.1059	7	0.1059	0.953	380 500	22 500	4 109	0.0321	750	0.154	0.156	0.155	0.155	0.1695	0.1715	0.1755	0.1775	0.417	0.0957
Squab	605 000	26	0.1525	7	0.1188	0.966	380 500	24 100	4 391	0.0327	760	0.154	0.154	0.154	0.154	0.1700	0.1720	0.1720	0.1720	0.415	0.0953
Dove	556 500	26	0.1463	7	0.1138	0.927	350 000	22 400	4 038	0.0313	730	0.168	0.168	0.168	0.168	0.1849	0.1859	0.1859	0.1859	0.420	0.0965
Eagle	556 500	30	0.1362	7	0.1362	0.853	350 000	27 200	4 688	0.0328	730	0.168	0.168	0.168	0.168	0.1849	0.1859	0.1859	0.1859	0.415	0.0957
Hawk	477 000	26	0.1355	7	0.1054	0.858	300 000	19 430	3 462	0.0290	670	0.196	0.196	0.196	0.196	0.216				0.430	0.0988
Hen	477 000	30	0.1261	7	0.1261	0.883	300 000	23 300	3 933	0.0304	670	0.196	0.196	0.196	0.196	0.216				0.424	0.0980
Wisp	397 500	26	0.1236	7	0.0961	0.783	250 000	16 190	2 885	0.0265	590	0.235				0.259				0.441	0.1015
Lark	397 500	30	0.1151	7	0.1151	0.806	250 000	19 980	3 277	0.0278	600	0.235		Same as dc		0.259		Same as dc		0.435	0.1006
Linnet	336 400	26	0.1138	7	0.0855	0.721	4/0	14 050	2 442	0.0244	530	0.278				0.306				0.451	0.1039
Orion	336 400	30	0.1059	7	0.1059	0.741	4/0	17 040	2 774	0.0255	530	0.278				0.306				0.445	0.1032
Ostrich	300 000	26	0.1074	7	0.0835	0.680	188 700	12 650	2 178	0.0230	490	0.311				0.342				0.458	0.1057
Piper	300 000	30	0.1000	7	0.1000	0.700	188 700	15 430	2 473	0.0241	500	0.311				0.342				0.462	0.1049
Partridge	266 800	26	0.1013	7	0.0788	0.642	3/0	11 250	1 936	0.0217	460	0.350				0.385				0.465	0.1074

Table A.4

\*Based on copper 97%, aluminum 61% conductivity.  
†For conductor at 75°C, air at 25°C, wind 1.4 miles per hour (2 ft/sec), frequency = 60 Hz.  
‡"Current Approx. 75% Capacity" is 75% of the "Approx. Current Carrying Capacity in Amps" and is approximately the current which will produce 50°C conductor temp. (25°C rise) with 25°C air temp., wind 1.4 miles per hour.

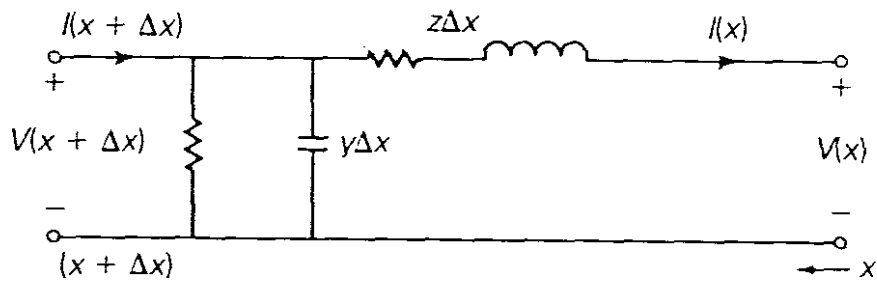
## COMPUTER-AIDED STUDY PROGRAMME

ON

THE BALANCED STEADY-STATE

OF

TRANSMISSION LINES

Transmission-line section  
of length  $\Delta x$ 

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17-07-1992



**TRANSMISSION LINES**

**BALANCED POWER SYSTEMS: STEADY-STATE OPERATION**

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5. REFERENCES	
(a) Power System Analysis and Design with Personal Computer Applications - J.D. Glover/ M. Sarma.	
(b) Elements of power systems analysis - W.D. Stevenson.	
(c) Power Systems - B.R. Gungor.	
(d) Electric Power Systems - S.A.Nasar.	

SECTION ONE

INTRODUCTION INTO THEORY OF THE STEADY STATE OPERATION OF  
TRANSMISSION LINES

1. SHORT LINE APPROXIMATIONS - ABCD PARAMETERS

It is convenient to represent a transmission line by a two port network:

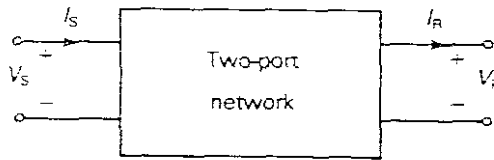


FIGURE 1.

where:  $V_s$  and  $I_s$  are the sending end voltage and current and  $V_r$  and  $I_r$  are the receiving end voltage and current respectively.

The sending and receiving end quantities are related as follows:-

$$\boxed{V_s = AV_r + BI_r \text{ volts}} \quad \text{--- (1)}$$

$$\boxed{I_s = CV_r + DI_r \text{ amps}} \quad \text{--- (2)}$$

where: A, B, C and D parameters depend on the transmission line constants R, L, C, and G.

These parameters are in general complex numbers. A and D are dimensionless whereas B has units of ohms and C has units of siemens (S)

The following circuit represents a short line which is less than 80km long.

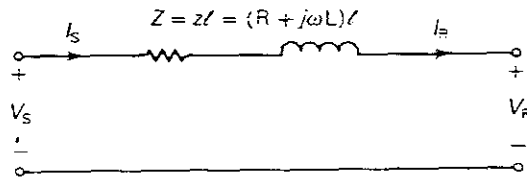


FIGURE 2.

Only series resistance and reactance are included. The shunt admittance is neglected. The circuit applies to either single phase or completely transposed three phase lines operating under balanced conditions.

$Z$  is the positive sequence series impedance,  $V_s$  and  $V_r$  are positive sequence line-to-neutral voltages, and  $I_s$  and  $I_r$  are positive sequence line currents.

We will only consider positive sequence networks in this session.

Total series impedance and series per unit length are distinguished from each other as follows:-

- $z = R + j\omega L$  ohms/m, series impedance per unit length.
- $y = G + j\omega C$  Siemens/m, shunt admittance per unit length.
- $Z = zl$  ohms, total series impedance.
- $Y = yl$  Siemens, total shunt admittance.
- $l =$  Line length metres.

Shunt conductance  $G$  accounts for real power loss between conductors or between conductors and ground. It is usually due to leakage currents at insulators and to corona. Insulator leakage current depends on the amount of dirt, salt and other contaminants on insulators as well as on meteorological factors, particularly the presence of moisture. Corona occurs when a high value of electric field strength at a conductor surface causes the air to become electrically ionised and to conduct. The real power loss due to corona loss depends on meteorological conditions, particularly rain and on conductor surface irregularities. This real power loss is usually small compared to conductor  $I^2R$  loss and is a very small component of the shunt admittance and is therefore usually neglected in power system studies.

Equations (1) and (2) can be represented in matrix format as follows:-

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad \text{--- (3)}$$

From figure 2:-

$$\begin{aligned} V_s &= V_r + ZI_r \\ I_s &= I_r \end{aligned}$$

Therefore in matrix format:-

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad \text{--- (4)}$$

and by comparing equations (3) and (4), the ABCD parameters for a short line are:-

$$\begin{aligned} A &= D = 1 \text{ per unit} \\ B &= Z \quad \text{ohms} \\ C &= 0 \quad \text{Siemens} \end{aligned} \quad \text{--- (5)}$$

## 2. MEDIUM LINES APPROXIMATIONS - ABCD PARAMETERS

Medium lines typically range from 80 to 250km at 60Hz. It is common to "lump" the total shunt capacitance and then locate half of it at each end of the line. Such a circuit is called a nominal- $\pi$  circuit and is shown as follows:-

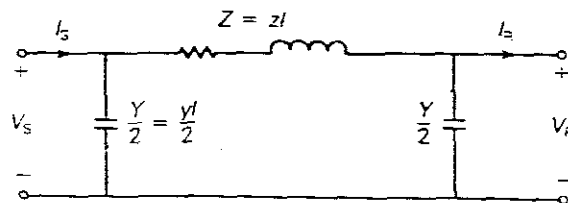


FIGURE 3.

From which:-

The current in the series branch equals  $I_r + \frac{V_r Y}{2}$  and

$$\begin{aligned} V_s &= V_r + Z \left( I_r + \frac{V_r Y}{2} \right) \\ &= V_r + Z I_r + Z \frac{V_r Y}{2} \\ &= V_r + \frac{Z V_r Y}{2} + Z I_r \end{aligned}$$

$V_s = V_r \frac{(1 + ZY)}{2} + Z I_r$	----- (6)
--	-----------

Now:-

$$I_s = I_r + \frac{V_r Y}{2} + \frac{V_s Y}{2}$$

and if equation (6) is substituted for  $V_s$ :-

$$\begin{aligned} I_s &= I_r + \frac{V_r Y}{2} + \left[ \frac{V_r (1 + ZY)}{2} + Z I_r \right] \frac{Y}{2} \\ &= I_r + \frac{V_r Y}{2} + \frac{V_r Y}{2} \left( \frac{1 + ZY}{2} \right) + \frac{Z I_r Y}{2} \\ &= \frac{V_r Y}{2} + \frac{V_r Y}{2} \left( \frac{1 + ZY}{2} \right) + I_r + \frac{Z I_r Y}{2} \\ &= V_r Y \left[ \frac{1}{2} + \frac{1}{2} \left( \frac{1 + ZY}{2} \right) \right] + \left[ \frac{1 + ZY}{2} \right] I_r \\ &= V_r Y \left[ \frac{1}{2} + \frac{1}{2} + \frac{ZY}{4} \right] + \left[ \frac{1 + ZY}{2} \right] I_r \end{aligned}$$

$I_s = V_r \left[ \frac{1 + ZY}{4} \right] Y + \left[ \frac{1 + ZY}{2} \right] I_r$	----- (7)
---	-----------

Writing (6) and (7) in matrix format:-

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z \\ Y(1 + \frac{YZ}{4}) & (1 + \frac{YZ}{2}) \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad \text{--- (8)}$$

Thus comparing (8) and (3) we get:-

$$\begin{aligned} A = D &= 1 + \frac{YZ}{2} \text{ per unit} \\ B &= Z \text{ ohms} \\ C &= Y \left(1 + \frac{YZ}{4}\right) \text{ Siemens} \end{aligned} \quad \text{--- (9)}$$

VOLTAGE REGULATION

Voltage regulation is the change in voltage at the receiving end of the line when the load varies from no-load to a specified full load at a specified power factor, while the sending end voltage is held constant.

Expressed in percent of full load voltage:-

$$\% \text{ VR} = \frac{|V_{rn}| - |V_{rfl}|}{|V_{rfl}|} \times 100 \quad \text{--- (10)}$$

where:-

VR = percent voltage regulation.

|V<sub>rn</sub>| = magnitude of the no-load receiving-end voltage.

|V<sub>rfl</sub>| = magnitude of the full-load receiving-end voltage.

In practice, transmission line voltages decrease when heavily loaded and increase when lightly loaded. When voltages on EHV lines are maintained within ± 5% of rated voltage, unusual operating problems are not encountered.

That is,

$$\frac{V_r}{V_s} \geq 0.95$$

is usually considered safe operating practice.

In addition to voltage regulation, line loadability is an important issue. Three major line loading limits are:-

- (1) The thermal limit
- (2) The voltage-drop limit
- (3) The steady-state stability limit.

#### THERMAL LIMIT

The maximum temperature of a conductor determines its thermal limit. Conductor temperature affects the sag between towers and the loss of conductor tensile strength due to annealing. If the temperature is too high, the prescribed conductor-to-ground clearances may not be met, or the elastic limit of the conductor may be exceeded such that it cannot shrink back to its original length when cooled. Conductor temperature depends on the current magnitude and its time duration, as well as on ambient temperature, wind velocity, and conductor surface conditions. Tables A.3 and A.4 give approximate current-carrying capacities of copper and ACSR conductors. (See attached Appendices)

#### EXAMPLE. 1.

The thermal limit, based on the approximate current-carrying capacity for a 795 000-cmil 26/2 ACSR conductors is 0,9 kA from Table A.4.

If the transmission line has two of these conductors per bundle, then the thermal limit will be  $2 \times 0,9 = 1,8\text{kA}$ .

The loadability of short lines is usually determined by conductor thermal limit and rating of circuit breakers.

#### VOLTAGE DROP

The loadability of medium lines is often determined by the voltage drop limit. If a line is heavily loaded but  $V_r \div V_s \geq 0,95$  it is usually considered to be operating safely.

#### STEADY-STATE STABILITY

The loadability of long lines has stability as its limiting factor. This means the ability of synchronous machines on either end of a line to remain in synchronism. (Discussed in more detail below).

A physical meaning can be assigned to the A and B parameters. By letting  $I_r$  be zero in (1) we see that:

$$A = V_s \div V_r \text{ at no-load}$$

$$V_r \text{ no-load} = V_s \div A$$

Similarly, B is the ratio of :-

$$B = V_s \div I_r \text{ when } V_r \text{ is short circuited}$$

The constant A is useful in computing regulation. Using (10) we get:

$$\% VR = \frac{|V_s| \div |A| - |V_{rfl}|}{|V_{rfl}|} \times 100 \quad \text{--- (11)}$$

ABCD constants are introduced here because they simplify workings.

The ABCD parameters apply to linear, passive (no sources of emf), bilateral two-port networks. Transmission lines are passive.

Note that for both short and medium length lines, the relationship is:-

$$AD - BC = 1 \quad \text{--- (12)}$$

Note also that since the line is the same when viewed from either end,  $A = D$ . A line is symmetrical if they look identical from both the input and output ports.

### 3. LONGLINES - ABCD PARAMETERS

For long lines, the medium line approximations become too approximate.

With long lines the R, L and C line constants are not lumped, but rather uniformly distributed along the length of the line. This will give an exact solution and ensure a high degree of accuracy.

If the circuit constants are:-

$$\begin{aligned} z &= R + j\omega L && \text{ohms/m} \\ y &= G + j\omega C && \text{Siemens/m} \end{aligned}$$



If G is neglected :

$z = R + j\omega L$	ohms/m
$y = j\omega C$	mhos/m

In order to account for the distributed nature of the line constants, a very small element of the line is considered. The difference in voltage and the difference in current between the ends of the element is calculated.

Such an element is represented by the following circuit, which has a length dx

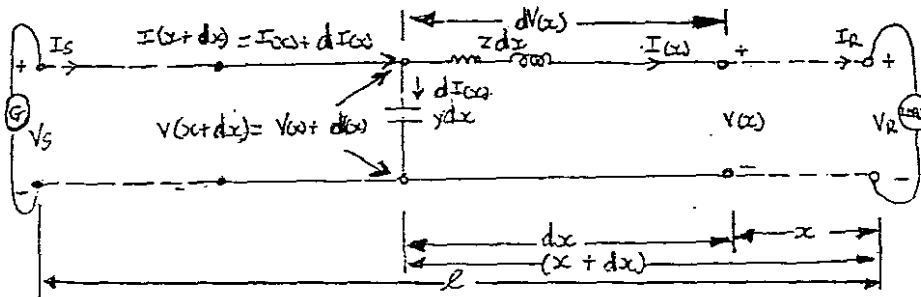


FIGURE 4.

where:  $dx$  is the distance in metres measured from the receiving end of the line to the small element of the line which has a length  $dx$ .  $V(x)$  and  $I(x)$  denote the voltage and current at position  $x$ . Similiary,  $V(x+dx)$  and  $I(x+dx)$  denote the voltage and current at position  $(x+dx)$ .

Also  $z dx$  is the series impedance of the elemental length of the line, and  $y dx$  is its shunt admittance. The voltage to neutral at the end of the element toward the load is  $V(x)$ , which is a complex expression of the rms voltage whose magnitude and phase vary with distance along the line. The voltage at the end of the element toward the generator is  $V(x) + dV(x)$ . The rise in voltage over the elemental length of the line in the direction of increasing  $x$  is  $dV(x)$ , which is the voltage at the end of the element toward the generator minus the voltage at the end of the element toward the load. The rise in voltage in the direction of increasing  $x$  is also the product of the current in the element and the series impedance of the element,  $I(x) z dx$ , therefore:

$$V(x) = I(x) z dx \quad \text{--- (13)}$$

Now writing a KVL equation:-

$$V(x + dx) = V(x) + \left[ (z dx) I(x) \right] \quad \text{--- (14)}$$

Similarly, writing a KCL equation:-

$$I(x + dx) = I(x) + dI(x) \quad \text{--- (15)}$$

where:-

$$dI(x) = V(x + dx) y dx$$

and

$$I(x + dx) = I(x) + \left[ (y dx) V(x + dx) \right] \quad \text{--- (16)}$$

from which can be shown that:-

$$V(x) = \left( \frac{e^{\tau x} + e^{-\tau x}}{2} \right) V_r + Z_c \left( \frac{e^{\tau x} - e^{-\tau x}}{2} \right) I_r \quad \text{--- (17)}$$

where:  $\tau = \text{gamma}$ ,  $Z_c = \text{characteristic impedance}$

and

$$I(x) = \frac{1}{Z_c} \left( \frac{e^{\tau x} - e^{-\tau x}}{2} \right) V_r + \left( \frac{e^{\tau x} + e^{-\tau x}}{2} \right) I_r \quad \text{--- (18)}$$

where :-  $\tau = \sqrt{zy} \text{ m}^{-1}$ , called the propagation constant --- (19)

$Z_c = \sqrt{z \div y}$  ohms, called the characteristic impedance --- (20)

$$\frac{e^{\tau x} + e^{-\tau x}}{2} = \text{Cosh}(\tau x) \quad \text{--- (21)}$$

$$\frac{e^{\tau x} - e^{-\tau x}}{2} = \text{Sinh } (\tau x) \quad \text{--- (22)}$$

Therefore from (17) and (18) we get:-

$$V(x) = \text{Cosh } (\tau x) V_r + Z_c \text{ Sinh } (\tau x) I_r \quad \text{--- (23)}$$

$$I(x) = \frac{1}{Z_c} \text{ Sinh } (\tau x) V_r + \text{Cosh } (\tau x) I_r \quad \text{--- (24)}$$

which give the rms values of the voltage and current and their phase angles at any specified point along the line in terms of the distance  $x$  from the receiving end to the specified point, provided the receiving-end voltage, current and the parameters of the line are known.

Now, (23) and (24) give the ABCD parameters of the distributed line. In matrix format,

$$\begin{bmatrix} V(x) \\ I(x) \end{bmatrix} = \begin{bmatrix} A(x) & B(x) \\ C(x) & D(x) \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad \text{--- (25)}$$

where:-

$$\begin{aligned} A(x) &= D(x) = \text{Cosh } (\tau x) \text{ per unit} \\ B(x) &= Z_c \text{ Sinh } (\tau x) \text{ ohms} \\ C(x) &= \frac{1}{Z_c} \text{ Sinh } (\tau x) \text{ Siemens} \end{aligned} \quad \text{--- (26)}$$

Further:-

At the sending end  $x = l$  (length)

and  $V(x) = V(l) = V_s$

and  $I(x) = I(l) = I_s$

where :  $l$  = length of the line

That is:

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad \text{--- (27)}$$

therefore where  $x = 1$ :-

$$\begin{aligned} A &= D = \text{Cosh } (\tau l) \text{ per unit} \\ B &= Z_c \text{ Sinh } (\tau l) \text{ ohms} \\ C &= \frac{1}{Z_c} \text{ Sinh } (\tau l) \text{ Siemens} \end{aligned} \quad \text{--- (28)}$$

from which we have:-

$$V_s = V_r \text{ Cosh } (\tau l) + I_r Z_c \text{ Sinh } (\tau l) \quad \text{--- (29)}$$

$$I_s = I_r \text{ Cosh } (\tau l) + \frac{V_r}{Z_c} \text{ Sinh } (\tau l) \quad \text{--- (30)}$$

which expresses  $V_s$  and  $I_s$  in terms of  $V_r$  and  $I_r$ .

Equations (29) and (30) can also be solved for  $V_r$  and  $I_r$  in terms of  $V_s$  and  $I_s$  to give:

$$V_r = V_s \text{ Cosh } (\tau l) - I_s Z_c \text{ Sinh } (\tau l) \quad \text{--- (31)}$$

$$I_r = I_s \text{ Cosh } (\tau l) - \frac{V_s}{Z_c} \text{ Sinh } (\tau l) \quad \text{--- (32)}$$

Note that:

The propagation constant  $\tau$  is a complex quantity with real and imaginary parts denoted  $\alpha$  and  $\beta$ . That is:

$$\tau = \alpha + j\beta \quad \text{--- (33)}$$

The quantity  $\tau l$  which  $\tau(m^{-1})l(m)$  is thus dimensionless.

Also:

$$e^{\tau l} = e^{(\alpha + j\beta)l} = e^{\alpha l} \cdot e^{j\beta l} = e^{\alpha l} /_{-} \beta l$$

and

$$e^{-\tau l} = e^{-\alpha l} /_{-} -\beta l$$

where: the unit for  $\beta l$  is the radian.

As:

$$\text{Cosh}(\tau l) = \frac{e^{\tau l} + e^{-\tau l}}{2}$$

$$\text{Cosh}(\tau l) = \frac{1}{2} [ e^{\alpha l} /_{-} \beta l + e^{-\alpha l} /_{-} -\beta l ] \quad \text{--- (34)}$$

$$\text{Sinh}(\tau l) = \frac{e^{\tau l} - e^{-\tau l}}{2} = \frac{1}{2} [ e^{\alpha l} /_{-} \beta l - e^{-\alpha l} /_{-} -\beta l ] \quad \text{--- (35)}$$

The characteristic impedance  $Z_c$  is a complex quantity having a real and imaginary part, but is usually expressed in polar form, namely:-

$$Z_c /_{-} \theta_c = \sqrt{z \div y} = \sqrt{\frac{R + j\omega L}{j\omega C}} \quad \text{--- (36)}$$

$\theta_c$  is minus as phase angle for  $R + j\omega L$  is  $< 90$  deg. and for  $j\omega C$  it equals  $90$  deg.

The ABCD parameters given in (28) are exact parameters valid for any length of line. For accurate calculations, these equations must be used for long overhead lines.

The ABCD parameters (5) and (9) are for short and medium lines are approximate parameters.

These ABCD parameters are circuit constants.

4. THE EQUIVALENT CIRCUIT OF A LONG LINE-ABCD PARAMETERS

The nominal- $\pi$  circuit (Figure 3) does not represent a transmission line exactly because they do not account for the parameters of the line being uniformly distributed. The discrepancy between the nominal- $\pi$  and the actual line becomes larger as the length of the line increases.

It is possible, however, to find the equivalent circuit of a long transmission line and to represent the line accurately, insofar as measurements at the ends of the line are concerned by a network of lumped parameters.

Let the following figure be a  $\pi$  circuit similar to that of figure 3 except that it represents the equivalent circuit of a long line.

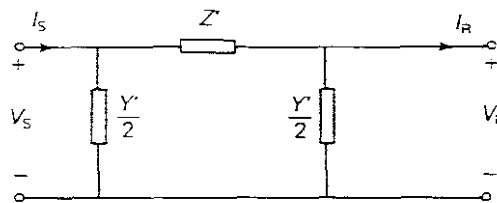


FIGURE 5.

Let the series arm of the equivalent- $\pi$  circuit be  $Z'$  and the shunt arms  $Y'/2$  to distinguish them from the arms of the nominal  $\pi$  circuit in figure 3.

The equivalent- $\pi$  circuit and the nominal- $\pi$  circuit are identical in structure except that  $Z'$  and  $Y'$  are used instead of  $Z$  and  $Y$ .

The objective is to determine  $Z'$  and  $Y'$  such that the equivalent  $\pi$  circuit has the ABCD parameters as those of the distributed line, namely (28) above.

The ABCD parameters of the equivalent- $\pi$  circuit, which has the same structure as the nominal- $\pi$  circuit are:-

$$\begin{aligned}
 A = D &= 1 + \frac{Y'Z'}{2} \text{ per unit} \\
 B &= Z' \text{ ohms} \\
 C &= Y' \left[ 1 + \frac{Y'Z'}{4} \right] \text{ Siemens}
 \end{aligned}
 \tag{37}$$

where we have replaced Z and Y in (9) with Z' and Y' in (37).

Using (6) and (7) and by substituting Z' and Y'/2 for Z and Y/2 we obtain the sending-end voltage and current for the equivalent circuit in terms of its series and shunt arms and its voltage and current at the receiving-end as well as its sending-end MVA, MW, MVars and power factor:

$$\begin{aligned}
 V_s &= V_r \left( 1 + \frac{Z'Y'}{2} \right) + Z'I_r \\
 I_s &= V_r \left[ \frac{1 + Z'Y'}{4} \right] Y' + \left[ \frac{1 + Z'Y'}{2} \right] I_r \\
 S_s &= V_s I_s^* = P_s(\text{MW}) + jQ_s(\text{MVars}) \\
 \text{Sending-end pf.} &= \text{Cosine of the angle between } V_s \text{ and } I_s.
 \end{aligned}
 \tag{38}$$

For our circuit to be equivalent to the long line, the coefficients of Vr and Ir in (38) must be identical to the coefficients of Vr and Ir in (29).

Now using the Vs equation in (38) and equating the coefficients of Ir in the two equations yields:

$$Z' = Z_c \sinh(\tau l)
 \tag{39}$$

$$\begin{aligned}
 Z' &= \sqrt{\frac{Z}{y} \operatorname{Sinh}(\tau l)} \\
 &= \sqrt{\frac{Z}{y} \cdot \frac{Z}{Z} \operatorname{Sinh}(\tau l)} \\
 &= \sqrt{\frac{Z^2}{yZ} \operatorname{Sinh}(\tau l)} \\
 &= \frac{Z}{\sqrt{yZ}} \operatorname{Sinh}(\tau l) \\
 &= \frac{Z}{\sqrt{yZ}} \cdot \frac{1}{1} \operatorname{Sinh}(\tau l)
 \end{aligned}$$

NB!  $Z = z l$   
 $\tau = \sqrt{y \div z}$

$$Z' = \frac{Z \cdot \operatorname{Sinh}(\tau l)}{\tau l} \text{ ----- (40)}$$

where the term  $\frac{\operatorname{Sinh}(\tau l)}{\tau l}$  is the factor by which the series

impedance of the nominal- $\pi$  must be multiplied to convert to the equivalent- $\pi$ .

For small values of  $\tau l$ ,  $\operatorname{Sinh} \tau l$  and  $\tau l$  are almost identical, and this fact shows that the nominal- $\pi$  represents the medium length line quite accurately insofar as the series arm is concerned.

Therefore:-

$$\begin{aligned}
 Z' &= ZF1 \\
 &= R' + jX'
 \end{aligned}$$

----- (41)



where:-

$$F1 = \frac{\text{Sinh } \tau l}{\tau l} \text{ per unit} \quad \text{--- (42)}$$

To investigate the shunt arms of the equivalent- $\pi$  circuit, we equate the coefficients of  $V_r$  in (29) and (38) and obtain :-

$$\frac{Z' Y'}{2} + 1 = \text{Cosh } \tau l$$

Substituting  $Z' = Z_c \text{ Sinh } \tau l$  from (39)

$$\frac{Y' Z_c \text{ Sinh } \tau l}{2} + 1 = \text{Cosh } \tau l$$

$$\frac{Y'}{2} = \frac{1}{Z_c} \frac{\text{Cosh } \tau l - 1}{\text{Sinh } \tau l} \quad \text{--- (43)}$$

$$\frac{Y'}{2} = \frac{\text{Cosh } \tau l - 1}{Z'} \quad \text{--- (44)}$$

or, by using the identity,

$$\tanh \frac{\tau l}{2} = \frac{\text{Cosh } \tau l - 1}{\text{Sinh } \tau l} \quad \text{--- (44a)}$$

$$\frac{Y'}{2} = \frac{\tanh (\tau l/2)}{Z_c} = \frac{\tanh (\tau l/2)}{\sqrt{\frac{z}{y}}}$$

Multiplying top and bottom by  $\frac{y l}{2}$  we get :-

$$\frac{Y'}{2} = \frac{\tanh(\tau l/2) (y l/2)}{\sqrt{z \div y} (y l/2)}$$

$$\frac{Y'}{2} = \frac{\tanh(\tau l/2) (y l/2)}{\sqrt{zy \div yy} (y l/2)}$$

$$\frac{Y'}{2} = \frac{\tanh(\tau l/2) (y l/2)}{[\sqrt{zy} \div y] (y l/2)}$$

$$\frac{Y'}{2} = \frac{\tanh(\tau l/2) (y l/2)}{\tau l/2}$$

NB!  $\tau = \sqrt{zy}$   
 $yl = Y$

$$\frac{Y'}{2} = \frac{Y \tanh(\tau l/2)}{2 \tau l/2}$$

----- (45)

where Y is the total shunt admittance of the line, and (45) shows the correction factor used to convert the admittance of the shunt arms of the nominal- $\pi$  to that of the equivalent- $\pi$ .

Since  $\tanh(\tau l/2)$  and  $\tau l/2$  are very nearly equal for small values of  $\tau l$ , the nominal- $\pi$  represents the medium length line quite accurately.  
 Therefore:

$$\frac{Y'}{2} = \frac{Y}{2} \text{ F2 Siemens}$$

$$\frac{Y'}{2} = G' + j Bc'$$

----- (46)

$$F2 = \frac{\tanh(\tau l/2)}{\tau l/2} \text{ p.u.}$$

----- (47)

Sum up:

Equations (42) and (47) give the correction factors F1 and F2 to convert Z and Y for the nominal- $\pi$  circuit to Z' and Y' for the equivalent- $\pi$  circuit.

The equivalent circuit is therefore:

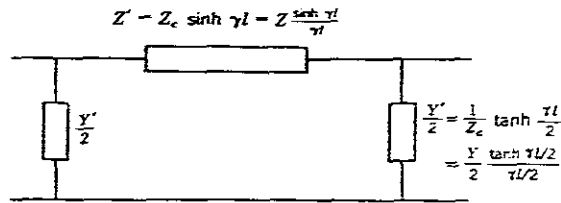


FIGURE 6.

EXAMPLE 2.

A three phase 765kV, 60Hz, 300km, completely transposed line has the following positive sequence impedance and admittance:

$$z = 0.0165 + j0.3306 = 0.3310/87.14 \text{ deg ohms/km}$$

$$y = j4.674e-6 \text{ Siemens/km}$$

Compare the equivalent and nominal- $\pi$  circuits for this line.

FOR THE NOMINAL- $\pi$  CIRCUIT:

$$Z = z l = (0.3310/87.14 \text{ deg}) (300) = 99.3/87.14 \text{ deg ohms}$$

$$\frac{Y}{2} = \frac{y l}{2} = \frac{j4.674e-6}{2} (300) = 7.011e-4/_90 \text{ deg Siemens}$$

From (42) and (47),

$$F1 = \frac{\text{Sinh } \tau l}{\tau l} \text{ per unit} \quad \text{--- (42)}$$

and using (19) and (35):

$$\begin{aligned} \tau l &= (\sqrt{zy}) (l) = \sqrt{(0.3310/87.14 \text{ deg}) (4.674e-6/90 \text{ deg})} (300) \\ &= 0.3731/_88.57 \text{ deg} \\ &= 0.00931 + j0.3730 \text{ per unit} \\ &= \alpha l + j\beta l \end{aligned}$$

NB!  $\beta l$  is in radians

$$\sinh(\tau l) = \frac{e^{\tau l} - e^{-\tau l}}{2} = \frac{1}{2} [ e^{\alpha l / \beta l} - e^{-\alpha l / \beta l} ]$$

$$= \frac{1}{2} [ e^{0.00931 / 0.3730 \text{rads}} - e^{-0.00931 / -0.3730 \text{rads}} ]$$

$$= 0.3645 / 88.63 \text{ deg}$$

Therefore:

$$F1 = \frac{0.3645 / 88.63 \text{ deg}}{0.3731 / 88.57 \text{ deg}} = 0.9769 / 0.06 \text{ deg per unit}$$

Now from:

$$F2 = \frac{\tanh(\tau l / 2)}{\tau l / 2} = \frac{\cosh(\tau l) - 1}{\sinh(\tau l)} \times \frac{1}{(\tau l / 2)}$$

$$\cosh(\tau l) = \frac{1}{2} [ e^{\alpha l / \beta l} + e^{-\alpha l / \beta l} ]$$

$$= \frac{1}{2} [ e^{0.00931 / 0.3730 \text{rads}} + e^{-0.00931 / -0.3730 \text{rads}} ]$$

$$= 0.9313 + j0.0034$$

$$F2 = \frac{(0.9313 + j0.0034) - 1}{(0.3645 / 86.63 \text{ deg}) (0.3731 / 2 / 88.57 \text{ deg})}$$

$$= 1.012 / -0.03 \text{ deg per unit}$$

Now from (41):

$$Z' = ZF1 = (99.3 / 87.14 \text{ deg}) (0.9769 / 0.06 \text{ deg}) = 97 / 87.2 \text{ deg}$$

and from (46):

$$\frac{Y'}{2} = \frac{Y}{2} F2 = (7.011e-4 / 90 \text{ deg}) (1.012 / -0.03 \text{ deg})$$

$$= 7.095e-4 / 89.97 \text{ deg Siemens}$$

$$= 3.7e-7 + j7.095e-4 \text{ Siemens}$$

Comparing these nominal and equivalent- $\pi$  circuit values,  $Z'$  is about 2% smaller than  $Z$  and  $Y'/2$  is about 1% larger than  $Y/2$ .

Note the small shunt conductance  $G' = 3.7e-7$  introduced in the equivalent- $\pi$  circuit.  $G'$  is however often neglected.

5. THE LOSSLESS LINE

A lossless line has zero resistance and conductance.

With line losses neglected, simpler expressions for line parameters are obtained. Since lines are generally designed to have low losses, the lossless line equations and concepts developed here can be used for quick and reasonably accurate calculations leading to initial analysis of a line. More accurate calculations can then be made with a personal computer program.

SURGE IMPEDANCE

In power-systems work, characteristic impedance is sometimes called surge-impedance. Surge impedance however is usually reserved for the special case of a lossless line.

For a lossless line, R = 0, G = 0  
Therefore Z = jwL ohms/m  
y = jwC Siemens/m

From (20) and (19)

$$Z_c = \frac{z}{y} = \frac{jwL}{jwC} = \frac{L}{C} \text{ ohms} \text{ --- (48)}$$

and

$$\tau = \sqrt{zy} = \sqrt{(jwL)(jwC)} = jw\sqrt{LC} = j\beta \text{ m}^{-1} \text{ --- (49)}$$

where:

$$\beta = w \sqrt{LC} \text{ m}^{-1} \text{ --- (50)}$$

The characteristic impedance  $Z_c = \sqrt{L/C}$  is called the surge impedance for a lossless line and is a pure resistance. The propagation constant  $\tau = \beta$  is pure imaginary.

ABCD PARAMETERS OF A LOSSLESS LINE

The ABCD parameters from (26) are:-

$$A(x) = D(x) = \text{Cosh}(\tau x) = \text{Cosh}(j\beta x)$$

$$= \frac{e^{j\beta x} + e^{-j\beta x}}{2} = \text{Cos}(\beta x) \text{ per unit}$$

$$\text{Sinh}(\tau x) = \text{Sinh}(j\beta x) = \frac{e^{j\beta x} - e^{-j\beta x}}{2} = j\text{Sin}(\beta x) \text{ per unit}$$

$$B(x) = Z_c \text{Sinh}(\tau l) = j\text{Sin}(\beta x) \left[ \begin{array}{c} L \\ - \\ C \end{array} \right] \text{ ohms}$$

$$C(x) = \frac{\text{Sinh}(\tau x)}{Z_c} = \frac{j\text{Sin}(\beta x)}{\left[ \begin{array}{c} L \\ - \\ C \end{array} \right]} \text{ Siemens}$$

If  $x = l$

$A = D = \text{Cos}(\beta l) \text{ per unit}$ $B = j\text{Sin}(\beta l) \sqrt{L/C} \text{ ohms}$ $C = \frac{j\text{Sin}(\beta x)}{\left[ \begin{array}{c} L \\ - \\ C \end{array} \right]} \text{ Siemens}$	<p>----- (51)</p>
--	-------------------

A comparison of lossless versus lossy ABCD parameters for the different lines is as follows:

PARAMETER	$A = D$	$B$	$C$
UNITS	Per Unit	$\Omega$	S
Short line (less than 80 km)	1	$Z$	0
Medium line—nominal $\pi$ circuit (80 to 250 km)	$1 + \frac{YZ}{2}$	$Z$	$Y \left( 1 + \frac{YZ}{4} \right)$
Long line—equivalent $\pi$ circuit (more than 250 km)	$\cosh(\gamma l)$ $= 1 + \frac{YZ'}{2}$	$Z_c \sinh(\gamma l)$ $= Z'$	$(1/Z_c) \sinh(\gamma l)$ $= Y \left( 1 + \frac{YZ'}{4} \right)$
Lossless line ( $R = G = 0$ )	$\cos(\beta l)$	$jZ_c \sin(\beta l)$	$\frac{j \sin(\beta l)}{Z_c}$

FIGURE 7. (TABLE 1.)

EQUIVALENT- $\pi$  CIRCUIT FOR A LOSSLESS LINE

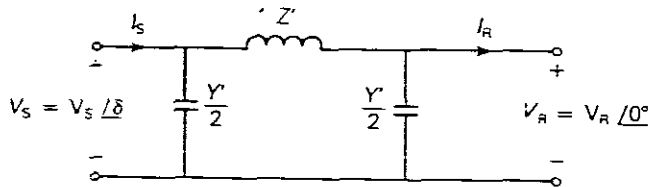


FIGURE 8.

$Z'$  and  $Y'$  are pure imaginary, thus the equivalent- $\pi$  circuit for a lossless line is also lossless.

WAVELENGTH

A wavelength is the distance required to change the phase of the voltage or current by  $2\pi$  radians or 360 deg.

For a lossless line and using (25):

$$V(x) = A(x)V_r + B(x)I_r$$

$$V(x) = \cos(\beta x)V_r + jZ_c \sin(\beta x)I_r \quad \text{--- (52)}$$

and

$$I(x) = C(x)V_r + D(x)I_r$$

$$I(x) = \frac{j\sin(\beta x)V_r}{Z_c} + \cos(\beta x)I_r \text{ --- (53)}$$

From (51) and (52), V(x) and I(x) change phase by 2π radians when

$$x = 2\pi/\beta$$

From which x is wavelength in this case.  
Therefore:

$$\text{Lambda} = 2\pi/\beta \text{ --- (54)}$$

Let W = wavelength (Lambda)

$$W = \frac{2\pi}{\beta} = \frac{2\pi}{w\sqrt{LC}} = \frac{2\pi}{2\pi f\sqrt{LC}} = \frac{1}{f\sqrt{LC}} \text{ metres --- (55)}$$

$$fW = \frac{1}{\sqrt{LC}} \text{ m/s called the velocity of propagation of the voltage or current for a lossless line. --- (56)}$$

For overhead lines, the velocity of propagation is ≈ 3e+8 m/s

Therefore, if f= 60Hz:

$$\text{wavelength} = \frac{3e+8}{60} = 5000\text{km} = 3100 \text{ miles}$$

Typical power line lengths are only a small fraction of the above 60Hz wavelength.

**SURGE IMPEDANCE LOADING (SIL)**

SIL is the "power" delivered by a lossless line to a load resistance equal to the surge impedance  $Z_c = \sqrt{L/C}$ .



The following figure shows a lossless line terminated by a resistance equal to its surge impedance.

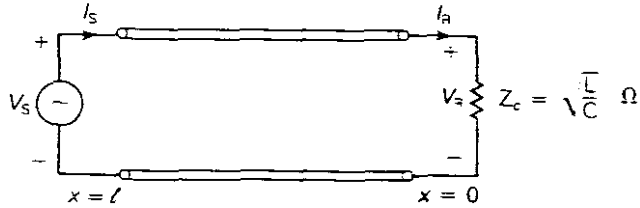


FIGURE 9.

At SIL,

$$I_r = \frac{V_r}{Z_c}$$

and from (52):

$$\begin{aligned} V(x) &= \cos(\beta x)V_r + jZ_c \sin(\beta x) \frac{V_r}{Z_c} \\ &= (\cos\beta x + j \sin\beta x)V_r \\ &= e^{j\beta x} V_r \text{ volts} \end{aligned}$$

$$|V(x)| = |V_r| \text{ volts}$$

Thus at SIL, the voltage profile is "flat", that is its magnitude at any point along a lossless line at SIL is constant.

Also from (53) and at SIL,  $I_r = \frac{V_r}{Z_c}$

$$\begin{aligned} I(x) &= (\cos\beta x + j \sin\beta x) \frac{V_r}{Z_c} \text{ amps} \\ &= e^{j\beta x} \frac{V_r}{Z_c} \text{ amps} \end{aligned}$$

Therefore the complex power flowing at any point x along the line is:

$$S(x) = P(x) + j Q(x) = V(x) I^*(x) \quad \text{--- (56)}$$

$$S(x) = (e^{j\beta x} V_r) \frac{e^{-j\beta x} V_r}{Z_c}$$

$$S(x) = \frac{|V_r|^2}{Z_c} \quad \text{--- (57)}$$

Thus the real power flow along a lossless line at SIL remains constant from the sending-end to the receiving-end. The reactive power flow is zero.

At rated line voltage, the real power delivered, or SIL is:

$$SIL = \frac{V^2 \text{ rated}}{Z_c} \text{ Watts} \quad \text{--- (58)}$$

where:  $Z_c$  is the surge impedance,  $V_{rated}$  could be single or line to line for three phase.

Power systems engineers find it convenient to express the power transmitted by a line in terms of a per unit of SIL. For instance, the permissible loading of a transmission line may be expressed as a fraction of its SIL.

VOLTAGE PROFILE

In practice, power lines are not terminated by their surge impedances. Loadings can vary from a small fraction of SIL during light load conditions up to multiples of SIL depending on line length and compensation during heavy loading. If a line is not terminated by its surge impedance, then the voltage profile is "not flat". The following figure shows voltage profiles of lines with a fixed sending voltage for line lengths "l" up to a 1/4 wavelength.

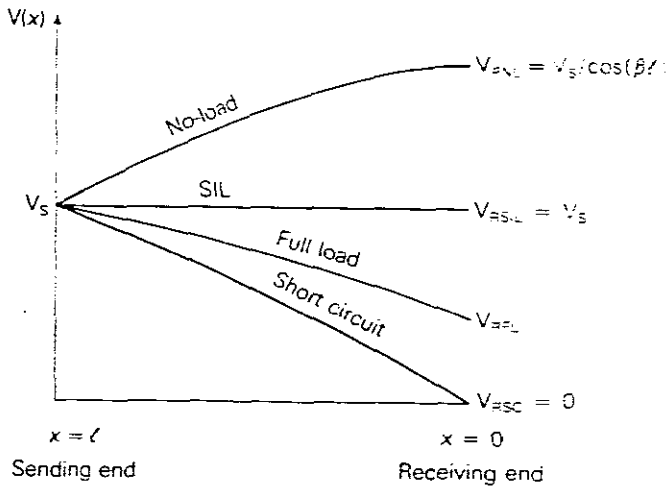


FIGURE 10.

Shunt compensation methods are used to reduce voltage fluctuations.

STEADY-STATE STABILITY LIMIT

From the equivalent- $\pi$  circuit of figure 5:

$$Z' = R' + j X' \text{ ----- (59)}$$

The equivalent- $\pi$  circuit of figure 8 is however used to obtain an equation for the real power delivered by a lossless line, therefore:

$$Z' = j X' \text{ ----- (60)}$$

The real power delivered by figure 8 is  $P_r$ . As the line is lossless,

$$P_s = P_r = P \text{ ----- (61)}$$

Where:

$$P = \frac{V_r V_s}{X'} \sin \delta \text{ ----- (62)}$$

See (69) below for derivation of (62).

If plotted for fixed voltage magnitudes, then as  $\delta$  (which is the sending-end phase angle) increases from 0 to 90 deg, the real power increases.

The maximum power that the line can deliver, which occurs when  $\delta = 90$  deg is:

$$P_{max} = \frac{V_s V_r}{X'} \text{ Watts ----- (63)}$$

where:

$$P_{max} = \text{the theoretical steady-state limit for a lossless line}$$

----- (64)

If an attempt were made to exceed this steady-state stability limit, then synchronous machines at the sending-end would lose synchronism with those at the receiving-end.

It is also convenient to express the steady-state stability limit in terms of the SIL, namely:

$$P_{max} = \frac{V_s \text{ p.u. } V_r \text{ p.u. (SIL)}}{\sin(2\pi l/W)} \text{ Watts} \quad \text{---(65)}$$

NB! for a lossless line:

If  $V_s = V_r = 765\text{kV}$ ,  $Z_c = 266.1 \text{ ohms}$ ,  $l = 300\text{km}$ ,  $W = 5000\text{km}$ , the steady-state stability limit is:

$$P_{max} = \frac{(1)(1)(765 \div 266.1)^2}{\sin \frac{2\pi \cdot 300}{5000}} = 5974\text{MW}$$

Note that the above is the theoretical maximum real power delivered for a lossless line.

**6. MAXIMUM POWER FLOW - LOSSY LINES**

For "LOSSY LINES" the maximum power flow can be expressed in terms of its ABCD parameters.

Although power at any point along a transmission line can always be found if the voltage, current and power factor are known. Very interesting equations for power can be derived in terms of the ABCD constants.

Using the following notation:

$$A = \text{Cosh}(\tau l) = A / \_ \theta a$$

$$B = Z' = Z' / \_ \theta z$$

$$V_s = V_s / \_ \delta$$

$$V_r = V_r / \_ 0 \text{ deg}$$

Then from:

$$V_s = A V_r + B I_r$$

$$I_r = \frac{V_s - A V_r}{B} = \frac{V_s e^{j\delta} - A V_r e^{j\theta a}}{Z' e^{j\theta z}}$$

Then the complex power delivered to the receiving-end is:

$$\begin{aligned}
 S_r &= P_r + j Q_r = V_r I_r^* = V_r \left[ \frac{V_s e^{j\delta} - A V_r e^{j\theta_a}}{Z' e^{j\theta_z}} \right]^* \\
 &= V_r \left[ \frac{V_s e^{j(\delta-\theta_z)} - A V_r e^{j(\theta_a-\theta_z)}}{Z'} \right]^* \\
 S_r &= \frac{V_r V_s e^{j(\theta_z-\delta)}}{Z'} - \frac{A V_r^2 e^{j(\theta_z-\theta_a)}}{Z'} \quad \text{---(66)}
 \end{aligned}$$

The real and reactive power delivered to the receiving-end are:

$$P_r = \frac{V_r V_s}{Z'} \cos(\theta_z - \delta) - \frac{A V_r^2}{Z'} \cos(\theta_z - \theta_a) \quad \text{---(67)}$$

$$Q_r = \frac{V_r V_s}{Z'} \sin(\theta_z - \delta) - \frac{A V_r^2}{Z'} \sin(\theta_z - \theta_a) \quad \text{---(68)}$$

NB! For a lossless line,  $\theta_a = 0$  deg,  $B = Z' = jX'$ ,  $\theta_z = 90$  deg  
 Therefore (67) reduces to:

$$P_r = \frac{V_r V_s}{X'} \cos(90 - \delta) - \frac{A V_r^2}{X'} \cos(90 \text{deg})$$

$$P_r = \frac{V_r V_s}{X'} \sin \delta \quad \text{---(69)}$$

which is the same as (62).

The theoretical maximum real power delivered or steady-state stability limit occurs for a "lossy line" when:

$$\delta = \theta_z \quad \text{---(70)}$$

Therefore:

$$Pr_{max} = \frac{V_r V_s}{Z'} - \frac{A V_r^2}{Z'} \cos(\theta_z - \theta_a) \text{ Watts} \quad \text{--- (71)}$$

The second term of (71) and because Z' is larger than X', Prmax for a lossy line is somewhat less than that for a lossless line as in (69).

EXAMPLE 3.

For a lossy line, if Vs = Vr = 765kV, and:

A = 0.9313pu, θa = 0.209deg, B = Z' = 97ohms, θz = 87.2deg

Zc = 266.1ohms,

Then from (71):

$$Pr_{max} = 5738 \text{ MW}$$

= the theoretical maximum  
power delivered

which can be expressed in terms of SIL as follows:

$$SIL = \frac{765^2}{266.1} = 2199 \text{ MW}$$

$$\text{Thus } Pr_{max} = \frac{5738}{2199} = 2.62 \text{ per unit}$$

7. LINE LOADABILITY

Power lines in practice are not operated to deliver their theoretical maximum power. Lines usually operate on the voltage drop limit Vr/Vs ≥ 0.95 and on maximum angular displacement of 30 deg to 35 deg across the line which is the margin of stability, during transient disturbances.

EXAMPLE 4.  
ON LINE LOADABILITY

A three phase 765kV, 60Hz, 300km, completely transposed line has four 1.272.000 cmil 54/3 ACSR conductors per bundle.

If the sending-end voltage is held constant at 1.0 p.u. of rated line voltage, determine:

Practical line loadability

- a. The practical line loadability (assume an  $V_r = 0.95$  pu and  $\delta = 35$  deg maximum angle across the line):

Now using (67) and the values of  $Z'$ ,  $\theta_z$ ,  $A$  and  $\theta_a$  from the previous example find  $P_r$ :

$$= \frac{(765)(.95 \times 765)}{97} \cos(87.2 - 35) - \frac{(0.9313)(0.95 \times 765)^2}{97} \cos(87.2 - .209)$$

$$= 3247 \text{ MW}$$

where  $P_r = 3247$  MW is the practical line loadability provided the thermal and voltage drop limits are not exceeded.

Full load current based on the practical line loadability

- b. The full load current at 0.986 pf. leading based on the practical line loadability:

$$I_{rfl} = \frac{P}{\sqrt{3} V_r \text{ pf}} = \frac{3247}{\sqrt{3} (0.95 \times 765) (0.986)} = 2.616 \text{ kA}$$

Receiving-end current for 2.616kA

- c. The exact receiving-end voltage for the full load current found in (b.) above

Now using:

$$V_s = AV_r + BI_r$$

and solving for  $V_r$ , we get:

$$V_{rfl}/\text{phase} = 420.7 \text{ and } V_{rfl} \text{ (line-to-line)} = 728.7 \text{ volts}$$

$$V_r = 0.953 \text{ per unit volts}$$

Percentage voltage regulation

- d. The percentage voltage regulation for the above full load current:

$$V_r = \frac{V_s}{A} = \frac{765}{0.9313} = 821.4 \text{ kV line-to-line}$$

and:

$$\text{PERCENT VR} = \frac{821.4 - 728.7}{728.7} \times 100\% = 12.72\%$$



Thermal limit

- e. The thermal limit of the line, based on the approximate current carrying capacity of the ACSR conductors given in Table A.4 (See attached appendix):

From Table A.4, the approximate current carrying capacity of four 1.272.000 cmil ACSR 54/3 conductors are:

$$4 \times 1.2 = 4.8\text{kA}$$

Conclusion:

Since the voltage  $V_{rfl} = 0.953$  it satisfies the voltage limit  $V_r/V_s \geq 0.95$ . The factor that limits line loadability for this 300km uncompensated line is the steady-state stability. The full current of 2.616kA is well below the thermal limit of 4.8kA. The 12.72% voltage regulation is too high because the no-load voltage is too high. Compensation techniques to reduce the no-load voltage is needed. (Explanation of compensation follows).

8. REACTIVE COMPENSATION TECHNIQUES

The performance of transmission lines especially those of medium and long lines can be improved by reactive compensation of a series or parallel type. Inductors and capacitors are used to increase line loadability and to maintain voltages near rated values.

Shunt compensation is the placement of inductors from each line to neutral to reduce shunt susceptance, particularly at light loads when the voltage at the receiving-end may otherwise become very high. However shunt reactors can reduce line loadability if they are not removed under full load conditions. In addition to shunt reactors, shunt capacitors are sometimes used to deliver reactive power and increase transmission voltages during heavy load conditions. Instead of shunt capacitors, synchronous capacitors (synchronous motors) can be used to control reactive power output, they are however slower than static var compensators.

Series compensation consists of a capacitor bank placed in series with each phase conductor of the line. They are used on long lines to increase the line loadability and are installed at selected points along a line. Their effect is to reduce the net series impedance, thereby reducing voltage drops and increasing the steady-state stability limit. A disadvantage of series capacitor banks is that automatic protection devices must be installed to bypass high currents during faults and to reinsert them after fault clearing.

Series compensation reduces the series impedance of the line, which is the principal cause of voltage drop and the most important factor in determining the maximum power which a line can transmit. See (69) and (71) where  $X'$  and  $Z'$  depend upon parameter B. We see that the maximum power transmitted is dependant upon the principal of constant B. If B is reduced by compensation, the maximum power of the line increases, a change in B will cause a change in the other parameters, A, C and D which are also functions of Z, however these changes will be small in comparison to the change in B.

When a nominal- $\pi$  circuit is used to represent the line and capacitor bank, the physical location of the capacitor bank along the line is not taken into account. If only the sending and receiving end conditions of the line are of interest, this will not create any significant error. However when the operation along the line is of interest, the physical location of the capacitor bank must be taken into account.

Long lines usually include intermediate substations. The following figure shows a line which includes two intermediate substations which divides a 500km line into three 167km line sections.

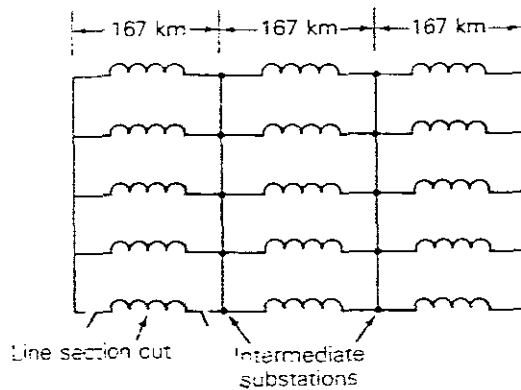


FIGURE 11.

Compensation is usually installed at line ends and at the intermediate substations.

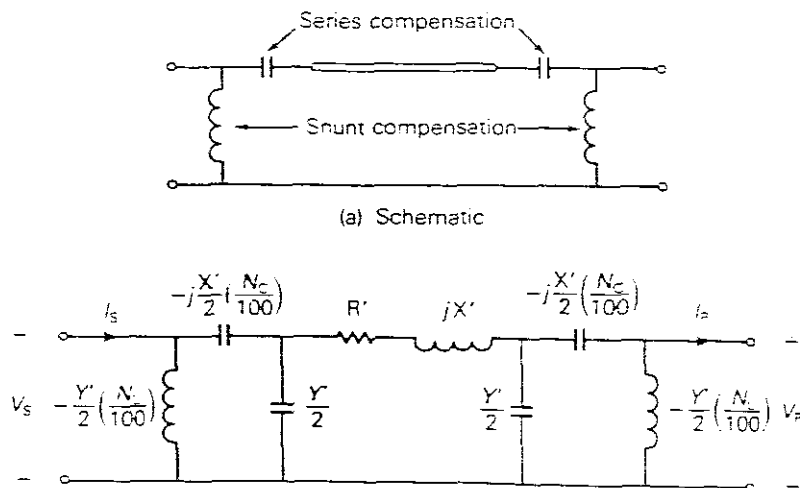


FIGURE 12.

The above figure shows a schematic and equivalent circuit for a compensated line section, where  $N_c$  is the amount of series capacitive compensation expressed in percent of the positive sequence line impedance and  $N_l$  is the amount of shunt reactive compensation in percent of the positive sequence line admittance. It is assumed that half of the compensation is installed at each end of the line section. The following two examples (examples 5 and 6) illustrate the effect of compensation:-

EXAMPLE 5

A three phase 765kV, 60Hz, 300km completely transposed line has the following positive sequence impedance and admittance.

$$z = 0.0165 + j 0.3306 = 0.3310/_87.14^\circ \text{ ohms/km}$$

$$y = j 4.674e-6 \text{ S/km}$$

Identical shunt reactors (inductors) are connected from each phase conductor to neutral at both ends of the line during light load conditions, providing 75% compensation. The reactors are removed during heavy load conditions. Full load is 1.90kA at unity pf and at 730kV. Assume that the sending end voltage is constant, determine the following:-

- a. Percent voltage regulation of the uncompensated line.
- b. The equivalent shunt admittance and series impedance of the compensated line.
- c. Percent voltage regulation of the compensated line.

Solution

- a. Find firstly the ABCD parameters for a line equivalent- $\pi$ :

$$Z_c = \frac{0.3310/_87.14^\circ}{4.674e-6/_90^\circ} = 266.1/_-1.43^\circ \text{ ohms}$$

$$\tau l = \sqrt{(0.331/_87.14^\circ)(4.674e-6/_90^\circ)} \times 300$$

$$= 0.3731/_88.57^\circ = 0.0931 + j0.373 \text{ per unit}$$

$$\text{Cosh} \tau l = 0.9313/_0.209^\circ$$

$$\text{Sinh} \tau l = 0.3645/_88.63^\circ$$

From which:

$$A = D = \text{Cosh} \tau l = 0.9313/_0.209^\circ \text{ per unit}$$

$$B = Z' = Z_c \text{Sinh} \tau l = 97/_87.2^\circ \text{ ohms}$$

$$C = \frac{\text{Sinh} \tau l}{Z_c} = 1.37e-3/_90.06^\circ \text{ Siemens}$$

Now using:  $V_s = AV_r + B I_r$   
 $= 442.3/_{-24.8\text{deg}}$  kV phase  
 $= 766$  kV line

then the no-load receiving-end voltage is:

$$V_{rnl} = \frac{V_s}{A} = \frac{766}{0.9313} = 822.6 \text{ kV line , and}$$

$$\text{PERCENT VR} = \frac{822.6 - 730}{730} \times 100\% = 12.68\%$$

- b. Finding firstly the shunt admittance of the equivalent- $\pi$  circuit without compensation:  
 Using (46) and the values found in Example 2. for  $\frac{Y}{2}$  and  $F_2$ :

$$\begin{aligned} \frac{Y'}{2} &= \frac{Y}{2} F_2 = (7.011e-4/_{-90\text{deg}}) (1.012/_{-0.03\text{deg}}) \\ &= 7.095e-4/_{-89.97\text{deg}} \text{ Siemens} \\ &= 3.7e-7 + j 7.095e-4 \text{ Siemens} \end{aligned}$$

From which:

$$Y' = 2(3.7e-7 + j 7.095e-4) = 7.4e-7 + j 14.188e-4$$

With 75% shunt compensation, the equivalent shunt admittance is:

$$\begin{aligned} Y_{eq} &= Y'(1 - \% \text{Compensation}) = Y'(1 - 75/100) \\ &= 3.547e-4/_{-89.88\text{deg}} \text{ Siemens} \end{aligned}$$

Since there is no series compensation, the equivalent series impedance is the same without compensation:

$$Z_{eq} = Z' = 97/_{-87.2 \text{ deg}} \text{ ohms} = R' + j X' = 4.74 + j 96.88$$

- c. From Figure 7. (Table 1.)

$A_{eq} = D_{eq} = \frac{1 + Y_{eq} Z_{eq}}{2} \text{ per unit}$	- - - - - (72)
$B_{eq} = Z_{eq} = Z' = Z_c \sinh \gamma l \text{ ohms}$	
$C_{eq} = Y_{eq} \left[ \frac{1 + Y_{eq} Z_{eq}}{4} \right] \text{ Siemens}$	

Therefore:

$$A_{eq} = 0.9828/_{-0.05\text{deg}} \text{ per unit}$$

Then:

$$\boxed{V_{rnl} = \frac{V_s}{A_{eq}} \text{------(73)}}$$

$$V_{rnl} = \frac{V_s}{A_{eq}} \frac{766}{0.9828} = 779.4 \text{ kV line}$$

Since the shunt reactors are removed during heavy load conditions,  $V_{rfl} = 730\text{kV}$  is the same as without compensation.

Therefore:

$$\boxed{\% VR = \frac{|V_s| \div |A_{eq}| - |V_{rfl}|}{|V_{rfl}|} \times 100 \text{------(74)}}$$

From which:  $\%VR = 6.77\%$

The use of shunt reactors at light loads improves the voltage regulation from 12.68% to 6.77% for this line. Before proceeding to the next example we must take note of the ABCD parameters for some common networks which will assist us in our problem solving.

Figure 13. shows the ABCD parameters of common networks:

Circuit	ABCD Matrix
<p>Series impedance</p>	$\begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$
<p>Shunt admittance</p>	$\begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix}$
<p>T circuit</p>	$\begin{bmatrix} (1 + YZ_1) & (Z_1 + Z_2 + YZ_1Z_2) \\ Y & (1 + YZ_2) \end{bmatrix}$
<p>Π circuit</p>	$\begin{bmatrix} (1 + Y_2Z) & Z \\ (Y_1 + Y_2 + Y_1Y_2Z) & (1 + Y_1Z) \end{bmatrix}$
<p>Series networks</p>	$\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} = \begin{bmatrix} (A_1A_2 + B_1C_2) & (A_1B_2 + B_1D_2) \\ (C_1A_2 + D_1C_2) & (C_1B_2 + D_1D_2) \end{bmatrix}$

FIGURE 13.

Figure 13 includes a series impedance network that approximates a short line, a  $\pi$ -circuit which can also be represented by a T-circuit and a shunt admittance network and their ABCD parameters. Also given are the ABCD parameters for networks in series, which are conveniently obtained by multiplying the ABCD matrices of the individual networks.

EXAMPLE 6

If identical series capacitors are installed in each phase at both ends of the line in Example 5 providing 30% compensation, determine the theoretical maximum power that this compensated line can deliver and compare with that of the uncompensated line:

Now:  $Z_c = 97/_87.2\text{deg} = R' + j X' = 4.738 + j 96.88$

Therefore:

$X' = 96.88$  ohms which is the equivalent series reactance without compensation

With 30% series compensation, half at each end of the line, the reactance of each series capacitor is:

$-j X_c = -j (0.5)(0.3)(96.88) = -j 14.53$  ohms

Using Figure 13, the ABCD matrix of a series impedance is:

$$\left[ \begin{array}{c|c} 1 & Z \\ \hline 0 & 1 \end{array} \right] \text{----- (75)}$$

Therefore:

$$\left[ \begin{array}{c|c} 1 & -j14.53 \\ \hline 0 & 1 \end{array} \right]$$

Also from Figure 13, the equivalent ABCD matrix of networks in series is obtained by multiplying the ABCD matrices of the individual networks.

For this example, there are three networks in series, the series capacitors at the sending-end, the line and the series capacitors at the receiving-end.

Therefore the equivalent ABCD matrix of the compensated line is, using the ABCD parameters from Example 5 is:

$$\left[ \begin{array}{c|c} 1 & -j14.53 \\ \hline 0 & 1 \end{array} \right] \left[ \begin{array}{c|c} 0.9313/_-.209^\circ & 97/_87.2^\circ \\ \hline 1.37e-3/_90.06^\circ & 0.9313/_-.209^\circ \end{array} \right] \left[ \begin{array}{c|c} 1 & -j14.53 \\ \hline 0 & 1 \end{array} \right]$$

which resolves to:

$$\left[ \begin{array}{c|c} A_{eq} & B_{eq} \\ \hline C_{eq} & D_{eq} \end{array} \right] = \left[ \begin{array}{c|c} 0.9512/_0.205^\circ & 69.7/_86.02^\circ \\ \hline 1.37e-3/_90.06^\circ & 0.9512/_0.205^\circ \end{array} \right]$$

From which:

$$A_{eq} = 0.9512 \text{ per unit} \quad \theta_{aeq} = 0.205 \text{ deg}$$

$$B_{eq} = Z'_{eq} = 69.7 \text{ ohms} \quad \theta_{zeq} = 86.02$$

Now from (71):

$$P_{rmax} = \frac{765^2}{69.7} - \frac{(0.9512)(765)^2}{69.7} \cos(86.02\text{deg} - 0.205\text{deg})$$

$$= 7813 \text{ MW}$$

= theoretical maximum power of the compensated line.

Now from Example 3 the theoretical maximum power = 5738 MW, which is without compensation.

Therefore this series compensated line is about 36.2% larger than the value in Example 3.

SECTION TWO  
EXPLANATION OF THE USAGE OF THE PACKAGE

The software package POWER includes a program entitled TRANSMISSION LINES - STEADY STATE OPERATION and relates to chapter 6 of the text book: Power System Analysis and Design with Computer Applications by J.D. Glover.

This program computes certain parameters, quantities and results for single or three phase transmission lines under steady-state conditions with or without compensation.

INPUT DATA

Input data to the program consists of:-

a. WITHOUT COMPENSATION

LINE DATA

- (1) Enter name of the line (any alphanumeric sequence)
- (2) Is the line a three phase or single phase line.?
- (3) Rated line voltage (kV)
- (4) Line length (km)
- (5) Line Constants  $R, wL, G$  and  $wC$ . (all per km.)

RECEIVING END DATA

- (1) Receiving-end full load voltage line-to-line (kV).
- (2) Receiving-end full load apparent power (MVA)
- (3) Receiving-end full load power factor (per unit) lagging or leading.

COMPENSATION DATA

There is no compensation data.



b. WITH SHUNT COMPENSATION (NO SERIES COMPENSATION) INSTALLED AT EACH END OF THE LINE, THE LINE HAVING NO INTERMEDIATE SUBSTATIONS AND THE SHUNT REACTORS BEING REMOVED. AT HEAVY (FULL) LOAD.

LINE DATA

- (1) Enter name of the line (any alphanumeric sequence)
- (2) Is the line a three phase or single phase line.?
- (3) Rated line voltage (kV)
- (4) Line length (km)
- (5) Line Constants R,wL,G and wC. (all per km.)

RECEIVING END DATA

- (1) Receiving-end full load voltage line-to-line (kV).
- (2) Receiving-end full load apparent power (MVA)
- (3) Receiving-end full load power factor (per unit) lagging or loading.

COMPENSATION DATA

- (1) Enter that line is compensated
- (2) Enter the % shunt compensation at sending-end
- (3) Enter the % shunt compensation at the receiving-end
- (4) Enter zero where prompted for series compensation and the number of intermediate substations.
- (5) Enter the total % shunt compensation when prompted.

c. WITH SHUNT (REACTOR) AND SERIES (CAPACITOR) COMPENSATION INSTALLED, THE LINE HAVING TWO INTERMEDIATE SUBSTATIONS DIVIDING LINE INTO THREE EQUAL LINE SECTIONS WITH EQUAL COMPENSATION AT LINE ENDS AND AT INTERMEDIATE SUBSTATIONS AND THE SHUNT REACTORS ARE REMOVED AT HEAVY (FULL) LOAD

LINE DATA

- (1) Enter name of the line (any alphanumeric sequence)
- (2) Is the line a three phase or single phase line.?
- (3) Rated line voltage (kV)
- (4) Line length (km)
- (5) Line Constants R,wL,G and wC. (all per km.)

RECEIVING END DATA

- (1) Receiving-end full load voltage line-to-line (kV).
- (2) Receiving-end full load apparent power (MVA)
- (3) Receiving-end full load power factor (per unit) lagging or leading.

COMPENSATION DATA

For example if the total series compensation is 22% and the total shunt compensation is 65%.

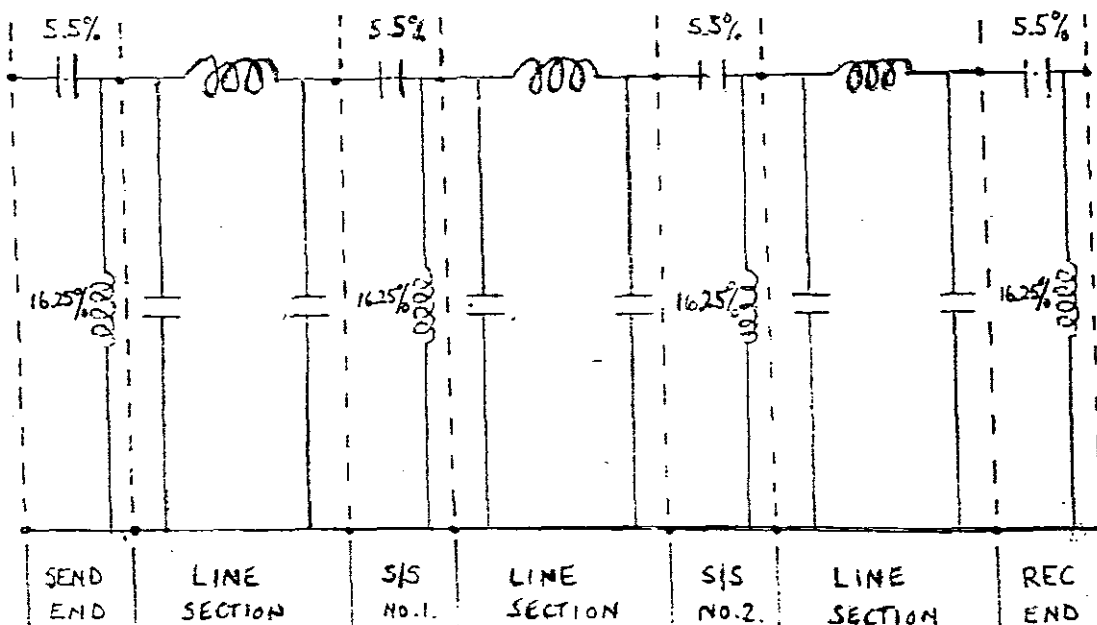


FIGURE 14.

(1) Shunt compensation at sending-end (%)	16.25
(2) Series compensation at sending-end (%)	5.5
(3) Shunt compensation at receiving-end (%)	16.25
(4) Series compensation at receiving-end (%)	5.5
(5) Number of intermediate substations	2
(6) Distance from sending-end to substation No.1(km)	(?)
(7) Shunt compensation at substations No.1. (%)	16.25
(8) Series compensation at substation No.1. (%)	5.5
(9) Distance from substation No.1 to substation No.2 (km)	(?)
(10) Shunt compensation at substation No.2 (%)	16.25
(11) Series compensation at substation No.2 (%)	5.5
(12) Total shunt compensation (%)	65
(13) Total series compensation (%)	22

OUTPUT DATA

Output data from the program consists of:-

a. WITHOUT COMPENSATION

(1) The characteristic impedance :-

$$Z_c = \sqrt{z \div y} \text{ ohms, called the characteristic impedance} \quad - - (20)$$

(2) The propagation constant:-

$$\tau = \sqrt{zy} \text{ m}^{-1}$$

----- (19)

where:-

$$\tau = \alpha + j\beta \text{ m}^{-1}$$

----- (33)

(3) The wavelength (km):

$$W = 2\pi/\beta$$

----- (54)

where  $\beta$  is obtained from (33) above.

(4) The surge impedance loading (MW)

$$SIL = \frac{V^2 \text{ rated}}{Z_c} \text{ Watts}$$

----- (58)

(5) The equivalent- $\pi$  circuit parameters:

(a) The series impedance:

$$\begin{aligned} Z' &= ZF1 \\ &= R' + jX' \end{aligned} \quad \text{----- (41)}$$

(b) The shunt admittance:

$$\begin{aligned} \frac{Y'}{2} &= \frac{Y}{2} \quad \text{Siemens} \\ \frac{Y'}{2} &= G' + j Bc' \\ Y' &= 2(Y/2)(F2) \end{aligned} \quad \text{----- (46)}$$

(c) The ABCD parameters expressed in polar notation:

$$\begin{aligned} A = D &= 1 + \frac{Y'Z'}{2} \quad \text{per unit} \\ B &= Z' \quad \text{ohms} \\ C &= Y' \left( 1 + \frac{Y'Z'}{4} \right) \quad \text{Siemens} \end{aligned} \quad \text{----- (37)}$$

(6) The sending-end voltage (line-to-line kV):

$$\begin{aligned} V_s &= AV_r + B I_r \\ V_s &= V_r \left( 1 + \frac{Z'Y'}{2} \right) + Z' I_r \end{aligned} \quad \text{----- (38)}$$

(7) The sending-end current (kA):

$$\begin{aligned} I_s &= CV_r + D I_r \\ I_s &= V_r \left[ \frac{1 + Z'Y'}{4} \right] Y' + \left[ \frac{1 + Z'Y'}{2} \right] I_r \end{aligned} \quad \text{--- (38)}$$

(8) The sending-end Apparent Power(MVA), Real Power(MW), Reactive Power(MVars) and Power Factor(per unit):

$$\begin{aligned} S_s &= V_s I_s^* = P_s(\text{MW}) + jQ_s(\text{MVars}) \\ \text{Sending-end pf.} &= \text{Cosine of the angle between } V_s \text{ and } I_s. \end{aligned} \quad \text{--- (38)}$$

(9) The voltage regulation (%)

$$\% VR = \frac{|V_{rn}| - |V_{rfl}|}{|V_{rfl}|} \times 100 \quad \text{--- (10)}$$

$$\% VR = \frac{|V_s| \div |A| - |V_{rfl}|}{|V_{rfl}|} \times 100 \quad \text{--- (11)}$$

(10) The theoretical maximum real power delivered to the receiving-end with rated terminal voltages(MW):

(1) For lossy lines:

$$Pr_{max} = \frac{V_r V_s}{Z'} - \frac{A V_r^2}{Z'} \cos(\theta_z - \theta_a) \quad \text{Watts} \quad \text{--- (71)}$$

(ii) For lossless line:

$$Pr = \frac{V_r V_s}{X'} \sin \delta \quad \text{--- (69)}$$

which is the same as (62).

b. WITH SHUNT COMPENSATION (NO SERIES COMPENSATION) INSTALLED AT EACH END OF THE LINE, THE LINE HAVING NO INTERMEDIATE SUBSTATIONS AND THE SHUNT REACTORS BEING REMOVED AT HEAVY (FULL) LOAD.

- (1) The equivalent full load ABCD parameters with the shunt compensation removed:-

NB! As there is no series nor shunt compensation (i.e. zero compensation), the ABCD parameters is the same as the ABCD parameters computed in (a)(5)(c) above, namely:-

$$\begin{aligned}
 A &= D = 1 + \frac{Y'Z'}{2} \text{ per unit} \\
 B &= Z' \text{ ohms} \\
 C &= Y' \left[ 1 + \frac{Y'Z'}{4} \right] \text{ Siemens}
 \end{aligned}
 \tag{37}$$

The parameters in (37) will change if series compensation is present. (See part c below).

These ABCD parameters are computed because they are needed for the calculation of Vs and Is under full load conditions.

- (2) The equivalent NO-LOAD ABCD parameters with shunt compensation included:-

NB! Shunt reactors providing a certain percentage compensation are connected during light load (No-load) conditions. The reactors are removed during heavy load (full) conditions.

Using figure 7. (Table 1)

$$\begin{aligned}
 A_{eq} &= D_{eq} = 1 + \frac{Y_{eq} Z_{eq}}{2} \text{ per unit} \\
 B_{eq} &= Z_{eq} = Z' = Z_c \sinh r l \text{ ohms} \\
 C_{eq} &= Y_{eq} \left[ 1 + \frac{Y_{eq} Z_{eq}}{4} \right] \text{ Siemens}
 \end{aligned}
 \tag{72}$$

A<sub>eq</sub> being needed to find the no-load sending-end voltage for regulation calculations.

(3) The sending-end voltage at full load (line-to-line kV):-

NB! Since the shunt reactors are removed during heavy (full) load conditions and as there is no series compensations, the ABCD parameters for an equivalent  $-\pi$  circuit are used. (Not  $A_{eq}, B_{eq}, C_{eq}, D_{eq}$ ).

$$\begin{aligned}
 V_s &= AV_r + B I_r \\
 V_s &= V_r \left( 1 + \frac{Z' Y'}{2} \right) + Z' I_r \quad \text{--- (38)}
 \end{aligned}$$

(4) The sending end current at full load (kA)

$$\begin{aligned}
 I_s &= C V_r + D I_r \\
 I_s &= V_r \left[ \frac{1 + Z' Y'}{4} \right] Y' + \left[ \frac{1 + Z' Y'}{2} \right] I_r \quad \text{--- (38)}
 \end{aligned}$$

(5) The sending-end Apparent Power (MVA), Real Power (MW), Reactive Power (MVars) and Power Factor (per unit):

$$\begin{aligned}
 S_s &= V_s I_s^* = P_s (\text{MW}) + j Q_s (\text{MVars}) \\
 \text{Sending-end pf.} &= \text{Cosine of the angle between } V_s \text{ and } I_s.
 \end{aligned} \quad \text{--- (38)}$$

(6) The voltage regulation (%)

$$\% \text{ VR} = \frac{|V_{rnl}| - |V_{rfl}|}{|V_{rfl}|} \times 100 \quad \text{--- (10)}$$

However, under no-load conditions, shunt compensation is present, therefore:-

$$V_{rnl} = \frac{V_s}{A_{eq}} \quad \text{--- (73)}$$

where  $A_{eq}$  is found from (72),

Therefore:-

$$\% VR = \frac{|Vs| \div |Aeq| - |Vrfl|}{|Vrfl|} \times 100 \quad \text{---(74)}$$

(7) The theoretical maximum real power delivered to the receiving-end with rated terminal voltages(MW):--

(1) For lossy lines:

$$Pr_{max} = \frac{VrVs}{Z'} - \frac{AVr^2}{Z'} \cos(\theta_z - \theta_a) \quad \text{Watts} \quad \text{---(71)}$$

where A comes from (37).

(ii) For lossless line:

$$Pr = \frac{VrVs}{X'} \sin \delta \quad \text{---(69)}$$

which is the same as (62).



c. WITH SHUNT (REACTOR) AND SERIES (CAPACITOR) COMPENSATION INSTALLED, THE LINE HAVING TWO INTERMEDIATE SUBSTATIONS DIVIDING LINE INTO THREE EQUAL LINE SECTIONS WITH EQUAL COMPENSATION AT LINE ENDS AND AT INTERMEDIATE SUBSTATIONS AND THE SHUNT REACTORS ARE REMOVED AT HEAVY (FULL) LOAD

(1) The full load ABCD parameters included series compensation but with the shunt compensation removed:-

NB! As there is series compensation included, an equivalent ABCD matrix for the networks in series must be obtained. That is, for example, an ABCD matrix for Figure 14 which comprises 7 networks in series with the shunt compensation reactors removed, namely:-

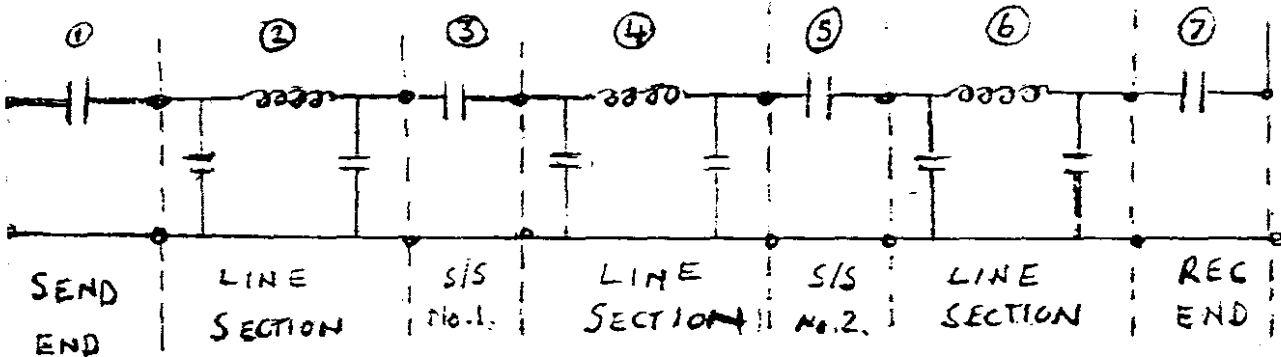


FIGURE 15.

Using Figure 13, the ABCD matrix of a series impedance is:-

$$\left[ \begin{array}{c|c} 1 & Z \\ \hline 0 & 1 \end{array} \right] \text{----- (75)}$$

which applies to series capacitor networks 1,3,5 and 7, where:-

$$Z = -j X_c = (1/4) (5.5 \div 100) (\text{Total series } wL)$$

and as each of the three line sections 2,4 and 6 are uncompensated, the ABCD parameters for these three sections will be based on the equivalent- $\pi$  circuit ABCD parameters, (See Figure 7-Table 1) but using the length of a line section only, which is from (37):-

$1 + \frac{Y'Z'}{2}$	$Z'$	----- (76)
$Y' \left[ 1 + \frac{Y'Z'}{4} \right]$	$\left[ 1 + \frac{Y'Z'}{2} \right]$	

...That is:-

For each line section only		----- (77)
$\left[ \begin{array}{c c} A & B \\ \hline C & D \end{array} \right]$		

Therefore the equivalent Aeq, Beq, Ceq and Deq matrix for the line is:-

$$\left[ \begin{array}{c|c} 1 & -jXc \\ \hline 0 & 1 \end{array} \right] \left[ \begin{array}{c|c} A & B \\ \hline C & D \end{array} \right] \left[ \begin{array}{c|c} 1 & -jXc \\ \hline 0 & 1 \end{array} \right] \left[ \begin{array}{c|c} A & B \\ \hline C & D \end{array} \right] \left[ \begin{array}{c|c} 1 & -jXc \\ \hline 0 & 1 \end{array} \right] \left[ \begin{array}{c|c} A & B \\ \hline C & D \end{array} \right] \left[ \begin{array}{c|c} 1 & -jXc \\ \hline 0 & 1 \end{array} \right]$$

which resolves to the equivalent full load ABCD parameters for the compensated line, namely:-

Aeq	Beq	----- (78)
Ceq	Deq	

(2) The NO-LOAD ABCD parameters including both shunt and series compensation:-

The resultant network is as follows:-

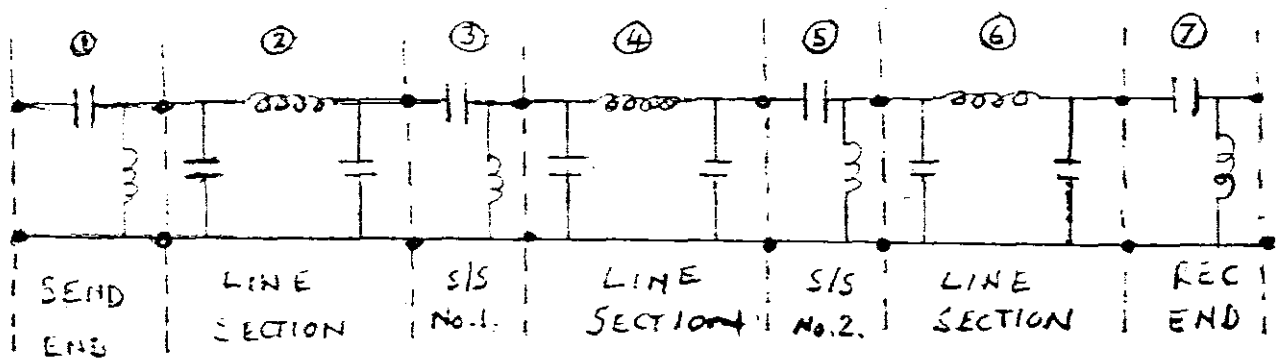


FIGURE 16.

which is altered as follows to eleven networks in cascade:-

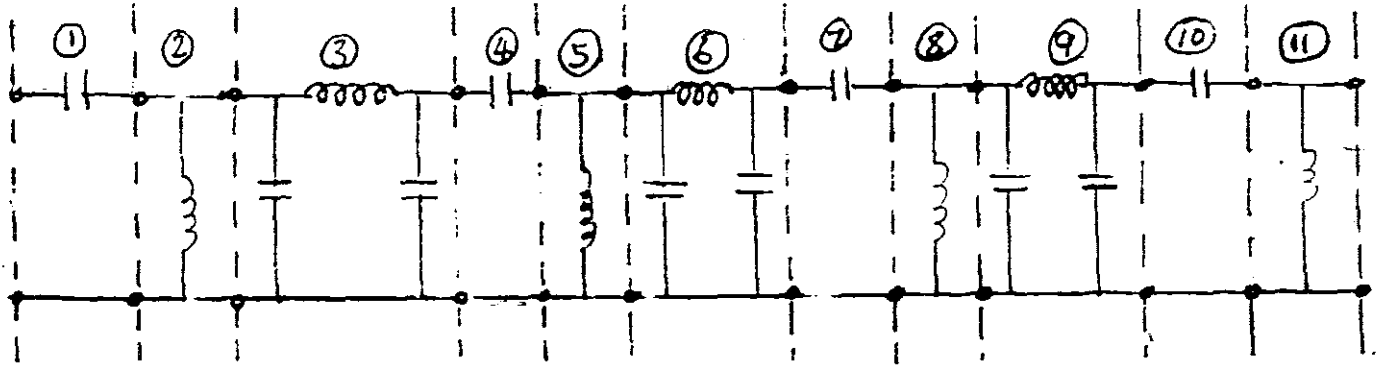


FIGURE 17.

Networks 1,4,7 and 10 are series networks having an ABCD matrix as follows:-

$$\begin{bmatrix} 1 & -jX_c \\ 0 & 1 \end{bmatrix}$$

Networks 2,5,8 and 11 are from Figure 13, shunt admittances having an ABCD matrix as follows:-

$$\begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \text{----- (79)}$$

Networks 3,6 and 9 are equivalent- $\pi$  circuits having an ABCD matrix as follows:-

For each line section only

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \text{----- (77)}$$

If the eleven network matrices are multiplied together an equivalent  $A_{eq}$ ,  $B_{eq}$ ,  $C_{eq}$  and  $D_{eq}$  matrix is obtained for the NO-LOAD conditions, namely:-

For the NO-LOAD conditions

$$\begin{bmatrix} A_{eq} & B_{eq} \\ C_{eq} & D_{eq} \end{bmatrix} \text{----- (80)}$$

(3) The sending-end voltage at full load (line-to-line kV):-

NB! Since the shunt reactors are removed during heavy (full) load conditions, the series compensation however remaining, the ABCD parameters used are those of (78).

Therefore:-

$$V_s = A_{eq}V_r + B_{eq}I_r \quad \text{--- (81)}$$

(4) The sending-end current at full load (kA) is likewise found:-

$$I_s = C_{eq}V_r + D_{eq}I_r \quad \text{--- (82)}$$

(5) The sending-end Apparent Power(MVA), Real Power(MW), Reactive Power(MVars) and Power Factor(per unit):

$$S_s = V_s I_s^* = P_s(\text{MW}) + jQ_s(\text{MVars}) \quad \text{--- (38)}$$

Sending-end pf. = Cosine of the angle between  $V_s$  and  $I_s$ .

(6) The voltage regulation (%)

NB! Under NO-LOAD conditions, both the shunt and series compensation is present, therefore the ABCD parameters found in (80) must be used:-

$$V_{rnl} = \frac{V_s}{A_{eq}} \quad \text{--- (83)}$$

Therefore:-

$$\% \text{ VR} = \frac{|V_s| \div |A_{eq}| - |V_{rfl}|}{|V_{rfl}|} \times 100 \quad \text{--- (84)}$$

where  $A_{eq}$  comes from (80).

(7) The theoretical maximum real power delivered to the receiving-end with rated terminal voltages(MW):

$$P_{rmax} = \frac{V_r V_s}{Z'} - \frac{A_{eq} V_r^2}{Z'} \cos(\theta_z - \theta_a) \quad \text{Watts} \quad \text{--- (85)}$$

where  $A_{eq}$  comes from (78).

SECTION THREE  
EXAMPLES SOFTWARE SOLUTION

1. INTRODUCTION

The computer software is now used to solve examples enabling the user to obtain output data.

```
C:\>cd\POWER
Press return
C:\ POWER > CHAP6
Press Enter (Access obtained)
```

Screen shows

```
TRANSMISSION LINES-STEADY STATE OPERATION
REFERENCE: J.D. GLOVER & M. SARMA
POWER SYSTEM ANALYSIS AND DESIGN
WITH PERSONAL COMPUTER APPLICATIONS
PWS PUBLISHES, BOSTON, 1987
CHAPTER SIX
```

```
This program was written by J.Duncan Glover
This program is copyright protected.
```

Press return to continue.

Screen shows

```
THIS PROGRAM EVALUATES A SINGLE PHASE OR
A BALANCED THREE PHASE TRANSMISSION LINE
UNDER STEADY STATE OPERATING CONDITIONS
```

```
THE FOLLOWING QUANTITIES ARE COMPUTED
```

```
(A)WITHOUT COMPENSATION
```

- (1) CHARACTERISTIC IMPEDANCE, EQ (6.2.16)
- (2) PROPAGATION CONSTANT, EQ (6.2.12)
- (3) WAVELENGTH, EQ (6.4.15)
- (4) SURGE INPEDANCE LOADING, EQ (6.4.21)
- (5) EQUIVALENT PI CIRCUIT SERIES IMPEDANCE, EQ(6.3.5)-EQ  
(6.3.6)
- (6) EQUIVALENT PI CIRCUIT SHUNT ADMITTANCE, EQ(6.3.1)-EQ  
(6.3.3)
- (7) ABCD PARAMETERS, EQ(6.3.1)-EQ(6.3.3)

```
(B) WITH COMPENSATION
```

- (1) EQUIVALENT FULL-LOAD ABCD PARAMETERS
- (2) SENDING END VOLTAGE, CURRENT AND POWER, EQ(6.1.3)
- (3) % VOLTAGE REGULATION, EQ(6.1.8)
- (4) THEORETICAL MAXIMUM REAL POWER DELIVERED  
TO THE RECEIVING END WITH RATED TERMINAL VOLTAGES

```
LINE DATA
```

```
ENTER THE NAME OF THE LINE (ANY ALPHANUMERIC SEQUENCE)
```

TAKE NOTE

Before proceeding it must be stated that the above reference to equation numbers, refers to those appearing in Chapter Six of the Glover Textbook and are different numbers to those appearing in this study programme. See Section One and Two of this study programme.

The writer of this study programme has attempted to write it in a manner so that none or very little reference is needed to the Glover Textbook or to any other reference listed in the bibliography.

The above is the general introductory steps which will appear everytime a steady-state problem is solved by means of this software package.

Each of the following solutions will therefore commence with the heading: LINE DATA.

2. SOFTWARE SOLUTIONS

EXAMPLE A  
AN UNCOMPENSATED LINE

A 400km, 500kV, 60Hz, three-phase uncompensated line has a positive sequence series impedance  $z = 0.03 + j 0.35$  ohms/km and a positive sequence shunt admittance  $y = j 4.4e- 6$  S/km. At full load the line delivers 1000MW at unity power factor and at a receiving-end voltage of 475kV. Using the TRANSMISSION LINES - STEADY-STATE OPERATION programme, determine :-

- (a) CHARACTERISTIC IMPEDANCE (ohm)
- (b) PROPAGATION CONSTANT (1/m)
- (c) WAVELENGTH(km)
- (d) SURGE IMPEDANCE LOADING (MW)
- (e) FOR THE EQUIVALENT PI CIRCUIT:
  - (1) SERIES IMPEDANCE(ohms)
  - (11) SHUNT ADMITTANCE(mhos)
  - (111) ABCD PARAMETERS:
    - A PARAMETERS(per unit)
    - B PARAMETERS(ohms)
    - C PARAMETERS(mhos)
    - D PARAMETERS(per unit)
- (f) SENDING END VOLTAGE (LINE-TO-LINE kV)
- (g) SENDING END CURRENT (kA)
- (h) SENDING END REAL POWER (MW)
- (i) SENDING END REACTIVE POWER (Mvars)
- (j) SENDING END APPARENT POWER (mva)
- (k) SENDING END POWER FACTOR (per unit)
- (l) VOLTAGE REGULATION (%)
- (m) THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)

SOLUTION:-

LINE DATA

ENTER THE NAME OF THE LINE (AND ALPHANUMERIC SEQUENCE)  
ENTER EX.A, PRESS RETURN  
IS THIS A THREE PHASE LINE (ENTER Y) OR A SINGLE PHASE LINE  
(ENTER N)?  
ENTER Y, PRESS RETURN  
ENTER THE RATED LINE VOLTAGE (LINE - LINE kV)  
ENTER 500, PRESS RETURN  
ENTER THE LINE LENGTH (km)  
ENTER 400  
ENTER THE SERIES RESISTANCE (ohms/km)  
ENTER 0.03, PRESS RETURN  
ENTER THE SERIES REACTANCE (ohms/km)  
ENTER 0.35, PRESS RETURN  
ENTER THE SHUNT CONDUCTANCE (mhos/km)  
ENTER 0, PRESS RETURN  
ENTER THE SHUNT SUSCEPTANCE (mhos/km)  
ENTER 4.4e-6, PRESS RETURN

RECEIVING END DATA

ENTER THE RECEIVING END FULL LOAD VOLTAGE (LINE-LINE kV)  
ENTER 475, PRESS RETURN  
ENTER THE RECEIVING END FULL LOAD APPARENT POWER (MVA)  
ENTER 1000, PRESS RETURN  
ENTER THE RECEIVING END FULL LOAD POWER FACTOR (per unit)  
ENTER 1, PRESS RETURN

COMPENSATION DATA

IS THE LINE COMPENSATED (Y OR N)?  
ENTER N, PRESS RETURN

DO YOU WANT TO CONTINUE (Y) OR RESET THE INPUT DATA (N)?  
ENTER (Y), PRESS RETURN

USE THE Ctrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS.

IF PRINTER NOT AVAILABLE, PRESS RETURN AND USE PAUSE TO OBSERVE THE DISPLAYED INPUT AND OUTPUT DATA. IF PRINTER AVAILABLE PROCEED AS FOLLOWS: PRESS Ctrl PRINT SCREEN  
PRESS RETURN

ONCE PRINTER HAS STOPPED PRINTING, REMOVE Ctrl PRINT SCREEN BY PRESSING Ctrl PRINT SCREEN AND PRESS RETURN.

THE SCREEN THEN ASKS YOU :-  
DO YOU WANT TO RUN IT AGAIN (ENTER Y) OR QUIT (N) ?

THE PRINTOUT OBTAINED OR THAT DISPLAYED ON YOUR SCREEN IS IN TWO PARTS, NAMELY INPUT AND OUTPUT DATA AND IS AS FOLLOWS:-

\*\*\*\*\*INPUT DATA\*\*\*\*\*

EX.A        THREE-PHASE        500 kV        400 km  
LINE DATA:  
SERIES RESISTANCE (ohms/km)        3.000E-02  
SERIES REACTANCE (ohms/km)        3.500E-01  
SHUNT CONDUCTANCE (mhos/km)        0.000E+00  
SHUNT SUSCEPTANCE (mhos/km)        4.400E-06  
  
RECEIVING END DATA:  
RECEIVING END FULL LOAD VOLTAGE (kV)        4.750E+02  
RECEIVING END FULL LOAD  
APPARENT POWER (MVA)        1.000E+03  
RECEIVING END FULL LOAD  
POWER FACTOR (per unit)        1.000E+00  
COMPENSATION DATA:  
THERE IS NO COMPENSATION

\*\*\*\*\*OUTPUT DATA\*\*\*\*\*

\*\*\*\*\*WITHOUT COMPENSATION\*\*\*\*\*  
CHARACTERISTIC IMPEDANCE (ohms)        2.826+02/ -2.450E+00DEG  
PROPAGATION CONSTANT (1/m)        5.314-05 + j 1.242E-03  
WAVELENGTH (km)        5.059+03  
SURGE IMPEDANCE LOADING (MW)        8.848+02  
  
EQUIVALENT PI CIRCUIT:  
SERIES IMPEDANCE (ohms)        1.103E+01 +j 1.344E+02  
SHUNT ADMITTANCE (mhos)        3.256E-06 +j 1.797E-03  
ABCD PARAMETERS:  
A PARAMETER (per unit)        8.793-01/ 6.602E-01DEG  
B PARAMETER (ohms)        1.348+02/ 8.531E+01DEG  
C PARAMETER (mhos)        1.689-03/ 9.021E+01DEG  
D PARAMETER (per unit)        8.793-01/ 6.602E-01DEG  
  
SENDING END VOLTAGE (LINE-TO-LINE kV)        5.264E+02/ 3.312E+01DEG  
SENDING END CURRENT (kA)        1.168E+00/ 2.401E+01DEG  
SENDING END REAL POWER (MW)        1.052E+03  
SENDING END REACTIVE POWER (Mvars)        1.687E+02  
SENDING END APPARENT POWER (MVA)        1.065E+03  
SENDING END POWER FACTOR (per unit)        9.874E-01 LAGGING  
VOLTAGE REGULATION (%)        2.604E+01  
THEORETICAL MAXIMUM REAL POWER  
DELIVED (MW)        1.702E+03



INTERPRETATION AND UNDERSTANDING OF  
THE OUTPUT DATA

For interpretation and understanding of the output data, the user is referred to Section One and more particularly to Section Two of this study programme. As this is an uncompensated line the user is to refer in particular to Section Two Part "a" (OUTPUT DATA).

- a) The characteristic impedance is found from equation (20).
- b) The propagation constant from equation (19). That is  $\alpha = 5.314E-5$  and  $\beta = 1.242E-3$
- c) The wavelength from (54), using for example  $\beta$  from (19):-

$$W = \frac{2\pi}{\beta} = \frac{2\pi}{1.242e-3} = 5.058e+3$$

Which is the same answer as the output data.

- d) Surge Impedance Loading (MW) is found from (58) :-

$$SIL = \frac{500^2}{2.826e + 2} = 8.84 \text{ MW}$$

Confirming the computer output data.

- e) (i) The series impedance is found by using (41)
- (ii) The shunt admittance by (46)
- (iii) The ABCD parameters by (37)
- f) The sending end voltage by (38). Theoretically checking this answer we get:-

$$I_r = \frac{1000e+6}{\sqrt{3}(475e+3)(1)} = 1215.47/0\text{deg}$$

$$V_s = AV_r + BI_r$$

$$= (0.8793/.6602\text{deg}) \left[ \frac{475e+3}{\sqrt{3}} \right] + (134.8/85.31\text{deg})(1215.47/0\text{deg})$$

$$= 5.264 \text{ kV (line)}$$

thus confirming the computer output data.

- g) The sending-end current from (38)
  - h) The sending-end MW from (38)
  - i) The sending-end MVars from (38)
  - j) The sending-end MVA from (38)
  - k) The sending-end power factor from (38)
  - l) The voltage regulation % from (11)
  - m) The Prmax from (71)
- Press N to quit

EXAMPLE B  
WITH SHUNT COMPENSATION (NO SERIES COMPENSATION)  
INSTALLED AT EACH END OF THE LINE, THE LINE HAVING  
NO INTERMEDIATE SUBSTATIONS AND THE SHUNT REACTORS  
BEING REMOVED AT HEAVY (FULL) LOAD.

A three phase 345kV, 200km, 60Hz line has a positive sequence impedance  $0,047 + j 0.37$  ohms/km and positive sequence shunt admittance  $0 + j 4.1 E^{-6}$  S/km. Full load at the receiving-end of the line is 800 MVA at 0.99 pf. leading and at 328kV. 75% total shunt reactive compensation is installed, half 37.5% at each end of the line. The shunt reactors are removed at heavy loads. There are no intermediate substations and there is no series compensation. Using the TRANSMISSION LINES-STEADY STATE OPERATION PROGRAMME determine:-

WITHOUT COMPENSATION

- (a) CHARACTERISTIC IMPEDANCE (ohms)
- (b) PROPAGATION CONSTANT (1/m)
- (c) WAVELENGTH(km)
- (d) SURGE IMPEDANCE LOADING (MW)
- (e) FOR THE EQUIVALENT PI CIRCUIT:
  - (1) SERIES IMPEDANCE(ohms)
  - (11) SHUNT ADMITTANCE(mhos)
  - (111) ABCD PARAMETERS:
    - A PARAMETERS(per unit)
    - B PARAMETERS(ohms)
    - C PARAMETERS(mhos)
    - D PARAMETERS(per unit)

WITH COMPENSATION

- f) FULL LOAD ABCD PARAMETERS  
(SHUNT COMPENSATION IS REMOVED)
  - A PARAMETER (per unit)
  - B PARAMETER (ohms)
  - C PARAMETER (mhos)
  - D PARAMETER (per unit)
- g) NO-LOAD ABCD PARAMETERS  
(SHUNT COMPENSATION IS INCLUDED):
  - A PARAMETER (per unit)
  - B PARAMETER (ohms)
  - C PARAMETER (mhos)
  - D PARAMETER (per unit)
- (h) SENDING END VOLTAGE (LINE-TO-LINE kV)
- (i) SENDING END CURRENT (kA)
- (j) SENDING END REAL POWER (MW)
- (k) SENDING END REACTIVE POWER (Mvars)
- (l) SENDING END APPARENT POWER (mva)
- (m) SENDING END POWER FACTOR (per unit)
- (n) VOLTAGE REGULATION (%)
- (o) THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)

SOLUTION

LINE DATA

ENTER THE NAME OF THE LINE (AND ALPHANUMERIC SEQUENCE)  
ENTER EX.B, PRESS RETURN  
IS THIS A THREE PHASE LINE (ENTER Y) OR A SINGLE PHASE LINE  
(ENTER N)?  
ENTER Y, PRESS RETURN  
ENTER THE RATED LINE VOLTAGE (LINE - LINE kV)  
ENTER 345, PRESS RETURN  
ENTER THE LINE LENGTH (km)  
ENTER 200  
ENTER THE SERIES RESISTANCE (ohms/km)  
ENTER 0.047, PRESS RETURN  
ENTER THE SERIES REACTANCE (ohms/km)  
ENTER 0.37, PRESS RETURN  
ENTER THE SHUNT CONDUCTANCE (mhos/km)  
ENTER 0, PRESS RETURN  
ENTER THE SHUNT SUSCEPTANCE (mhos/km)  
ENTER 4.1e-6, PRESS RETURN

RECEIVING END DATA

ENTER THE RECEIVING END FULL LOAD VOLTAGE (LINE-LINE kV)  
ENTER 328, PRESS RETURN  
ENTER THE RECEIVING END FULL LOAD APPARENT POWER (MVA)  
ENTER 800, PRESS RETURN  
ENTER THE RECEIVING END FULL LOAD POWER FACTOR (per unit)  
ENTER 0.99, PRESS RETURN  
IS THE POWER FACTOR LAGGING(ENTER Y) OR LEADING(ENTER N)  
ENTER N, PRESS RETURN

COMPENSATION DATA

IS THE LINE COMPENSATED (Y OR N)?  
ENTER Y, PRESS RETURN

Screen shows:-

COMPENSATION INPUT DATA AT EACH LOCATION IS GIVEN IN PER CENT  
OF TOTAL SHUNT SUSCEPTANCE OR SERIES REACTANCE OF THE LINE

ENTER THE % SHUNT REACTIVE COMPENSATION AT THE SENDING-END  
ENTER 37.5, PRESS RETURN  
ENTER THE % SERIES CAPACITIVE COMPENSATION AT THE SENDING-END  
ENTER 0, PRESS RETURN  
ENTER THE % SHUNT REACTIVE COMPENSATION AT THE RECEIVING-END  
ENTER 37.5, PRESS RETURN  
ENTER THE % SERIES CAPACITIVE COMPENSATION AT THE RECEIVING-END  
ENTER 0, PRESS RETURN  
ENTER THE NUMBER OF INTERMEDIATE SUBSTATIONS(0, 1 OR 2)  
ENTER 0, PRESS RETURN

DO YOU WANT TO CONTINUE (Y) OR RESET THE INPUT DATA (N)?  
ENTER (Y), PRESS RETURN

USE THE Ctrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS.  
IF PRINTER NOT AVAILABLE, PRESS RETURN AND USE PAUSE TO OBSERVE THE DISPLAYED INPUT AND OUTPUT DATA. IF PRINTER AVAILABLE PROCEED AS FOLLOWS: PRESS Ctrl PRINT SCREEN  
PRESS RETURN  
ONCE PRINTER HAS STOPPED PRINTING, REMOVE Ctrl PRINT SCREEN BY PRESSING Ctrl PRINT SCREEN AND PRESS RETURN.

THE SCREEN THEN ASKS YOU:-  
DO YOU WANT TO RUN IT AGAIN (ENTER Y) OR QUIT (N)?

THE PRINTOUT OBTAINED OR THAT DISPLAYED ON YOUR SCREEN IS IN TWO PARTS, NAMELY INPUT AND OUTPUT DATA AND IS AS FOLLOWS:-

\*\*\*\*\*INPUT DATA\*\*\*\*\*

EX.B        THREE-PHASE        345 kV        200 km

LINE DATA:

SERIES RESISTANCE (ohms/km)	4.700E-02
SERIES REACTANCE (ohms/km)	3.700E-01
SHUNT CONDUCTANCE (mhos/km)	0.000E+00
SHUNT SUSCEPTANCE (mhos/km)	4.100E-06

RECEIVING END DATA:

RECEIVING END FULL LOAD VOLTAGE (kV)	3.280E+02
RECEIVING END FULL LOAD APPARENT POWER (MVA)	8.000E+02
RECEIVING END FULL LOAD POWER FACTOR (per unit)	9.900E-01 LEADING

COMPENSATION DATA:

SHUNT COMPENSATION AT SENDING-END (%)	37.5
SERIES COMPENSATION AT SENDING-END (%)	0
SHUNT COMPENSATION AT RECEIVING-END (%)	37.5
SERIES COMPENSATION AT RECEIVING-END (%)	0
NUMBER OF INTEMEDATE SUBSTATIONS	0
TOTAL SHUNT COMPENSATION (%)	75
TOTAL SERIES COMPENSATION (%)	0

\*\*\*\*\*OUTPUT DATA\*\*\*\*\*

\*\*\*\*\*WITHOUT COMPENSATION\*\*\*\*\*

CHARACTERISTIC IMPEDANCE (ohms)	3.016E+02/ -3.620E+00DEG
PROPAGATION CONSTANT (1/m)	7.807E-05 + j 1.234E-03
WAVELENGTH (km)	5.091E+03
SURGE IMPEDANCE LOADING (MW)	3.946E+02

EQUIVALENT PI CIRCUIT:

SERIES IMPEDANCE (ohms)	9.211E+00 +j 7.327E+01
SHUNT ADMITTANCE (mhos)	5.336E-07 +j 8.242E-04

ABCD PARAMETERS:

A PARAMETER (per unit)	9.698E-01/ 2.254E-01DEG
B PARAMETER (ohms)	7.384E+01/ 8.283E+01DEG
C PARAMETER (mhos)	8.117E-04/ 9.007E+01DEG
D PARAMETER (per unit)	9.698E-01/ 2.254E-01DEG

\*\*\*\*\*WITH COMPENSATION\*\*\*\*\*

FULL LOAD ABCD PARAMETERS  
(SHUNT COMPENSATION IS REMOVED)

A PARAMETER (per unit)	9.698E-01/ 2.254E-01DEG
B PARAMETER (ohms)	7.384E+01/ 8.283E+01DEG
C PARAMETER (mhos)	8.117E-04/ 9.007E+01DEG
D PARAMETER (per unit)	9.698E-01/ 2.254E-01DEG

NO-LOAD ABCD PARAMETERS  
(SHUNT COMPENSATION IS INCLUDED):

A PARAMETER (per unit)	9.925E-01/ 5.591E-02DEG
B PARAMETER (ohms)	7.384E+01/ 8.283E+01DEG
C PARAMETER (mhos)	2.053E-04/ 8.988E+01DEG
D PARAMETER (per unit)	9.925E-01/ 5.591E-02DEG

SENDING END VOLTAGE (LINE-TO-LINE kV)	3.363E+02/ 2.992E+01DEG
SENDING END CURRENT (kA)	1.396E+00/ 1.459E+01DEG
SENDING END REAL POWER (MW)	8.479E+02
SENDING END REACTIVE POWER (Mvars)	2.324E+02
SENDING END APPARENT POWER (MVA)	8.792E+02
SENDING END POWER FACTOR (per unit)	9.644E-01 LAGGING
VOLTAGE REGULATION (%)	1.169E+01
THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)	1.411E+03

INTERPRETATION AND UNDERSTANDING OF THE OUTPUT DATA
--

For interpretation and understanding of the input and output data, the user is referred to Section One and more particularly to Section Two of this Study Programme. As this is a shunt compensated line the user is to refer in particular to Section Two Part "b" (OUTPUT DATA)

WITHOUT COMPENSATION
----------------------

a) to e) are found from (20), (19), (54), (41), (46) and (37).

WITH COMPENSATION

(f) The equivalent full load ABCD parameters with shunt compensation removed and as there is no series compensation, the ABCD parameters are computed from (37).

These ABCD parameters would change if series compensation was present. (See Ex.C where series compensation is included.)

These ABCD parameters with shunt reactors removed are computed as are needed for the calculation of Vs and Is under full load conditions.

g) The equivalent NO-LOAD ABCD (Aeq, Beq, Ceq and Deq) parameters with shunt compensation included are computed from (72).

The following theoretical steps would be used to find Aeq, Beq, Ceq, Deq :-

(1) Find  $\frac{Y}{2}$  of equivalent- $\pi$  without compensation for 200km.

$$Y = 4.1E-6 \times 200 = 8.20E-6 \text{ Siemens}$$

$$\frac{Y}{2} = 4.1E-6 / \_90\text{deg Siemens}$$

(2) Find  $F2 = \frac{\text{Cosh}(\tau l) - 1}{\text{Sinh}(\tau l) (\tau l/2)}$  by first finding:-

$$\tau l = 0.2473 / \_86.379\text{deg}$$

$$\text{Cosh} \tau l = 0.9698 / \_0.224\text{deg}$$

$$\text{Sinh} \tau l = 0.2447 / \_86.46\text{deg}$$

and

$$F2 = 1.00621 / \_-0.02\text{deg}$$

(3) Find  $\frac{Y'}{2} = \frac{Y}{2} F2 = 4.12546E-4 / \_89.99\text{deg}$

(4)  $Y' = 2 \left[ \frac{Y}{2} F2 \right] = 8.250E-4 / \_89.99\text{deg}$

(5)  $Y_{eq} = Y'(1 - \% \text{ compensation}) = Y'(1 - 0.75)$   
 $= 2.0618E-4 / \_89.96\text{deg}$

(6) Find  $Z_{eq} = Z'$  (no series compensation)  
 $= Z_c \sinh r l = 73.827 / -82.84 \text{deg}$   
 $= \boxed{B_{eq}}$  and agrees with printout.

(7) Find  $A_{eq} = 1 + \frac{Y_{eq} Z_{eq}}{2} = D_{eq}$   
 $= 0.992$  which agrees with printout.

(8) Find  $C_{eq} = Y_{eq} \left[ \frac{1 + Y_{eq} Z_{eq}}{4} \right]$   
 $= 2.054E-4 / 89.9 \text{deg}$  which agrees with printout.

(h) The sending-end voltage at full has been computed by using the full load ABCD parameters without shunt compensation.

The following theoretical steps would be used:-

From (f) above:  $A = 0.9698 / -0.2254 \text{deg} = D$   
 $B = 73.84 / -82.83 \text{deg}$   
 $C = 0.008117 / -90 \text{deg}$

Find  $I_r = \frac{800E+6}{\sqrt{3} \cdot 328E+3} = 1408.17 / -8.11 \text{deg} \text{ A}$

$V_r = 189370.89 \text{ V phase}$

$V_s = A V_r + B I_r$   
 $= 36.36 / -29.9 \text{deg} \text{ kV line which agrees with printout.}$

(i) Find  $I_s = C V_r + D I_r$   
 $= 1.39 \text{kA}$  which agrees with printout.

(j)(k)(l)(m) are easily found from  $S_s = P_s + j Q_s$

(n) The voltage regulation(%) is found from (74) where  $A_{eq}$  comes from (g)(7) above.

(o)  $P_{rmax}$  is found from (71) where  $A$  comes (37).

EXAMPLE C

WITH SHUNT (REACTOR) AND SERIES (CAPACITOR) COMPENSATION INSTALLED, THE LINE HAVING TWO INTERMEDIATE SUBSTATIONS DIVIDING LINE INTO THREE EQUAL LINE SECTIONS WITH EQUAL COMPENSATION AT LINE ENDS AND AT INTERMEDIATE SUBSTATIONS AND THE SHUNT REACTORS ARE REMOVED AT HEAVY (FULL) LOAD

A 650km, 765kV, 60Hz three phase transmission line has a positive-sequence series impedance  $z = 0.0185 + j0.3170$  ohms/km and a positive-sequence shunt admittance  $y = j4.875E-6$  S/km. Full load at the receiving-end is 2500MVA at 0.99 p.f. leading and at 95% of rated voltage ( $0.95 \times 765 = 726.8$ kV). Two intermediate substations divide the line into three equal line sections. Twenty-two percent total series capacitive compensation and 65% total shunt reactive (inductive) compensation is installed with equal compensation at the line ends and at the intermediate substations. The shunt reactors are removed during heavy loads. Using the TRANSMISSION LINES-STEADY-STATE OPERATION program, determine:-

WITHOUT COMPENSATION

- (a) CHARACTERISTIC IMPEDANCE (ohms)
- (b) PROPAGATION CONSTANT (1/m)
- (c) WAVELENGTH(km)
- (d) SURGE IMPEDANCE LOADING (MW)
- (e) FOR THE EQUIVALENT PI CIRCUIT:
  - (1) SERIES IMPEDANCE(ohms)
  - (11) SHUNT ADMITTANCE(mhos)
  - (111) ABCD PARAMETERS:
    - A PARAMETERS(per unit)
    - B PARAMETERS(ohms)
    - C PARAMETERS(mhos)
    - D PARAMETERS(per unit)

WITH COMPENSATION

- (f) FULL LOAD ABCD PARAMETERS  
(SHUNT COMPENSATION IS REMOVED)
  - A PARAMETER (per unit)
  - B PARAMETER (ohms)
  - C PARAMETER (mhos)
  - D PARAMETER (per unit)
- (g) NO-LOAD ABCD PARAMETERS  
(SHUNT AND SERIES COMPENSATION ARE INCLUDED):
  - A PARAMETER (per unit)
  - B PARAMETER (ohms)
  - C PARAMETER (mhos)
  - D PARAMETER (per unit)
- (h) SENDING END VOLTAGE (LINE-TO-LINE kV)
- (i) SENDING END CURRENT (kA)
- (j) SENDING END REAL POWER (MW)
- (k) SENDING END REACTIVE POWER (Mvars)
- (l) SENDING END APPARENT POWER (mva)
- (m) SENDING END POWER FACTOR (per unit)
- (n) VOLTAGE REGULATION (%)
- (o) THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)



SOLUTION

LINE DATA

ENTER THE NAME OF THE LINE (AND ALPHANUMERIC SEQUENCE)  
ENTER EX.C, PRESS RETURN  
IS THIS A THREE PHASE LINE (ENTER Y) OR A SINGLE PHASE LINE  
(ENTER N)?  
ENTER Y, PRESS RETURN  
ENTER THE RATED LINE VOLTAGE (LINE - LINE kV)  
ENTER 765, PRESS RETURN  
ENTER THE LINE LENGTH (km)  
ENTER 650  
ENTER THE SERIES RESISTANCE (ohms/km)  
ENTER 0.0185, PRESS RETURN  
ENTER THE SERIES REACTANCE (ohms/km)  
ENTER 0.3170, PRESS RETURN  
ENTER THE SHUNT CONDUCTANCE (mhos/km)  
ENTER 0, PRESS RETURN  
ENTER THE SHUNT SUSCEPTANCE (mhos/km)  
ENTER 4.875e-6, PRESS RETURN

RECEIVING END DATA

ENTER THE RECEIVING END FULL LOAD VOLTAGE (LINE-LINE kV)  
ENTER 726.8, PRESS RETURN  
ENTER THE RECEIVING END FULL LOAD APPARENT POWER (MVA)  
ENTER 2500, PRESS RETURN  
ENTER THE RECEIVING END FULL LOAD POWER FACTOR (per unit)  
ENTER 0.99, PRESS RETURN  
IS THE POWER FACTOR LAGGING(ENTER Y) OR LEADING(ENTER N)  
ENTER N, PRESS RETURN

COMPENSATION DATA

IS THE LINE COMPENSATED (Y OR N)?  
ENTER Y, PRESS RETURN

Screen shows:-

COMPENSATION INPUT DATA AT EACH LOCATION IS GIVEN IN PER CENT  
OF TOTAL SHUNT SUSCEPTANCE OR SERIES REACTANCE OF THE LINE

ENTER THE % SHUNT REACTIVE COMPENSATION AT THE SENDING-END  
ENTER 16.25, PRESS RETURN  
ENTER THE % SERIES CAPACITIVE COMPENSATION AT THE SENDING-END  
ENTER 5.5, PRESS RETURN  
ENTER THE % SHUNT REACTIVE COMPENSATION AT THE RECEIVING-END  
ENTER 16.25, PRESS RETURN  
ENTER THE % SERIES CAPACITIVE COMPENSATION AT THE RECEIVING-END  
ENTER 5.5, PRESS RETURN  
ENTER THE NUMBER OF INTERMEDIATE SUBSTATIONS(0, 1 OR 2)  
ENTER 2, PRESS RETURN  
ENTER THE DISTANCE FROM THE SENDING-END TO SUBSTATION ONE (km)  
ENTER 216.67  
ENTER THE % SHUNT REACTIVE COMPENSATION AT SUBSTATION ONE  
ENTER 16.25  
ENTER THE % SERIES CAPACITIVE COMPENSATION AT SUBSTATION ONE

DO YOU WANT TO CONTINUE (Y) OR RESET THE INPUT DATA (N)  
ENTER Y

USE THE Ctrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS.

IF PRINTER NOT AVAILABLE, PRESS RETURN AND USE PAUSE TO OBSERVE THE DISPLAYED INPUT AND OUTPUT DATA. IF PRINTER AVAILABLE PROCEED AS FOLLOWS: PRESS Ctrl PRINT SCREEN  
PRESS RETURN

ONCE PRINTER HAS STOPPED PRINTING, REMOVE Ctrl PRINT SCREEN BY PRESSING Ctrl PRINT SCREEN AND PRESS RETURN.

THE SCREEN THEN ASKS YOU:-

DO YOU WANT TO RUN IT AGAIN (ENTER Y) OR QUIT (N)?

THE PRINTOUT OBTAINED OR THAT DISPLAYED ON YOUR SCREEN IS IN TWO PARTS, NAMELY INPUT AND OUTPUT DATA AND IS AS FOLLOW:-

\*\*\*\*\*INPUT DATA\*\*\*\*\*

```
EX.C      THREE-PHASE      765 kV      650 km
LINE DATA:
SERIES RESISTANCE (ohms/km)          1.850E-02
SERIES REACTANCE (ohms/km)          3.170E-01
SHUNT CONDUCTANCE (mhos/km)         0.000E+00
SHUNT SUSCEPTANCE (mhos/km)       4.875E-06

RECEIVING END DATA:
RECEIVING END FULL LOAD VOLTAGE (kV)  7.268E+02
RECEIVING END FULL LOAD
APPARENT POWER (MVA)                 2.500E+03
RECEIVING END FULL LOAD
POWER FACTOR (per unit)              9.900E-01 LEADING

COMPENSATION DATA:
SHUNT COMPENSATION AT SENDING-END(%)  16.25
SERIES COMPENSATION AT SENDING-END(%)  5.5
SHUNT COMPENSATION AT RECEIVING-END(%) 16.25
SERIES COMPENSATION AT RECEIVING-END(%) 5.5
NUMBER OF INTERMEDIATE SUBSTATIONS    2
DISTANCE FROM SENDING END
TO SUBSTATION 1 (km)                 216.67
SHUNT COMPENSATION AT SUBSTATION 1 (%) 16.25
SERIES COMPENSATION AT SUBSTATION 1 (%) 5.5
DISTANCE FROM SUBSTATION 1
TO SUBSTATION 2 (km)                 216.67
SHUNT COMPENSATION AT SUBSTATION 2 (%) 16.25
SERIES COMPENSATION AT SUBSTATION 2 (%) 5.5
TOTAL SHUNT COMPENSATION(%)          65
TOTAL SERIES COMPENSATION(%)         22
```

\*\*\*\*\*OUTPUT DATA\*\*\*\*\*

\*\*\*\*\*WITHOUT COMPENSATION\*\*\*\*\*

CHARACTERISTIC IMPEDANCE (ohms)	2.552E+02/ -1.670E+00DEG
PROPAGATION CONSTANT (1/m)	3.626E-05 + j 1.244E-03
WAVELENGTH (km)	5.052E+03
SURGE IMPEDANCE LOADING (MW)	2.293E+03

EQUIVALENT PI CIRCUIT:

SERIES IMPEDANCE (ohms)	9.533E+00 +j 1.844E+02
SHUNT ADMITTANCE (mhos)	1.152E-05 +j 3.353E-03

ABCD PARAMETERS:

A PARAMETER (per unit)	6.911E-01/ 1.413E+00DEG
B PARAMETER (ohms)	1.847E+02/ 8.704E+01DEG
C PARAMETER (mhos)	2.835E-03/ 9.038E+01DEG
D PARAMETER (per unit)	6.911E-01/ 1.413E+00DEG

\*\*\*\*\*WITH COMPENSATION\*\*\*\*\*

FULL LOAD ABCD PARAMETERS

(SHUNT COMPENSATION IS REMOVED)

A PARAMETER (per unit)	7.491E-01/ 1.333E+00DEG
B PARAMETER (ohms)	1.530E+02/ 8.622E+01DEG
C PARAMETER (mhos)	2.878E-03/ 9.038E+01DEG
D PARAMETER (per unit)	7.491E-01/ 1.333E+00DEG

NO-LOAD ABCD PARAMETERS

(SHUNT AND SERIES COMPENSATION ARE INCLUDED):

A PARAMETER (per unit)	9.190E-01/ 3.660E-01DEG
B PARAMETER (ohms)	1.593E+02/ 8.605E+01DEG
C PARAMETER (mhos)	9.790E-04/ 8.999E+01DEG
D PARAMETER (per unit)	9.190E-01/ 3.660E-01DEG

SENDING END VOLTAGE (LINE-TO-LINE kV)	7.371E+02/ 4.681E+01DEG
SENDING END CURRENT (kA)	2.059E+00/ 4.484E+01DEG
SENDING END REAL POWER (MW)	2.627E+03
SENDING END REACTIVE POWER (Mvars)	9.014E+01
SENDING END APPARENT POWER (MVA)	2.628E+03
SENDING END POWER FACTOR (per unit)	9.994E-01 LAGGING
VOLTAGE REGULATION (%)	1.037E+01
THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)	3.570E+03

INTERPRETATION AND UNDERSTANDING OF THE INPUT AND OUTPUT DATA
--

For interpretation and understanding of the input and output data, the user is referred to Section One and more particularly to Section Two of the Study Programme. As this is a shunt and series compensated line the user is to refer in particular to Section Two Part "c" (INPUT AND OUTPUT DATA).

INPUT DATA

COMPENSATION DATA

Figure 14, Section Two Part "C" shows an equivalent circuit of the transmission line. For convenience the figure is repeated below but now includes the total length of the line and the distances for each line section.

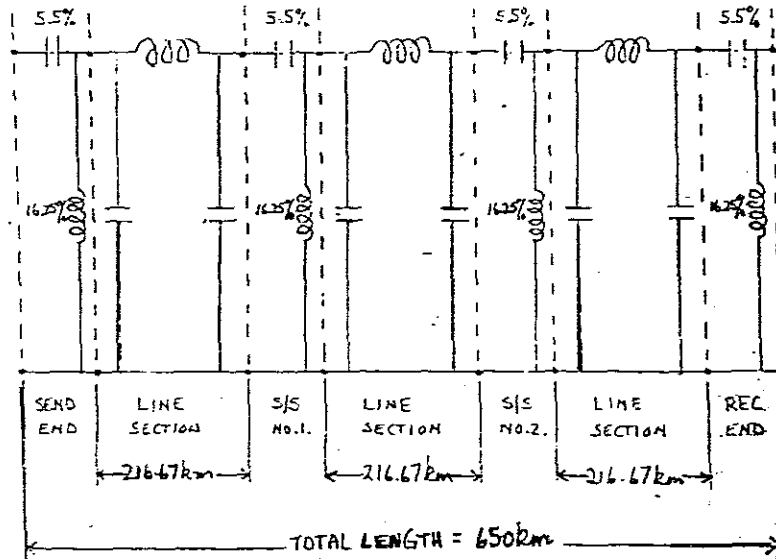


FIGURE 18.

Figure 18 shows how the total series compensation of 22% apportioned into 4 equal parts at line ends and at intermediate substations. It shows how the total shunt compensation is apportioned in a similar manner along the line.

OUTPUT DATA

WITHOUT COMPENSATION

a) to e) are found from (20), (19), (54), (41), (46), and (37).

WITH COMPENSATION

(f) The equivalent full load  $A_{eq}, B_{eq}, C_{eq}, D_{eq}$  (EQ.78) parameters have been computed and include the series compensation but exclude the shunt compensation. See Figure 15 and (75), (76) and (77) which shows the steps used in computing these parameters (78).

These parameters are computed as are needed for the calculation of  $V_s$  and  $I_s$  under full load conditions.

- (g) The equivalent NO-LOAD ABCD [equation (80)  $A_{eq}, B_{eq}, C_{eq}, D_{eq}$ ] parameters have been computed and include both the series and shunt compensation.

The resultant network is shown in Figure 17 and includes eleven cascaded networks each having an ABCD matrix.

Figure 16 and 17 and (75), (79) and (77) show the steps used in computing these parameters (80).

- (h) The sending-end voltage is computed using (81).
- (i) The sending-end current is computed using (82).
- (j)  $k, l, m$  are computed using (38).
- (n) The voltage regulation (%) is computed by using (83) and (84) where  $A_{eq}$  comes from (80).
- (o)  $P_{rmax}$  is computed using (85) where  $A_{eq}$  comes from (78).

SECTION FOUR  
SELF EVALUATION PROBLEMS

**NB!** The computer program used is an USA program written for a frequency of 60Hz. The program does not provide for the entering of different frequencies. The self-evaluation problems which follow are therefore based on 60Hz and not on the standard RSA frequency of 50Hz.

QUESTION A

Repeat EXAMPLE A from Section Three for a line length of 650 km. Determine from your computed results:-

- (1) The sending-end phase angle.
- (2) The % transmission efficiency.
- (3) The theoretical steady-state stability limit of the line in MW and the receiving-end current corresponding to this limit at the  $V_r$  and pf. given. If this line has three ACSR 1113-kcmil conductors per phase, is the steady-state current limit sufficiently below that of the thermal limit. If so, by how many kA?

ANSWERS

- (1) Sending-end phase angle = 9.39deg Lagging.
- (2) Transmission Efficiency = 92.5%.
- (3) Steady-state stability limit = 1129MW.  
 $I_r = 1.372\text{kA}$ .  
Thermal limit = 1.958kA below steady-state current limit.

QUESTION B

A 10km long, single phase short transmission line has  $0.5/60\text{deg}$  ohms/km impedance. The line is rated at 3.47kV and supplies a 316.8kW load at 0.8 pf. lagging. If the receiving-end voltage is 3.3kV what are the computed values for:-

- (1) The sending-end voltage, current, real power, reactive power, apparent power and pf.
- (2) The % voltage regulation of the line.

**NB!** For the program to run it needs a non zero value for shunt susceptance. For this question assume an susceptance of  $1\text{E}-6$ .

ANSWERS

- (1)  $V_s = 3.85\text{kV}$ ,  $I_s = 0.12\text{kA}$ ,  $P_s = 0.3528\text{MW}$ ,  $Q_s = 0.2998\text{MVars}$   
 $S_s = 0.463\text{MVA}$ , pf = 0.762 lagging.
- (2) %VR = 16.94

QUESTION C

A 300km, 500kV, 1365MVA, 60Hz three phase uncompensated lossless line has a positive-sequence series reactance = 0.34 ohms/km and a positive-sequence shunt admittance =  $j 4.5E-6$  S/km. If the receiving-end voltage is 475kV what are the computed values for:-

- (1) Surge impedance of the lossless line.
- (2) Propagation constant of the lossless line.
- (3) The wavelength of the lossless line.
- (4) Surge impedance loading in MW.
- (5)  $X'$  for the equivalent- $\pi$  circuit of the lossless line.
- (6) ABCD parameters of the lossless line.
- (7) The % voltage regulation of the lossless line.
- (8) The theoretical maximum real power delivered in MW.

In each of the above do theoretical calculations using lossless line formulae to prove that your computed values are correct.

ANSWERS

- (1) Surge impedance = 274.9 ohms.
- (2) Propagation constant =  $j0.3711$  per unit.
- (3) Wavelength 5080km.
- (4) SIL = 909.5MW (3ph).
- (5)  $X' = j99.68$  ohms.
- (6)  $A = 0.9319/_0\text{deg}$  per unit.  
 $B = 99.68/_90\text{deg}$  ohms.  
 $C = 1.319E-3/_90\text{deg}$  mhos.  
 $D = 0.9319/_0\text{deg}$  per unit
- (7) %VR = 19.11.
- (8)  $P_{\text{rmax}} = 2508\text{MW}$ .

QUESTION D

- (a) If identical capacitors are installed at the ends of the line in EXAMPLE A, Section Three, providing 40% total series compensation, compute values for:-
  - (1) The equivalent ABCD parameters [  $A_{\text{eq}}$ ,  $B_{\text{eq}}$ ,  $C_{\text{eq}}$  and  $D_{\text{eq}}$  ] of the line at full load.
  - (2) The % voltage regulation of the line.Sketch the equivalent circuit of the series compensated line clearly showing the three cascaded networks and their ABCD matrices.  
Why is series compensation used?
- (b) If the line in EXAMPLE A, Section Three has 65% shunt (inductor) compensation and 40% series compensation, half installed at each end of the line, compute values for the equivalent ABCD parameters [  $A_{\text{eq}}$ ,  $B_{\text{eq}}$ ,  $C_{\text{eq}}$  and  $D_{\text{eq}}$  ] at no-load.

ANSWERS

- (a) (1)  $A_{eq} = 0.9247 / \underline{0.6378} \text{deg}$  per unit.  
 $B_{eq} = 86.66 / \underline{82.32} \text{deg}$  ohms.  
 $C_{eq} = 0.001689 / \underline{90.21} \text{deg}$  mhos.  
 $D_{eq} = 0.9247 / \underline{0.6378} \text{deg}$  per unit.  
(2) %VR = 13.70
- (b)  $A_{eq} = 0.9748 / \underline{0.2075} \text{deg}$  per unit.  
 $B_{eq} = 86.66 / \underline{82.32} \text{deg}$  ohms.  
 $C_{eq} = 0.0005792 / \underline{89.80} \text{deg}$  mhos.  
 $D_{eq} = 0.9748 / \underline{0.2075} \text{deg}$  per unit.

EXAMPLE E

Repeat EXAMPLE C from Section Three where the transmission line has only one intermediate substation and the total series capacitive compensation of the line is 21% and the total shunt inductive compensation of the line is 48%. Compute values for:-

WITHOUT COMPENSATION

- (a) CHARACTERISTIC IMPEDANCE (ohms)  
(b) PROPAGATION CONSTANT (1/m)  
(c) WAVELENGTH(km)  
(d) SURGE IMPEDANCE LOADING (MW)  
(e) FOR THE EQUIVALENT PI CIRCUIT:  
(1) SERIES IMPEDANCE(ohms)  
(11) SHUNT ADMITTANCE(mhos)  
(111) ABCD PARAMETERS:  
A PARAMETERS(per unit)  
B PARAMETERS(ohms)  
C PARAMETERS(mhos)  
D PARAMETERS(per unit)

WITH COMPENSATION

- f) FULL LOAD ABCD PARAMETERS  
(SHUNT COMPENSATION IS REMOVED)  
A PARAMETER (per unit)  
B PARAMETER (ohms)  
C PARAMETER (mhos)  
D PARAMETER (per unit)  
g) NO-LOAD ABCD PARAMETERS  
(SHUNT AND SERIES COMPENSATION ARE INCLUDED):  
A PARAMETER (per unit)  
B PARAMETER (ohms)  
C PARAMETER (mhos)  
D PARAMETER (per unit)  
(h) SENDING END VOLTAGE (LINE-TO-LINE kV)  
(i) SENDING END CURRENT (kA)  
(j) SENDING END REAL POWER (MW)  
(k) SENDING END REACTIVE POWER (Mvars)  
(l) SENDING END APPARENT POWER (mva)  
(m) SENDING END POWER FACTOR (per unit)  
(n) VOLTAGE REGULATION (%)  
(o) THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)



ANSWERS

\*\*\*\*\*WITHOUT COMPENSATION\*\*\*\*\*

CHARACTERISTIC IMPEDANCE (ohms)	2.552+02/ -1.670E+00DEG
PROPAGATION CONSTANT (1/m)	3.626E-05 + j 1.244E-03
WAVELENGTH (km)	5.052E+03
SURGE INPEDANCE LOADING (MW)	2.293E+03

EQUIVALENT PI CIRCUIT:

SERIES IMPEDANCE (ohms)	9.533E+00 +j 1.844E+02
SHUNT ADMITTANCE (mhos)	1.152E-05 +j 3.353E-03
ABCD PARAMETERS:	
A PARAMETER (per unit)	6.911E-01/ 1.413E+00DEG
B PARAMETER (ohms)	1.847E+02/ 8.704E+01DEG
C PARAMETER (mhos)	2.835E-03/ 9.038E+01DEG
D PARAMETER (per unit)	6.911E-01/ 1.413E+00DEG

\*\*\*\*\*WITH COMPENSATION\*\*\*\*\*

FULL LOAD ABCD PARAMETERS

(SHUNT COMPENSATION IS REMOVED)

A PARAMETER (per unit)	7.464E-01/ 1.337E+00DEG
B PARAMETER (ohms)	1.550E+02/ 8.627E+01DEG
C PARAMETER (mhos)	2.866E-03/ 9.038E+01DEG
D PARAMETER (per unit)	7.464E-01/ 1.337E+00DEG

NO-LOAD ABCD PARAMETERS

(SHUNT AND SERIES COMPENSATION ARE INCLUDED):

A PARAMETER (per unit)	8.722E-01/ 5.944E-01DEG
B PARAMETER (ohms)	1.587E+02/ 8.617E+01DEG
C PARAMETER (mhos)	1.512E-03/ 9.006E+01DEG
D PARAMETER (per unit)	8.722E-01/ 5.944E-01DEG

SENDING END VOLTAGE (LINE-TO-LINE kV)	7.403E+02/ 4.734E+01DEG
SENDING END CURRENT (kA)	2.051E+00/ 4.483E+01DEG
SENDING END REAL POWER (MW)	2.627E+03
SENDING END REACTIVE POWER (Mvars)	1.152E+02
SENDING END APPARENT POWER (MVA)	2.629E+03
SENDING END POWER FACTOR (per unit)	9.990E-01 LAGGING
VOLTAGE REGULATION (%)	1.677E+01
THEORETICAL MAXIMUM REAL POWER DELIVERED (MW)	3.526E+03

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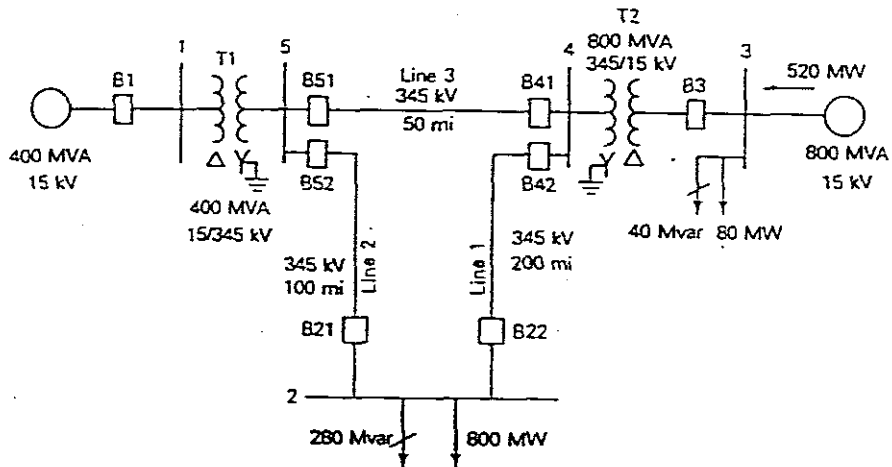
COMPUTER-AIDED STUDY PROGRAMME

ON

THE FORMATION OF A YBUS AND ZBUS

IN

MULTI-BUS POWER SYSTEMS



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19-10-1992

**THE USE OF A COMPUTER FOR EXPERIMENTATION ON THE FORMATION  
OF A Ybus AND Zbus IN MULTI-BUS POWER SYSTEMS**

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SECTION A  
 INTRODUCTION INTO THE THEORY FOR THE FORMATION OF Y AND Z BUS  
 MATRICES FOR USE IN MULTI-BUS REPRESENTATION OF POWER SYSTEMS

1. INTRODUCTION

When dealing with multi-bus representation of large power systems, analysis by the y-parameter or z-parameter method is required.

For balanced system generations (e.g. for the analysis of power flow, economic operation and symmetrical faults), we need only consider the positive sequence networks.

For unbalanced system operations (e.g. for the analysis of unsymmetrical faults) negative and zero sequence networks as well as positive sequence networks have to be included.

2. MEANING OF Y BUS AND Z BUS

The junctions formed when two or more pure elements (R, L, C or an ideal source of voltage or current) are connected to each other at their terminals are called *nodes*. Usually it is convenient to consider only those nodes to which more than two elements are connected and to call these junction points *major nodes*.

In order to consider some features of node equations let us consider the following one-line diagram:-

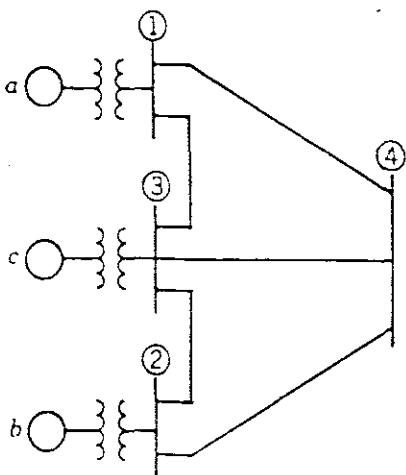


FIGURE.1

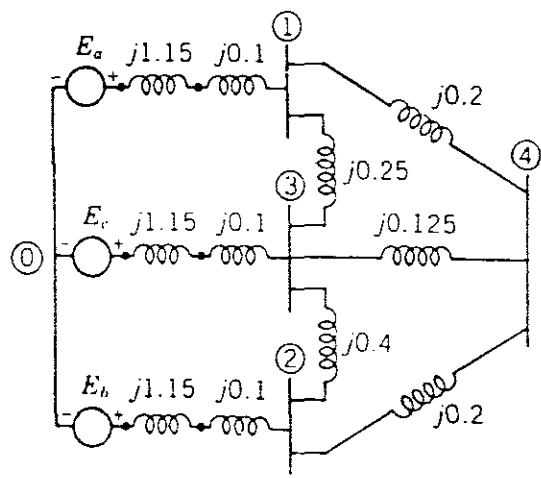


FIGURE.2

Figure one shows generators connected through transformers to high tension buses 1 and 3 which supplies a synchronous motor load at bus 2. The reactance diagram for Figure 1, with reactances specified in per unit is shown in Figure 2.

Nodes are indicated by dots, but numbers are assigned only to major nodes.

If Figure 2 is redrawn with emf's and impedances being replaced by equivalent current sources and shunt admittances, the resulting circuit is Figure 3.

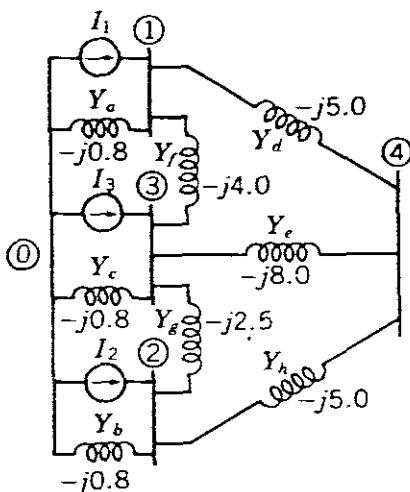


FIGURE 3

Single-subscript notation will be used to designate the voltage of each bus with respect to the neutral taken as the reference node 0.

Applying Kirchoff's current law at node 1 with current into the node from the source equated to current away from the nodes gives:-

$$I_1 = V_1 Y_a + (V_1 - V_3) Y_f + (V_1 - V_4) Y_d \quad \text{--- (1)}$$

and the node 4:-

$$0 = (V_4 - V_1) Y_d + (V_4 - V_2) Y_h + (V_4 - V_3) Y_e \quad \text{--- (2)}$$

Rearranging these equation yields:-

$$I_1 = V_1 (Y_a + Y_f + Y_d) - V_3 Y_f - V_4 Y_d \quad \text{--- (3)}$$

$$0 = -V_1 Y_d - V_2 Y_h - V_3 Y_e + V_4 (Y_d + Y_e + Y_h) \quad \text{--- (4)}$$

Similar equations can be formed for nodes 2 and 3, and the four equations can be solved simultaneously for voltages V1, V2, V3 and V4. All branch currents can be found when these voltages are known. The required number of node equations is one less than the number of nodes in the network.

We have not written the other two equations because we can already see how to formulate node equations in standard notation. In both (3) and (4) it is apparent that the current flowing into the network from current sources connected to a node is equated to the sum of several products. At any node, one of the products is the voltage of that node with reference to the node 0 times the sum of all admittances which terminate on the node. This product accounts for the current that flows away from the node if the voltage is zero at each other node. Each other product equals the negative of the voltage at another node times the admittance connected directly between the other node and the node at which the equation is formulated. For instance at node 1 a product is  $-Y_3V_3$  which accounts for the current away from node 1 when all node voltages are zero except that at node 3.

The standard form for the four independent equations in matrix format is:-

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \quad \text{--- (5)}$$

where: from (3) and (4) and Figure 3:

$$\begin{array}{l} Y_{11} = Y_a + Y_f + Y_d \\ Y_{12} = 0 \\ Y_{13} = -Y_f \\ Y_{14} = -Y_d \\ Y_{21} = 0 \\ Y_{22} = Y_b + Y_g + Y_h \\ Y_{23} = -Y_g \\ Y_{24} = -Y_h \\ \text{etc.} \end{array} \quad \text{--- (6)}$$

The symmetry of the equations in this form makes them easy to remember and their extension to any number of nodes is apparent.

The order of the Y subscripts is effect-cause; that is, the first subscript is that of the node at which current is being expressed, and the second subscript is that of the voltage causing this component of current.

The Y matrix is designated Ybus and called the bus admittance matrix. It is symmetrical around the principal diagonal. The admittances Y11, Y22, Y33 and Y44 are called the self admittances at the nodes, and each equates the sum of all the admittances terminating on the node identified by the repeated subscripts. The other admittances are the mutual admittances of the nodes, and each equals the negative of the sum of all admittances connected directly between the nodes identified by the double subscripts. As shown above the mutual admittance Y13 equals -Yf. Some authors call the self and mutual admittances the driving points and transfer admittances.

**EXAMPLE ON THE DIRECT FORMATION  
OF THE BUS ADMITTANCE MATRIX YBUS  
AND THE INDIRECT FORMATION OF  
THE IMPEDANCE BUS MATRIX ZBUS**

If the emf's in Figure 2 are  $E_a = 1.5/\underline{0^\circ}$ ,  $E_b = 1.5/\underline{-36.87^\circ}$  and  $E_c = 1.5/\underline{0^\circ}$  all in per unit find the Ybus and the Zbus for the network:-

The current sources are:-

$$I_1 = I_3 = \frac{1.5/\underline{0^\circ}}{j1.25} = 1.2/\underline{-90^\circ} = 0 - j1.2 \text{ p.u.}$$

$$I_2 = \frac{1.5/\underline{-36.87^\circ}}{j1.25} = 1.2/\underline{-126.87^\circ} = -0.72 - j0.96 \text{ p.u.}$$

The self admittances are from Figure 3:-

$$\begin{aligned} Y_{11} &= -j5 - j4 - j0.8 = -j9.8 \\ Y_{22} &= -j5 - j2.5 - j0.8 = -j8.3 \\ Y_{33} &= -j4 - j2.5 - j8 - j0.8 = j15.3 \\ Y_{44} &= -j5 - j5 - j8 = -j18 \end{aligned}$$

and the mutual admittances in p.u. are:-

$$\begin{aligned} Y_{12} &= Y_{21} = 0 & Y_{23} &= Y_{32} = +j2.5 \\ Y_{13} &= Y_{31} = -(-j4) = +j4 & Y_{24} &= Y_{42} = +j5 \\ Y_{14} &= Y_{41} = +j5 & Y_{34} &= Y_{43} = +j8 \end{aligned}$$

These mutual admittances having opposite signs to that shown on Figure 3.

Now substituting these values into (5) we get the node equations in matrix form:-

$$\begin{bmatrix} 0 - j1.2 \\ -0.72 - j0.96 \\ 0 - j1.2 \\ 0 \end{bmatrix} = \begin{bmatrix} -j9.8 & j0.0 & j4.0 & j5.0 \\ j0.0 & -j8.3 & j2.5 & j5.0 \\ j4.0 & j2.5 & -j15.3 & j8.0 \\ j5.0 & j5.0 & j8.0 & -j18.0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

The square matrix above is recognized as the bus admittance matrix Ybus, therefore:

$$\boxed{I_{bus} = Y_{bus} V_{bus}} \text{ - - - - - (7)}$$

and as we wish to solve for V1, V2, V3 and V4,

$$\boxed{V_{bus} = Y_{bus}^{-1} I_{bus}} \text{ - - - - - (8)}$$

where:

$$\boxed{Y_{bus}^{-1} = Z_{bus}} \text{ - - - - - (9)}$$

where: Zbus is called the bus impedance matrix and is found by inverting the Ybus.

and:

$$\boxed{V_{bus} = Z_{bus} I_{bus}} \text{ - - - - - (10)}$$

The inversion of the Ybus matrix can be manually done by using mathematical steps or inverted by using a software program which is the current trend.

If the Ybus above is inverted by either of these two methods the following is obtained:-

$$\begin{bmatrix} j0.4774 & j0.3706 & j0.4020 & j0.4142 \\ j0.3706 & j0.4872 & j0.3922 & j0.4126 \\ j0.4020 & j0.3922 & j0.4558 & j0.4232 \\ j0.4142 & j0.4126 & j0.4232 & j0.4733 \end{bmatrix}$$

and this square another matrix is called the bus impedance matrix Zbus.

Now using (10) we get

$$\begin{bmatrix} V1 \\ V2 \\ V3 \\ V4 \end{bmatrix} = \begin{bmatrix} j0.4774 & j0.3706 & j0.4020 & j0.4142 \\ j0.3706 & j0.4872 & j0.3922 & j0.4126 \\ j0.4020 & j0.3922 & j0.4558 & j0.4232 \\ j0.4142 & j0.4126 & j0.4232 & j0.4733 \end{bmatrix} \begin{bmatrix} 0 - j1.20 \\ -0.72 -j0.96 \\ 0 - 1.20 \\ 0 \end{bmatrix}$$



which yields:-

$$\begin{bmatrix} V1 \\ V2 \\ V3 \\ V4 \end{bmatrix} = \begin{bmatrix} 1.411 & -j0.2668 \\ 1.3830 & -j0.3508 \\ 1.4059 & -j0.2824 \\ 1.4009 & -j0.2971 \end{bmatrix}$$

from which the node voltages are:-

$$\begin{aligned} V1 &= 1.411 -j0.2668 = 1.436 /_{-} -10.71^{\circ} \text{ p.u.} \\ V2 &= 1.3830 -j0.3508 = 1.427 /_{-} -14.24^{\circ} \text{ p.u.} \\ V3 &= 1.4059 -j0.2824 = 1.434 /_{-} -11.36^{\circ} \text{ p.u.} \\ V4 &= 1.4009 -j0.2971 = 1.432 /_{-} -11.97^{\circ} \text{ p.u.} \end{aligned}$$

Examination of the above indicates that it is necessary to first form the Ybus before finding the Zbus. As this method is simple most studies are either based on the use of Ybus or when necessary, on inverting the Ybus to obtain the Zbus matrix. However for large systems, matrix inversion becomes time consuming and expensive and therefore it is better to use another method other than the above to directly formulate the Zbus.

EXAMPLE ON THE DIRECT  
FORMATION OF THE BUS  
IMPEDANCE MATRIX ZBUS

We shall outline, without proof, a basic procedure to build up Zbus by adding an element at a time. Recall that our aim is to obtain the positive-sequence Zbus, so the elements are per-phase impedances for an equivalent Y system. (See Gungor p197). We first assume that part of Zbus (say, three buses) has been constructed with ground reference and is in the form:

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \end{matrix}$$

Now following the procedures prescribed by "Gungor", we get:

PROCEDURE A

To add a branch Z from a new bus, say, bus 4, to ground, we expand Zbus by a row and a column, and place Z in the diagonal of the resultant matrix thus:

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} & \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ \hline 0 & 0 & 0 & Z \end{bmatrix} \end{matrix}$$

PROCEDURE B

To add a branch Z from a new bus, say, bus 4, to an old bus, say bus 2, we expand Zbus by repeating row 2 as row 4 and column 2 as column 4, and add Z to Z22 to form the last diagonal of the resultant matrix thus:

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} & \left[ \begin{array}{ccc|c} Z_{11} & Z_{12} & Z_{13} & Z_{12} \\ Z_{21} & Z_{22} & Z_{23} & Z_{22} \\ Z_{31} & Z_{32} & Z_{33} & Z_{32} \\ \hline Z_{21} & Z_{22} & Z_{23} & Z_{22} + Z \end{array} \right] \end{matrix}$$

PROCEDURE C

To add a link Z from an old bus, say, 2, to ground, we repeat procedure B and then reduce the resultant Zbus by eliminating the additional bus (4) by the use of equation 11 with impedance thus:

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & (4) \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} & \left[ \begin{array}{ccc|c} Z_{11} & Z_{12} & Z_{13} & Z_{12} \\ Z_{21} & Z_{22} & Z_{23} & Z_{22} \\ Z_{31} & Z_{32} & Z_{33} & Z_{32} \\ \hline Z_{21} & Z_{22} & Z_{23} & Z_{22} + Z \end{array} \right] \end{matrix}$$

NB! The Z in Row 4, Column 4 in procedure C is usually different from Z in Row 4, Column 4 in Procedure B, then:

$$\boxed{Z_{bus} = Z_A - Z_B Z_D^{-1} Z_C} \quad \text{--- (11)}$$

To add a link Z from an old bus, say, bus 2, to an old bus, say, bus 3 (procedure D), we expand Zbus by a new row whose elements are the elements of row 2 minus the elements of row 3, and a new column in the same way, and then form the last diagonal element as  $Z_{22} + Z_{33} - Z_{23} - Z_{32} + Z$ . Finally, we eliminate the additional bus (4) by network reduction, therefore Zbus equals:

$$\left[ \begin{array}{ccc|c} \begin{matrix} 1 & 2 & 3 & (4) \\ Z_{11} & Z_{12} & Z_{13} & (Z_{12} - Z_{13}) \\ Z_{21} & Z_{22} & Z_{23} & (Z_{22} - Z_{23}) \\ Z_{31} & Z_{32} & Z_{33} & (Z_{32} - Z_{33}) \\ \hline (Z_{21} - Z_{31}) & (Z_{22} - Z_{32}) & (Z_{23} - Z_{33}) & Z_{22} + Z_{33} - Z_{23} - Z_{32} + Z \end{matrix} \end{array} \right]$$

So:

$$Z_{bus} = Z_A - Z_B Z_D^{-1} Z_C$$

NB! In general, to form Zbus, we start with the first element connected to the reference bus of the system and follow the preceding procedures in any order we like, noting that for hand formation at least, judicious choices may save a little time.

EXAMPLE 1

Form directly the Zbus for the following system.

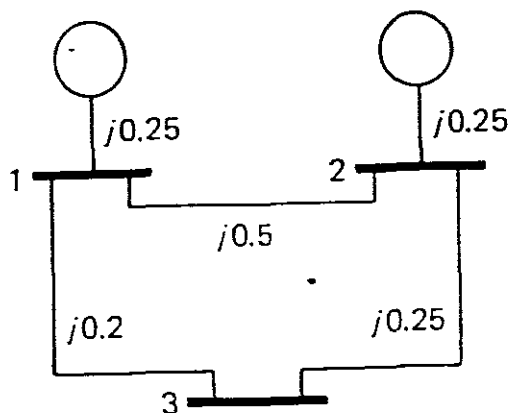


FIGURE 4

STARTING WITH THE FIRST ELEMENT:

1. Add  $Z = j0.25$  from bus 1 to ground by procedure A:

$$Z_{bus} = \begin{matrix} & 1 \\ 1 & [j0.25] \end{matrix}$$

2. Add  $Z = j0.5$  from bus 1 to bus 2 by procedure B:

$$Z_{bus} = \begin{matrix} & 1 & 2 \\ 1 & \begin{bmatrix} j0.25 & j0.25 \\ j0.25 & j0.25 \end{bmatrix} \\ 2 & \end{matrix}$$

3. Add  $Z = j0.25$  from bus 2 to ground by procedure C:

$$Z_{bus} = \begin{matrix} & 1 & 2 & (3) \\ 1 & \begin{bmatrix} j0.25 & j0.25 & j0.25 \\ j0.25 & j0.75 & j0.75 \end{bmatrix} \\ 2 & \\ (3) & \hline & j0.25 & j0.75 & j1.0 \end{matrix}$$

$$ZD^{-1} = \frac{1}{j} = -j$$

$$ZBZD^{-1} ZC = \begin{bmatrix} j0.25 \\ j0.75 \end{bmatrix} [-j][j0.25 \ j0.75] = \begin{bmatrix} j0.0625 & j0.1875 \\ j0.1875 & j0.5625 \end{bmatrix}$$

$$Z_{bus} = \begin{matrix} 1 & 2 \\ j0.1875 & j0.0625 \\ j0.0625 & j0.1875 \end{matrix}$$

4. Add  $Z = j0.25$  from bus 2 to bus 3 by procedure B:

$$Z_{bus} = \begin{matrix} 1 & 2 & (3) \\ j0.1875 & j0.0625 & j0.0625 \\ j0.0625 & j0.1875 & j0.1875 \\ (3) & j0.0625 & j0.1875 & j0.4375 \end{matrix}$$

5. Add  $Z = j0.2$  from bus 1 to bus 3 by procedure D:

For:

$$\begin{aligned} Z_{11} - Z_{13} &= j0.125 \\ Z_{21} - Z_{23} &= -j0.125 \\ Z_{31} - Z_{33} &= -j0.375 \\ Z_{11} + Z_{33} - Z_{13} - Z_{31} + Z &= -j0.700 \end{aligned}$$

$$Z_{bus} = \begin{matrix} 1 & 2 & 3 & (4) \\ j0.1875 & j0.0625 & j0.0625 & j0.125 \\ j0.0625 & j0.1875 & j0.1875 & -j0.125 \\ j0.0625 & j0.1875 & j0.4375 & -j0.375 \\ (4) & j0.125 & -j0.125 & -j0.375 & j0.700 \end{matrix}$$

$$ZD^{-1} = \frac{1}{j0.7} = -j1.4286$$

$$ZBZD^{-1} ZC = \begin{bmatrix} j0.125 \\ -j0.125 \\ j0.375 \end{bmatrix} [-j1.4286][j0.125 \ -j0.125 \ -j0.375]$$

$$= \begin{bmatrix} j0.0223 & -j0.0233 & -j0.0670 \\ -j0.0233 & j0.0233 & j0.0670 \\ -j0.0670 & j0.0670 & j0.2099 \end{bmatrix}$$

$$Z_{bus} = j \begin{bmatrix} 0.1652 & 0.0484 & 0.1295 \\ 0.0484 & 0.1652 & 0.1205 \\ 0.1295 & 0.1205 & 0.2366 \end{bmatrix}$$

Obviously, the formation of Zbus in this manner is lengthy. However, it is easily adapted to computer applications.

EXAMPLE 2

Establish buses 1, 2, and 3 of the five-bus system presented in Figure 5 by direct formation of Zbus.

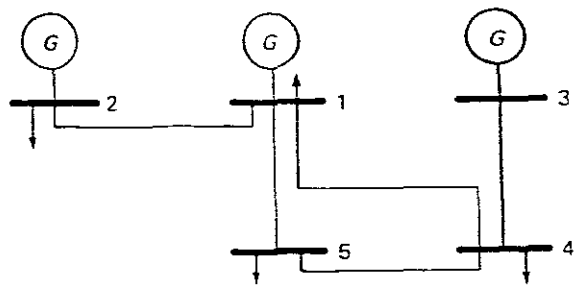


FIGURE 5

Line Data (p.u.)

Bus Code	Impedance	$\frac{1}{2}$ Charging Susceptance	Rating MVA
1-2	$0.030 + j0.103$	$j0.05$	60
1-4	$0.105 + j0.347$	$j0.01$	10
1-5	$0.080 + j0.262$	$j0.02$	20
3-4	$0.106 + j0.403$	$j0.01$	50
4-5	$0.033 + j0.118$	$j0.05$	15

From the line data of Figure 5, we have, at bus 1,

$$y_{10} = j(0.05 + 0.01 + 0.02) = j0.08$$

$$y_{12} = \frac{1}{0.03 + j0.103} = 2.6067 - j8.9495$$

$$y_{14} = \frac{1}{0.105 + j0.347} = 0.7989 - j2.6401$$

$$y_{15} = \frac{1}{0.08 + j0.262} = 1.0660 - j3.4913$$

Similarly,

$$y_{20} = j0.05$$

$$y_{30} = j0.01$$

$$y_{40} = j(0.01 + 0.01 + 0.05) = j0.07$$

$$y_{50} = j(0.02 + 0.05) = j0.07$$

$$y_{23} = 0$$

$$y_{24} = 0$$

$$y_{25} = 0$$

$$y_{34} = \frac{1}{(0.106 + j0.403)} = 0.6104 - j2.3208$$

$$y_{35} = 0$$

$$y_{45} = \frac{1}{(0.033 + j0.118)} = 2.1981 - j7.8599$$

Therefore,

$$Y_{11} = y_{10} + y_{12} + y_{14} + y_{15} = 4.4716 - j15.0009$$

$$Y_{12} = Y_{21} = -2.6067 + j8.9495$$

$$Y_{14} = Y_{41} = -0.7989 + j2.6401$$

$$Y_{15} = Y_{51} = -1.0660 + j3.4913$$

$$Y_{22} = y_{20} + y_{12} = 2.6067 - j8.8995$$

$$Y_{33} = y_{30} + y_{34} = 0.6104 - j2.3108$$

$$Y_{34} = Y_{43} = -0.6104 + j2.3208$$

$$Y_{44} = y_{40} + y_{41} + y_{43} + y_{45} = 3.6074 - j12.7508$$

$$Y_{45} = Y_{54} = -2.1981 + j7.8599$$

$$Y_{55} = y_{50} + y_{51} + y_{54} = 3.2641 - j11.2812$$

The remaining Ybus elements are all zero.

Now forming Zbus directly:-

$$Y_{10} = j0.08$$

$$Z_{10} = -j12.5$$

1. Add  $Z = -j12.5$  from bus 1 to ground by procedure A:

$$Z_{bus} = \begin{matrix} & 1 \\ 1 & [-j12.5] \end{matrix}$$

2. Add  $Z = 0.03 + j0.103$  from bus 1 to bus 2 by procedure B:

$$Z_{bus} = \begin{matrix} & 1 & 2 \\ 1 & [-j12.5 & -j12.5] \\ 2 & [-j12.5 & (0.03 - j12.397)] \end{matrix}$$

3. Add  $Z = 1/y_{20} = -j20$  from bus 2 to ground by procedure C:

$$Z_{bus} = \begin{matrix} & 1 & 2 & (3) \\ 1 & [-j12.5 & -j12.5 & -j12.5] \\ 2 & [-j12.5 & (0.03 - j12.397) & (0.03 - j12.397)] \\ (3) & [-j12.5 & (0.03 - j12.397) & (0.03 - j32.397)] \end{matrix}$$

$$= \begin{matrix} & 1 & 2 & (3) \\ 1 & [12.5/\underline{-90} & 12.5/\underline{-90} & 12.5/\underline{-90}] \\ 2 & [12.5/\underline{-90} & 12.397/\underline{-89.86} & 12.397/\underline{-89.86}] \\ (3) & [12.5/\underline{-90} & 12.397/\underline{-89.86} & 32.397/\underline{-89.95}] \end{matrix}$$

$$ZD^{-1} = 0.03087/\underline{-89.95}$$

$$ZBZD^{-1} ZC = \begin{matrix} & 1 & 2 \\ 1 & [12.5/\underline{-90} & 12.397/\underline{-89.86}] \\ 2 & [12.5/\underline{-90} & 12.397/\underline{-89.86}] \end{matrix} [0.0309/\underline{-89.95}] [12.5/\underline{-90} \quad 12.397/\underline{-89.86}]$$

$$= \begin{matrix} & 1 & 2 \\ 1 & [4.823/\underline{-90.05} & 4.783/\underline{-89.81}] \\ 2 & [4.783/\underline{-89.91} & 4.7483/\underline{-89.77}] \end{matrix}$$

$$Z_{bus} = Z_A - ZBZD^{-1} Z_C$$

$$= \begin{matrix} & 1 & 2 \\ 1 & [0.0042 & -j7.6770 & -0.0075 & -j7.7170] \\ 2 & [-0.0075 & -j7.7170 & 0.0110 & -j7.653] \\ 3 & [0 & 0 & 0 & -j100] \end{matrix}$$

4. Add  $Z = 1/y_{30} = -j100$  from bus 3 to ground by procedure A:

$$Z_{bus} = \begin{matrix} & 1 & 2 & 3 \\ 1 & [0.0042 & -j7.6770 & -0.0075 & -j7.7170] \\ 2 & [-0.0075 & -j7.7170 & 0.0110 & -j7.653] \\ 3 & [0 & 0 & 0 & -j100] \end{matrix}$$

### COMPUTER APPLICATIONS

Although hand calculations of  $Y_{bus}$  and  $Z_{bus}$  for very small systems would not be too cumbersome and time consuming, use of the computer for larger systems will save time and effort.

SECTION B  
EXPLANTION OF THE USAGE OF PROGRAMS

a. PROGRAM - AUBURN

The software program is called "NETWORK MATRICES". The program will build both Bus Admittance and Bus Impedance matrices for a multiport power system. It can either build a Ybus or a Zbus directly but separately or it can build both simultaneously. It can also form Positive Sequence or Zero Sequence Bus Admittance/Bus Impedance matrices for multiport networks. Results of the formation of these matrices can also be displayed on your screen.

INPUT DATA

Input data for the program consists of (1) Bus Information, (2) Line Data, (3) Transformer Data and (4) Branch Data.

(1) BUS INFORMATION

The maximum number of buses in addition to the reference bus that this program can handle is twenty. The program allows a choice of whether or not names for buses are required and is displayed as such.

One has also to choose at this stage whether or not the Ybus or Zbus is to be formed directly or whether or not both need be formed. Also a choice as to whether or not a Positive or a Zero Sequence Bus Admittance/Bus Impedance is desired. The program also enables input data to be entered from the keyboard or from an existing Data File.

(2) LINE DATA

Line data in either Impedance or Admittance may be entered. R and X or G and B for a line need to be per unit values. If Conductance is infinite, enter  $G = 0$ . If line Susceptance  $Y_c$  be neglected enter  $Y_c/2 = 0$ . Lines are treated as  $\pi$ - networks with  $1/2$  charging susceptances at each end. When entering line data one has to enter the line data appearing between nodes or buses. The screen displays an equivalent  $\pi$  - network as well as showing what lines have been entered to prevent duplication.

Also displayed is Bus Information, for example:-

BUS INFORMATION:	
BUS NO.	BUS NAME
0	REF
1	NONE NAME
2	NONE NAME
3	NONE NAME
4	NONE NAME
5	NONE NAME
6	NO MORE LINE



NB! It will be noticed that for a 5 bus system the Bus Information ends with a "6 No more LINE" statement. Therefore once you have completed entering line data between all the 5 buses, 6 must be pressed in order to tell the program that you have completed your entries.

### (3) TRANSFORMER DATA

Transformer data requires that besides entering the bus nodes between which the transformers are situated in the system, it also requires the transformer Tap Setting. On giving a tap setting an equivalent  $\pi$ -circuit is calculated by the program for the transformer in question and these values are displayed on the screen as well as an equivalent diagram showing the formulae used to calculate its parameters.

The process is repeated for each transformer situated in the power system.

### (4) BRANCH DATA

Branch data is different from line data. Branch data are those impedance/admittances which are found in a power system between any bus and the reference bus 0.

NB! When entering Line Data, paragraph (2) above, the program will terminate if 0 is entered as one of the nodes between which line data exists. Line Data can therefore only exist between buses, provided the 0 bus is not selected. The program does allow for a bus other than 0 to be selected as a reference, in which case the necessary adaptation will have to be made.

Branch data is typically the impedances of sources such as generators which appear between the reference bus 0 and any other bus.

### STORING DATA

The program enables one to store data entered from the keyboard. The program prompts for a 4 character name, no extension to the name chosen must be given. Once name entered then the input data is stored in a data file, e.g. GARYB.DAT.

The program further requires a 5 character name with no extension to be entered and which gives a name for the Ybus MATRIX. If only a Ybus formation was previously selected then the storing is complete. If however you previously required the program to form both a Ybus and a Zbus simultaneously, then it will prompt you to give a 5 character name with no extension, under which Zbus will be stored. If only Zbus was previously chosen then you will only be prompted for a 5 character name with no extension for this matrix only.

If both are previously requested then these matrices will be stored separately in bus files, for example:-

GARRY.BUS. (Ybus)  
LARRY.BUS. (Zbus)

UPDATING DATA

There is no short cut to directly update data or to extend an existing power system to include an increased/decreased number of buses, lines etc. One has to proceed through the program step by step until you are prompted to choose between "keyboard or EXISTING DATA FILE" input. Prior to this step one would have had to enter the same number of buses where only line, transformer or branch data is to be updated. Where the number of buses are to be increased/decreased this has to be stated before this step.

Existing Data File selection is then chosen. You are then prompted for the Data file needed, e.g. GARYB.DAT.

You are then requested and are taken through the updating steps.

RUNNING THE PROGRAM

The program prompts as to whether or not you wish to display the Ybus/Zbus or both. The program is run by merely pressing ENTER.

OUTPUT DATA

The screen then displays the results of the Ybus/Zbus. This it does by displaying one column of a matrix at a time. It also displays on the right hand side of the screen the columns so far displayed and is therefore an indication of which column is being displayed at that moment.

Should one wish to  your results, one has to do so by using the PRINT SCREEN key on your keyboard

The program then gives a summary of your multiport power system, listing the total lines, transformers and branches in the network as well as reminding you of the files under which you have stored your data.

Enter is pressed at this stage to exit to DOS.

b. PACKAGE - GUNGOR

This software package includes among others, two programs, ZYBUS AND ZBUS.

ZYBUS programs contains a Ybus, Zbus - forming program where the Ybus is directly formed from a multiport network power system and the Zbus is then obtained by inverting the formed Ybus matrix. This program also enables network reduction and allows for the elimination of some of the buses of a system and in this way simplifies the system. The result obtained from this reduction is an equivalent Ybus which has been reduced and is called Yeq. This Yeq can be inverted into Zeq. This ZYBUS program forms the Ybus matrix of a power system by an algorithm, using line data. To obtain access to this program one must enter "ZYBUSB" after C:>CD\Gungor.

ZBUS PROGRAM

This ZBUS program forms the bus impedance matrix Zbus directly from the number of buses, generator and line data for a multiport power system. To obtain access to this program one must enter "ZBUSB" after C:>CD\Gungor.

INPUT DATA

ZYBUS PROGRAM

Input data for the program consists of:-

- (1) Print option
- (11) System data requesting:
  - NB = Number of buses, Nl = Number of lines
  - NE = Number of equivalent Buses = NB
  - for no reduction and Buses 1 to NE are retained for Yeq.
- (111) Line Data (1 to NL) and each line data is entered under the heading NS, NR, R, Xl, Bc ("Commas" important)
  - where NS = Sending-end bus number,
  - NR = Receiving-end bus number,
  - R = Resistance (pu)
  - Xl = Inductive Reactance (pu)
  - Bc = 1/2 Charging susceptance (pu).

NB! The program does not provide for entering generator impedances, therefore these impedances are entered as 1/2 charging susceptances.

The line data will thus be:-

Ns	Nr	R	Xl	Bc
1	2	0	.2	-10
1	3	0	.25	0
2	3	0	.4	0

ZBUS PROGRAM

Input data for the program consists of:-

- (1) Print Option
- (11) System data requesting:
  - NB = Number of buses, Nl = Number of lines and
  - NG = Number of generators. Under NG one must enter RG = Generator resistance (pu) and XG = Generator reactance (pu). These two values to be separated by a "comma".
- (111) Line Data (1 to NL in ascending order of both Ns and Nr with Ns<Nr for each entry) is entered under the headings NS,NR,R XL where:-
  - NS = Sending-end bus number
  - NR = Receiving-end bus number
  - R = Resistance of line
  - XL = Inductive reatance of line

NB! The program in this case, different to ZYBUSB, allows for generator impedances to be entered and are therefore not treated as 1/2 charging susceptances.

The program however does not provide for 1/2 charging susceptances.

STORING DATA

The programs provide no facilities for storing entered data except under the printing option below.

UPDATING DATA

The programs provide no facilities for updating data and one has to reset before a new run.

RUNNING THE PROGRAM

On completion of the Input Data, enter is pressed to run the program and the results are displayed on the screen.

OUTPUT DATA ZYBUSB
-----------------------

The output data lists the Ybus, Zbus and Yeq as required.

Note: This program will form a singular Ybus but will not invert it. Hence Yeq is not produced for a singular Ybus.

If the Ybus matrix is singular, then at the end of its listing it will state that "MATRIX IS SINGULAR". Zbus can then not be obtained by inversion.

OUTPUT DATA ZBUSB
----------------------

The output data lists the direct formation of Zbus as required.

PRINTING
----------

The program prompts at its beginning a "PRINT OPTION" as follows:

```
P = 0 FOR SCREEN OUTPUT ONLY
P = 1 FOR SCREEN & PRINTED OUTPUT
P = 2 FOR SCREEN & DISK OUTPUT (ZYBUSB.OUT)
```

P=0 merely enables the output data to be displayed on the screen.

P=1 option prints a printer output as the input data is entered step by step and once the program is run the printer then simultaneously prints the results as a hard copy.

p=2 option lists the output data on the screen and simultaneously stores the results in the ZYBUSB.OUT /ZBUSB.OUT file.

To print the output, enter:

```
C:\GUNGOR>TYPE ZYBUSB.OUT(OR ZBUSB.OUT)
```

The data is once again displayed on the screen and the "PRINT SCREEN" key can be pressed to obtain an output. The "PAUSE" key is operated to stop the listing at the desired point.

Alternatively, enter:

```
C:\GUNGOR>MORE<ZBUSB.OUT(OR ZBUSB.OUT)
```

where this command replaces the necessity to use the "PAUSE" key. To print the file ZYBUSB.OUT/ZBUSB.OUT enter:

```
C:\GUNGOR>PRINT ZYBUSB.OUT(OR ZBUSB.OUT)
```

and then press "enter" after being prompted by the words:

```
NAME OF LIST DEVICE[PRN]:
```

SECTION C  
EXPERIMENTATION USING PROGRAMS

A. EXPERIMENT USING PROGRAM AUBURN - NETWORK ANALYSIS

EXPERIMENT ONE  
3 BUS POWER SYSTEM

INFORMATION AVAILABLE:-

A one-line diagram of a three bus system is shown in Figure 6

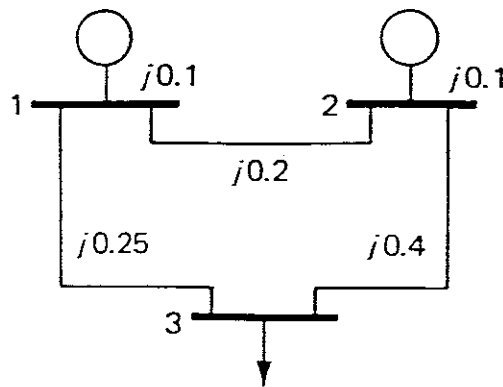


FIGURE 6

The power system contains no transformers and no line susceptances. The generators have reactances of  $j0.1$  and lines have reactances of  $j0.2$  (1 to 2),  $j0.25$  (1 to 3) and  $j0.4$  (2 to 3).

PART ONE

C:\AUBURN> NET  
The screen shows

LESSON 3:  
NETWORK MATRIX

After pressing enter it shows:-

" WELCOME TO NETWORK MATRICES "

Press Enter and then select option 1 for building both Bus Admittance/Bus Impedance.

Now entering BUS INFORMATION:

Enter 3

Enter N if you do not wish to name your buses.

Enter N again to maintain the 0 as the reference bus.

The screen then displays the BUS INFORMATION.

As we wish to obtain the Ybus/Zbus select "B"

Select "P" for obtaining the positive sequence Ybus/Zbus.

Select "IY" to use the Inverse Ybus matrix method to form the Zbus rather than the "BU" option which provides a method of building an algorithm.

Select "K" to enter data from the keyboard.

Once we have stored our results we will repeat this experiment then using data from a Data File (selection "F").

We have now completed entering the BUS INFORMATION and now proceed to input the LINE DATA.

Select Y as system does have Lines.

Select I as line data is in per-unit Impedance and not in per-unit Admittance.

The screen now shows:-

BUS INFORMATION:		TWO MORE COMMENTS:	
Bus No.	Bus Name	1.R & X or G & B is	
0	REF	formatted as F10.4, and	
1	NONE NAME	they are all PER UNIT	
2	NONE NAME	values;	
3	NONE NAME	2.If branch Conductance G	
4	NONE NAME	is infinite, enter G = 0;	
5	NONE NAME	If line Susceptance Yc be	
6	No more LINE	neglected, enter Yc/2=0.	

POSITIVE SEQUENCE

Please input the number of buses for the LINE you would like to add.

From node

Enter to read

From node 1 to node 2 and enter

R = 0  
X = 0.2  
Yc/2 = 0

Enter:

From node 1 to node 3

R = 0  
X = 0.25  
Yc/2 = 0

Enter:

From node 2 to node 3

R = 0  
X = 0.4  
Yc/2 = 0

NB! As there are only 3 lines, then if one looks at the BUS INFORMATION on the screen it can be seen that it provides:

"4 NO MORE LINE"

Therefore enter "4" after the "From node" prompt to complete the Line Data and to move into the transformer data.

As multiport system does not include any transformers, press "N"

We now move to input the "BRANCH DATA"

Select Y and enter:

From node 0 to 1

R = 0  
X = 0.1

and enter

From node 0 to node 2

R = 0  
X = 0.1

NB! As there are only two buses to be entered then from the BUS INFORMATION on the screen select

"4 NO MORE BRANCH"

This completes the BRANCH DATA.

The screen now prompts and asks for a 4 character name, no extension to be given, for storing the data entered so far, for example:

Choose "GARI"

The program then asks if the data will be stored under the name GARIB.DAT?

Select "Y"

We now move to build the Ybus/Zbus.

As we are to build both simultaneously we have to give a name to both of them. Such names to be <5 characters and no extensions.



For example:

Ybus MATRIX = FARRY

Zbus MATRIX = MARRY

Press Enter to "DISPLAY" Ybus/Zbus. (The print screen key is used to print results)

The following results (Singular column at a time) are obtained:

YBUS

```

POSITIVE SEQUENCE:
Y Bus matrix is as follows:
COLUMN 1 :
Ybus[ 1, 1] =      0.0000 + j  -19.0000
Ybus[ 2, 1] =      0.0000 + j   5.0000
Ybus[ 3, 1] =      0.0000 + j   4.0000
Y-bus :
*
*
*
Z-bus :
```

Press ENTER key to display next column.

```

POSITIVE SEQUENCE:
Y Bus matrix is as follows :
COLUMN 2 :
Ybus[ 1, 2] =      0.0000 + j   5.0000
Ybus[ 2, 2] =      0.0000 + j -17.5000
Ybus[ 3, 2] =      0.0000 + j   2.5000
Y-bus :
* *
* *
* *
Z-bus :
```

Press ENTER key to display next column.

```

POSITIVE SEQUENCE:
Y Bus matrix is as follows :
COULMN 3 :
Ybus[ 1, 3] =      0.0000 + j   4.0000
Ybus[ 2, 3] =      0.0000 + j   2.5000
Ybus[ 3, 3] =      0.0000 + j -6.5000
Y-bus :
* * *
* * *
* * *
Z-bus :
```

Press ENTER key to display Zbus matrix.

$$\text{ZBUS} = \text{YBUS}^{-1}$$

```
POSITIVE SEQUENCE:
Z Bus matrix is as follows :
COLUMN 1 :
Zbus[ 1, 1] = 0.0000 + j 0.0717
Zbus[ 2, 1] = 0.0000 + j 0.0283
Zbus[ 3, 1] = 0.0000 + j 0.0550
Y-bus :
* * *
* * *
* * *
Z-bus :
*
*
*
```

Press ENTER key to DISPLAY next column.

```
POSITIVE SEQUENCE
Z Bus matrix is as follows :
COLUMN 2 :
Zbus[ 1, 2] 0.0000 + j 0.0283
Zbus[ 2, 2] 0.0000 + j 0.0717
Zbus[ 3, 2] 0.0000 + j 0.0450
Y-bus :
* * *
* * *
* * *
Z-bus :
* *
* *
* *
```

Press ENTER key to DISPLAY next column.

```
POSITIVE SEQUENCE
Z Bus matrix is as follows :
COLUMN 3 :
Zbus[ 1, 3] 0.0000 + j 0.0550
Zbus[ 2, 3] 0.0000 + j 0.0450
Zbus[ 3, 3] 0.0000 + j 0.2050
Y-bus :
* * *
* * *
* * *
Z-bus :
* * *
* * *
* * *
```

Press ENTER key to continue.

Press "enter" to move towards exiting from program.

The screen now shows a summary of the stored Ybus/Zbus as well as a summary of the multiport system, namely:-

```
Zbus matrix is stored under the name, MARRY.BUS
Ybus matrix is stored under the name, FARRY.BUS
SUMMARY:
There are totally 3 line(s), 0 transformer(s),
and 2 branch(es) in the network.
Press ENTER key to get the last page !
```

Y-bus :  
\* \* \*  
\* \* \*

Z-bus :  
\* \* \*  
\* \* \*  
\* \* \*

Press "Enter" to exit to "DOS"

PART TWO

Now REPEAT the EXPERIMENT but use the stored data in GARIB.DAT.

Follow the previous steps in part one until prompted for entering data from the keyboard or existing branch file.

Select "F"

Then enter "I" for original impedance data. The screen then displays a list of the sub-directories \*.DAT and includes GARIB.DAT.

Enter GARIB.DAT where prompted and then select "Y" for yes and then "N" for not editing data at this stage.

You are then prompted and asked if you wish to keep the original name. Choose "O".

Enter original of Ybus, namely FARRY.BUS and original name to Zbus, namely MARRY.BUS.

Follow the prompted steps to display your results, from which it can be seen that they are the same as that obtained in "PART ONE".

Exit to "DOS".

EXPERIMENT TWO  
5 BUS POWER SYSTEM

INFORMATION AVAILABLE:

A one-line diagram of a 5 bus system is shown in Figure 7.

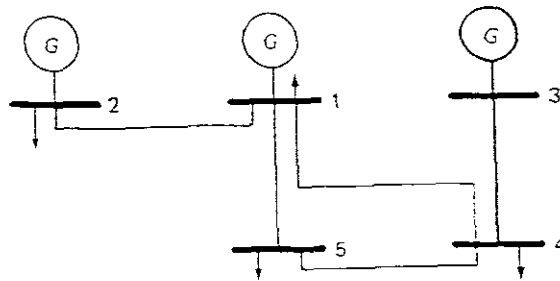


FIGURE 7

LINE DATA (pu)

Bus Code	Impedance (pu)	1/2 Charging Susceptance (pu)	Rating MVA
1-2	0.030 +j0.103	j0.05	60
1-4	0.105 +j0.347	j0.01	10
1-5	0.080 +j0.262	j0.02	20
3-4	0.106 +j0.403	j0.01	50
4-5	0.33 +j0.118	j0.05	15

The 5 bus power system contains no transformers but includes 1/2 shunt susceptances. There are no generator impedances, therefore there are no branches (ref bus to given bus). The pu impedances are based on a 100MVA common base.

PART ONE

C:\AUBURN> NET

Select 1 to build both Ybus/Zbus  
Enter 5 buses besides reference bus.  
Choose Y to give names to the 5 buses., namely:-

REFERENCE BUS : CHARLIE  
BUS 1 : PETER  
BUS 2 : GEORGE  
BUS 3 : DAVID  
BUS 4 : TERRENCE  
BUS 5 : ARTHUR

Keep reference bus as the "0" bus.

The screen shows:-

BUSES INFORMATION :	Bus No.	Bus Name
	0	CHARLIE
	1	PETER
	2	GEORGE
	3	DAVID
	4	TERRANCE
	5	ARTHUR

Press ENTER key to continue.

Choose "B" to build both Ybus/Zbus  
Choose "P" to form Positive Sequence Ybus/Zbus.  
Choose "IY" to use Inverse Ybus matrix method for Zbus.  
Choose "K" for entering data from keyboard.

Enter Line Data:-

The line input data is Impedance (pu).

Enter to read:

From node 1 to node 2  
R = 0.03  
X = 0.103  
Yc/2 = 0.05

Enter:

From node 1 to node 4  
R = 0.105  
X = 0.347  
Yc/2 = 0.01

Enter:

From node 1 to node 5  
R = 0.08  
X = 0.262  
Yc/2 = 0.02

Enter:

From node 3 to node 4  
R = 0.106  
X = 0.403  
Yc/2 = 0.01

Enter:

From node 4 to node 5  
R = 0.33  
X = 0.118  
Yc/2 = 0.05

Enter "6" as there are only 5 buses.

Move past TRANSFORMER DATA as there are no transformers included in the 5 bus system.

There are also no branches, therefore move past BRANCH DATA also.

The screen now prompts and asks for a 4 character name, no extensions.

CHOOSE "GAR3"

Next the Ybus matrix must be named using <5 characters with no extension:-

CHOOSE "CARRY"

For Zbus matrix:

CHOOSE "HARRY"

Proceed to display results. The following results (Singular Column at a time) are obtained:-

YBUS

POSITIVE SEQUENCE:			
Y Bus matrix is as follows:			Y-bus :
			*
			*
COLUMN	1 :		
Ybus[ 1, 1]	=	4.4716 + j -15.0009	*
Ybus[ 2, 1]	=	-2.6067 + j 8.9495	*
Ybus[ 3, 1]	=	0.0000 + j 0.0000	
Ybus[ 4, 1]	=	-0.7989 + j 2.6401	
Ybus[ 5, 1]	=	-1.0660 + j 3.4913	
			Z-bus :

Press ENTER key to display next column.

```
POSITIVE SEQUENCE:
Y Bus matrix is as follows:

COLUMN 2 :

Ybus[ 1, 2] = -2.6067 + j      8.9495
Ybus[ 2, 2] =  2.6067 + j     -8.8995
Ybus[ 3, 2] =  0.0000 + j      0.0000
Ybus[ 4, 2] =  0.0000 + j      0.0000
Ybus[ 5, 2] =  0.0000 + j      0.0000

Y-bus :
* *
* *
*
*

Z-bus :
```

Press ENTER key to display next column.

```
POSITIVE SEQUENCE:
Y Bus matrix is as follows:

COLUMN 3 :

Ybus[ 1, 3] =  0.0000 + j      0.0000
Ybus[ 2, 3] =  0.0000 + j      0.0000
Ybus[ 3, 3] =  0.6104 + j     -2.3108
Ybus[ 4, 3] = -0.6104 + j      2.3208
Ybus[ 5, 3] =  0.0000 + j      0.0000

Y-bus :
* *
* *
*
* *
*

Z-bus :
```

Press ENTER key to display next column.

```
POSITIVE SEQUENCE:
Y Bus matrix is as follows:

COLUMN 4 :

Ybus[ 1, 4] = -0.7989 + j      2.6401
Ybus[ 2, 4] =  0.0000 + j      0.0000
Ybus[ 3, 4] = -0.6104 + j      2.3208
Ybus[ 4, 4] =  4.0961 + j     -5.8516
Ybus[ 5, 4] = -2.6868 + j      0.9607

Y-bus :
* * *
* *
* *
* * *
* *

Z-bus :
```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows:

    COLUMN 5 :

Ybus[ 1, 5] =  -1.0660 + j    3.4913
Ybus[ 2, 5] =   0.0000 + j    0.0000
Ybus[ 3, 5] =   0.0000 + j    0.0000
Ybus[ 4, 5] =  -2.6868 + j    0.9607
Ybus[ 5, 5] =   3.7528 + j   -4.3820

                                Y-bus :
                                * * * *
                                * *
                                * *
                                * * * *
                                *   * *

                                Z-bus :
```

Press ENTER key to display Z Bus matrix

ZBUS AS YBUS -1

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows:

    COLUMN 1 :

Zbus[ 1, 1] =   0.0150 + j   -3.5239
Zbus[ 2, 1] =   0.0097 + j   -3.5422
Zbus[ 3, 1] =  -0.0201 + j   -3.6241
Zbus[ 4, 1] =  -0.0161 + j   -3.6095
Zbus[ 5, 1] =  -0.0051 + j   -3.6009

                                Y-bus :
                                * * * *
                                * *
                                * *
                                * * * *
                                *   * *

                                Z-bus :
                                *
                                *
                                *
                                *
                                *
```

Press ENTER key to DISPLAY next column.



```
POSITIVE SEQUENCE:
Z Bus matrix is as follows:

COLUMN 2 :

Zbus[ 1, 2] = 0.0097 + j -3.5422
Zbus[ 2, 2] = 0.0347 + j -3.4571
Zbus[ 3, 2] = -0.0257 + j -3.6428
Zbus[ 4, 2] = -0.0217 + j -3.6282
Zbus[ 5, 2] = -0.0105 + j -3.6196

Y-bus :
* * * *
* *
* *
* * * *
* * * *

Z-bus :
* *
* *
* *
* *
* *
```

Press ENTER key to DISPLAY next column.

```
POSITIVE SEQUENCE:
Z Bus matrix is as follows:

COLUMN 3 :

Zbus[ 1, 3] = -0.0201 + j -3.6241
Zbus[ 2, 3] = -0.0257 + j -3.6428
Zbus[ 3, 3] = 0.1639 + j -3.1182
Zbus[ 4, 3] = 0.0605 + j -3.5084
Zbus[ 5, 3] = -0.0426 + j -3.5879

Y-bus :
* * * *
* *
* *
* * * *
* * * *

Z-bus :
* * *
* * *
* * *
* * *
* * *
```

Press ENTER key to DISPLAY next column.

POSITIVE SEQUENCE:  
Z Bus matrix is as follows:

COLUMN 4 :

Zbus[ 1, 4] =	-0.0161 + j	-3.6095
Zbus[ 2, 4] =	-0.0217 + j	-3.6282
Zbus[ 3, 4] =	0.1639 + j	-3.5084
Zbus[ 4, 4] =	0.0605 + j	-3.4942
Zbus[ 5, 4] =	-0.0426 + j	-3.5735

Y-bus :  
\* \* \* \*  
\* \*  
\* \*  
\* \* \* \*  
\* \* \* \*

Z-bus :  
\* \* \*  
\* \* \*  
\* \* \*  
\* \* \*  
\* \* \*

Press ENTER key to DISPLAY next column.

POSITIVE SEQUENCE:  
Z Bus matrix is as follows:

COLUMN 5 :

Zbus[ 1, 5] =	-0.0051 + j	-3.6009
Zbus[ 2, 5] =	-0.0105 + j	-3.6196
Zbus[ 3, 5] =	-0.0426 + j	-3.5879
Zbus[ 4, 5] =	-0.0387 + j	-3.5735
Zbus[ 5, 5] =	0.0581 + j	-3.4989

Y-bus :  
\* \* \* \*  
\* \*  
\* \*  
\* \* \* \*  
\* \* \* \*

Z-bus :  
\* \* \* \*  
\* \* \* \*  
\* \* \* \*  
\* \* \* \*  
\* \* \* \*

Zbus matrix is stored under the name, HARRY.BUS

Ybus matrix is stored under the name, CARRY.BUS

Y-bus:  
\* \* \* \*  
\* \*  
\* \*  
\* \* \* \*  
\* \* \* \*

SUMMARY:

There are totally 5 line(s), 0 transformer(s),  
and 0 branch(es) in the network.

Press ENTER key to get the last page !

Z-bus :  
\* \* \* \* \*  
\* \* \* \* \*  
\* \* \* \* \*  
\* \* \* \* \*  
\* \* \* \* \*

Exit to "DOS"

PART TWO

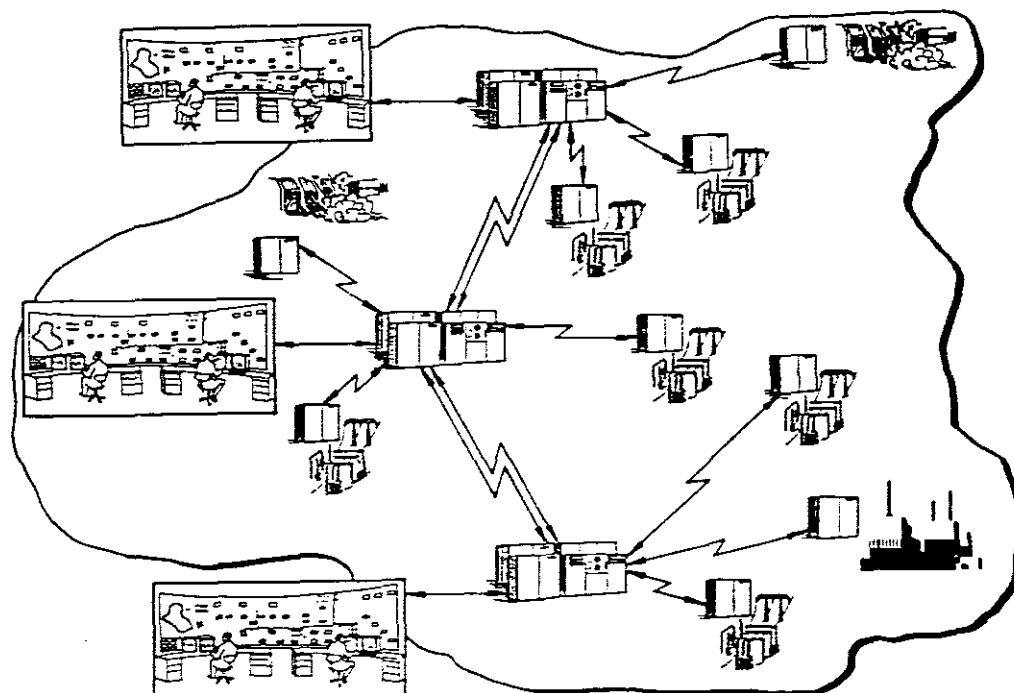
Now repeat the experiment but use the stored data in GAR3B.DAT.

Follow the previous steps in PART TWO of EXPERIMENT ONE except  
use:-

CARRY.BUS FOR THE Ybus  
HARRY.BUS FOR THE Zbus

Follow the prompted steps to display your results and check to  
ensure that they are the same as has been obtained in PART ONE  
of this EXPERIMENT.

Exit to "DOS"



**EXPERIMENT THREE**  
**7 BUS POWER SYSTEM**  
**WITH FUTURE EXPANSION TO A**  
**12 BUS POWER SYSTEM**

INFORMATION AVAILABLE:-

A one-line diagram of this 7 bus expanded to 12 bus system is shown in Figure 8

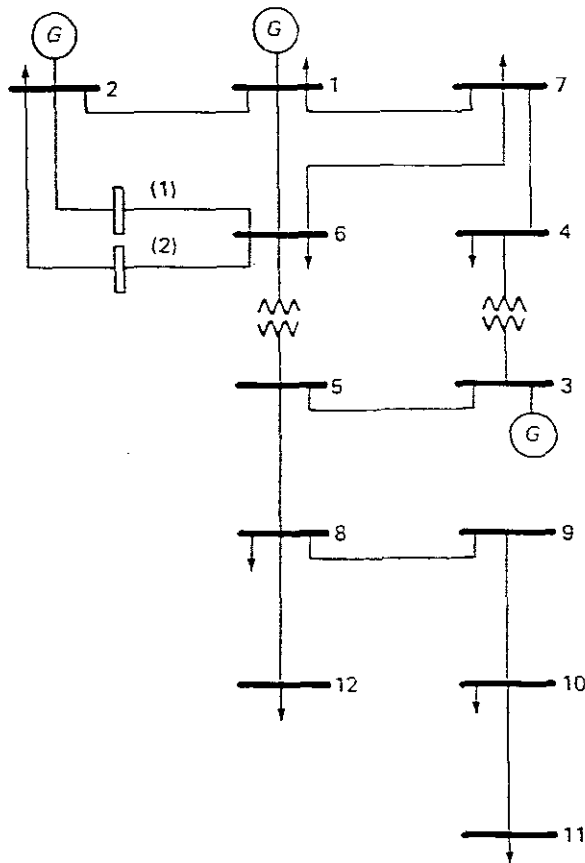


FIGURE 8

Line-Transformer Data (pu)

Bus Code	Positive Sequence Impedance	Charging Susceptance	Zero Sequence Impedance	Mutual Impedance	Nontap Bus	Tap Setting			Rating (MVA)
						Initial	Minimum	Maximum	
1-2	$0.072 - j0.288$	$j0.018$	$0.299 + j0.953$						25
1-6	$0.056 - j0.148$	$j0.009$	$0.161 + j0.437$						35
1-7	$0.109 - j0.225$	$j0.057$	$0.261 + j0.699$						25
2-6(1)	$0.083 + j0.216$	$j0.013$	$0.237 + j0.642$	$0.12 + j0.32$					20
2-6(2)	$0.083 + j0.216$	$j0.013$	$0.237 + j0.642$						20
3-4	$0.001 - j0.053$	—	$0.001 + j0.053$		4	1.00	0.90	1.10	150
3-5	$0.014 + j0.127$	$j0.134$	$0.093 + j0.394$						200
4-7	$0.093 - j0.244$	$j0.014$	$0.266 + j0.721$						75
5-6	$0.001 - j0.026$	—	$0.001 + j0.026$		6	0.98	0.90	1.10	100
6-7	$0.090 + j0.236$	$j0.014$	$0.245 + j0.680$						25
5-8	$0.001 + j0.010$	—	$0.001 + j0.010$		8	0.99	0.90	1.10	200
8-9	$0.080 + j0.200$	$j0.015$	$0.240 + j0.680$						75
8-12	$0.100 + j0.220$	$j0.060$	$0.260 + j0.710$						30
9-10	$0.090 + j0.210$	$j0.016$	$0.250 + j0.700$						75
10-11	$0.120 + j0.250$	$j0.050$	$0.310 + j0.920$						40

The 7 bus power system which can be expanded to a 12 bus contains TRANSFORMERS,  $\frac{1}{2}$  SHUNT SUSCEPTANCES but no branches as no generator impedances are given. The pu impedances are based on a common base of 100 MVA for both the 7 bus and 12 bus systems. Also included are Positive and Zero Sequence impedances, therefore both Positive and Zero Sequences Ybus/Zbus can be obtained. The data also includes TAP SETTINGS for TRANSFORMERS which vary from an INITIAL setting to a MINIMUM and then a MAXIMUM tap setting. The NON-TAP BUS is also given. Also listed is a MUTUAL IMPEDANCE for the two parallel lines connected between bases 2 and 6.

PART ONE

C:\AUBURN>NET

Select 1 to build Ybus/Zbus

Choose 7 buses initially.

Do not use names for buses.

Keep the reference bus, therefore the screen shows:-

BUSES INFORMATION:	Bus No.	Bus Name
	0	REF
	1	NONE NAME
	2	NONE NAME
	3	NONE NAME
	4	NONE NAME
	5	NONE NAME
	6	NONE NAME
	7	NONE NAME

Press ENTER key to continue.

Choose "B" to build Ybus/Zbus

Choose "P" for positive sequence matrices

Choose "IY" to invert Ybus to Zbus

Choose "K" to input for keyboard.

Enter Line Data as impedances (pu):-

Enter to read:

From node 1 to node 2  
R = 0.072  
X = 0.288  
Yc/2 = 0.018

Enter:-

From node 1 to node 6  
R = 0.056  
X = 0.148  
Yc/1 = 0.009

Enter:-

From node 1 to node 7  
R = 0.109  
X = 0.225  
Yc/2 = 0.057

Enter:- (NB! There are two lines in parallel)

From node 2 to node 6  
R = 0.083  
X = 0.216  
Yc/2 = 0.013

Enter:-

From node 2 to node 6  
R = 0.083  
X = 0.216  
Yc/2 = 0.013

NB! From node 3 to 4 only a transformer is in circuit and its data must be entered under TRANSFORMER DATA.

Enter:-

From node 3 to node 5  
R = 0.014  
X = 0.127  
Yc/2 = 0.134

Enter:-

From node 4 to node 7  
R = 0.093  
X = 0.244  
Yc/2 = 0.014

NB! From node 5 to node 6 only a transformer is in circuit and its data must be entered under TRANSFORMER DATA.

Enter:-

From node 6 to node 7  
R = 0.090  
X = 0.236  
Yc/2 = 0.014

Press 8 to end the entering of LINE DATA and to proceed to enter TRANSFORMER DATA.

Choose Y as there are two transformers.

Enter:-

From node 3 to node 4  
R = 0.001  
X = 0.053

TAP = 1.1 (Choose maximum Tap Setting)

The nontap bus is bus 4

The screen shows the transformer as an equivalent  $\pi$ -circuit and shows the determined values for this equivalent circuit, namely:-

Enter TAP of the transformer: TAP=1.1	Processed so far: All of lines. From bus 3 to 4 (T)
Z' = R' + j X' where: R' = R*T = 0.0011 X' = X*T = 0.0583	
From node 3 to ground : T*Zt/(T-1) = 0.0110 + j 0.5830	
From node 4 to ground : T*T*Zt/(1-T) = -0.0121 + j -0.6413	
Press ENTER key to continue.	

Enter:-

From node 5 to node 6  
R = 0.001  
X = 0.026

TAP = 1.1 (Choose Maximum Tap Setting)

The non-tap bus is bus 6

<p>Enter TAP of the transformer: TAP=1.1</p> <p>Z' = R' + jX' where: R' = R*T = 0.0011  X' = X*T = 0.0286</p> <p>From node 5 to ground :  T*Zt/(T-1) = 0.0110 + j 0.2860</p> <p>From node 6 to ground :  T*T*Zt/(1-T) = -0.0121 + j -0.3146</p> <p>Press ENTER key to continue.</p>	<p>Processed so far:  All of lines.  From bus 3 to 4 (T)  From bus 5 to 6 (T)</p>
---	---

Press 8 to end ENTERING of TRANSFORMER DATA and to proceed to BRANCH DATA.

As there is no branch data choose "N"

You have finished ENTERING data.

Store this data under "GAR4" (Namely GAR4B. DAT)

Let name for buses be:-

Ybus = JARRY

Zbus = KARRY

Follow steps to display results. The following results (Singular Column at a time) are obtained:-

YBUS

<p>POSITIVE SEQUENCE:  Y Bus matrix is as follows:</p> <p>COLUMN 1 :</p> <p>Ybus[1, 1] = 4.7972 + j -12.6942  Ybus[2, 1] = -0.8170 + j 3.2680  Ybus[3, 1] = 0.0000 + j 0.0000  Ybus[4, 1] = 0.0000 + j 0.0000  Ybus[5, 1] = 0.0000 + j 0.0000  Ybus[6, 1] = -2.2364 + j 5.9105  Ybus[7, 1] = -1.7438 + j 3.5997</p> <p>Press ENTER key to display next column.</p>	<p>Y-bus :</p> <p>1 2 3 4 5 6 7 8 9 10</p> <p>1 *  2 *  3  4  5  6 *  7 *  8  9  10</p> <p>Z-bus :</p> <p>1 2 3 4 5 6 7 8 9 10</p> <p>1  2  3  4  5  6  7  8  9  10</p>
--	---





```

                                Y-bus :
                                1 2 3 4 5 6 7 8 9 10
POSITIVE SEQUENCE:           1 * *
Y Bus matrix is as follows:   2 * *
                                3      * *
                                4      * *
                                5      *
                                6 * *
                                7 *      *
                                8
                                9
                                10
COLUMN 4 :
Ybus[1, 4] = 0.0000 + j      0.0000
Ybus[2, 4] = 0.0000 + j      0.0000
Ybus[3, 4] = -0.3235 + j     17.1466
Ybus[4, 4] = 1.6580 + j     -19.1523
Ybus[5, 4] = 0.0000 + j      0.0000
Ybus[6, 4] = 0.0000 + j      0.0000
Ybus[7, 4] = -1.3639 + j     3.5785

                                Z-bus :
                                1 2 3 4 5 6 7 8 9 10
                                1
                                2
                                3
                                4
                                5
                                6
                                7
                                8
                                9
                                10
Press ENTER key to display next column.

```

```

                                Y-bus :
                                1 2 3 4 5 6 7 8 9 10
POSITIVE SEQUENCE:           1 * *
Y Bus matrix is as follows:   2 * *
                                3      * * *
                                4      * *
                                5      *   *
                                6 * *      *
                                7 *      *
                                8
                                9
                                10
COLUMN 5 :
Ybus[1, 5] = 0.0000 + j      0.0000
Ybus[2, 5] = 0.0000 + j      0.0000
Ybus[3, 5] = -0.8576 + j     7.7795
Ybus[4, 5] = 0.0000 + j      0.0000
Ybus[5, 5] = 2.3347 + j    -46.0502
Ybus[6, 5] = -1.3428 + j     34.9134
Ybus[7, 5] = 0.0000 + j      0.0000

                                Z-bus :
                                1 2 3 4 5 6 7 8 9 10
                                1
                                2
                                3
                                4
                                5
                                6
                                7
                                8
                                9
                                10
Press ENTER key to display next column.

```

```

                                Y-bus :
                                1 2 3 4 5 6 7 8 9 10
POSITIVE SEQUENCE:           1 * *           *
Y Bus matrix is as follows:   2 * *           *
                                3           * * *
                                4           * *
                                5           * * *
                                6 * *           * *
                                7 *           * *
                                8
                                9
                                10
COLUMN 6 :
Ybus[1, 6] = -2.2364 + j      5.9105
Ybus[2, 6] = -3.1002 + j      8.0680
Ybus[3, 6] =  0.0000 + j      0.0000
Ybus[4, 6] =  0.0000 + j      0.0000
Ybus[5, 6] = -1.3428 + j     34.9134
Ybus[6, 6] =  7.9680 + j    -49.3683
Ybus[7, 6] = -1.4107 + j      3.6993

                                Z-bus :
                                1 2 3 4 5 6 7 8 9 10
                                1
                                2
                                3
                                4
                                5
                                6
                                7
Press ENTER key to display next column. 8
                                           9
                                           10

```

```

                                Y-bus :
                                1 2 3 4 5 6 7 8 9 10
POSITIVE SEQUENCE:           1 * *           * *
Y Bus matrix is as follows:   2 * *           *
                                3           * * *
                                4           * *           *
                                5           * * *
                                6 * *           * * *
                                7 *           * * *
                                8
                                9
                                10
COLUMN 7 :
Ybus[1, 7] = -1.7438 + j      3.5997
Ybus[2, 7] =  0.0000 + j      0.0000
Ybus[3, 7] =  0.0000 + j      0.0000
Ybus[4, 7] = -1.3639 + j      3.5785
Ybus[5, 7] =  0.0000 + j      0.0000
Ybus[6, 7] = -1.4107 + j      3.6993
Ybus[7, 7] =  4.5184 + j    -10.7925

                                Z-bus :
                                1 2 3 4 5 6 7 8 9 10
                                1
                                2
                                3
                                4
                                5
                                6
                                7
Press ENTER key to display next column. 8
                                           9
                                           10

```

ZBUS AS YBUS-1

```

    POSITIVE SEQUENCE:
    Z Bus matrix is as follows:

    COLUMN 1 :

    Zbus[1, 1] = 0.0208 + j -1.9508
    Zbus[2, 1] = 0.0034 + j -2.0004
    Zbus[3, 1] = -0.0076 + j -1.8581
    Zbus[4, 1] = -0.0093 + j -2.0390
    Zbus[5, 1] = -0.0028 + j -1.8373
    Zbus[6, 1] = -0.0020 + j -2.0093
    Zbus[7, 1] = -0.0037 + j -2.0120

    Y-bus :
    1 2 3 4 5 6 7 8 9 10
    1 * *           * *
    2 * *           *
    3             * * *
    4             * *   *
    5             *   * *
    6 * *           * * *
    7 *             *   * *
    8
    9
    10

    Z-bus :
    1 2 3 4 5 6 7 8 9 10
    1 *
    2 *
    3 *
    4 *
    5 *
    6 *
    7 *
    8
    9
    10

    Press ENTER key to DISPLAY next column.
  
```

```

    POSITIVE SEQUENCE:
    Z Bus matrix is as follows:

    COLUMN 2 :

    Zbus[1, 2] = 0.0034 + j -2.0004
    Zbus[2, 2] = 0.0266 + j -1.9260
    Zbus[3, 2] = -0.0058 + j -1.8557
    Zbus[4, 2] = -0.0075 + j -2.0398
    Zbus[5, 2] = -0.0001 + j -1.8277
    Zbus[6, 2] = 0.0010 + j -1.9971
    Zbus[7, 2] = -0.0070 + j -2.0254

    Y-bus :
    1 2 3 4 5 6 7 8 9 10
    1 * *           * *
    2 * *           *
    3             * * *
    4             * *   *
    5             *   * *
    6 * *           * * *
    7 *             *   * *
    8
    9
    10

    Z-bus :
    1 2 3 4 5 6 7 8 9 10
    1 * *
    2 * *
    3 * *
    4 * *
    5 * *
    6 * *
    7 * *
    8
    9
    10

    Press ENTER key to DISPLAY next column.
  
```

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows:

    COLUMN 3 :

Zbus[1, 3] = -0.0076 + j  -1.8581
Zbus[2, 3] = -0.0058 + j  -1.8557
Zbus[3, 3] =  0.0100 + j  -1.6073
Zbus[4, 3] =  0.0122 + j  -1.7844
Zbus[5, 3] = -0.0005 + j  -1.6710
Zbus[6, 3] = -0.0016 + j  -1.8461
Zbus[7, 3] = -0.0034 + j  -1.8426

    Y-bus :
    1 2 3 4 5 6 7 8 9 10
1 * *           * *
2 * *           *
3           * * *
4           * *   *
5           *   * *
6 * *           * * *
7 *           *   * *
8
9
10

    Z-bus :
    1 2 3 4 5 6 7 8 9 10
1 * * *
2 * * *
3 * * *
4 * * *
5 * * *
6 * * *
7 * * *
8
9
10

Press ENTER key to DISPLAY next column.

```

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows:

    COLUMN 4 :

Zbus[1, 4] = -0.0093 + j  -2.0390
Zbus[2, 4] = -0.0075 + j  -2.0398
Zbus[3, 4] =  0.0122 + j  -1.7844
Zbus[4, 4] =  0.0174 + j  -1.9228
Zbus[5, 4] = -0.0011 + j  -1.8407
Zbus[6, 4] = -0.0031 + j  -2.0305
Zbus[7, 4] = -0.0029 + j  -2.0121

    Y-bus :
    1 2 3 4 5 6 7 8 9 10
1 * *           * *
2 * *           *
3           * * *
4           * *   *
5           *   * *
6 * *           * * *
7 *           *   * *
8
9
10

    Z-bus :
    1 2 3 4 5 6 7 8 9 10
1 * * * *
2 * * * *
3 * * * *
4 * * * *
5 * * * *
6 * * * *
7 * * * *
8
9
10

Press ENTER key to DISPLAY next column.

```

```

          Y-bus :
          1 2 3 4 5 6 7 8 9 10
1 * *           * *
2 * *           *
3           * * *
4           * *           *
5           *   * *
6 * *           * * *
7 *           *   * *
8
9
10

          Z-bus :
          1 2 3 4 5 6 7 8 9 10
1 * * * * *
2 * * * * *
3 * * * * *
4 * * * * *
5 * * * * *
6 * * * * *
7 * * * * *
8
9
10

    POSITIVE SEQUENCE:
    Z Bus matrix is as follows:

    COLUMN 5 :

    Zbus[1, 5] = -0.0028 + j   -1.8373
    Zbus[2, 5] = -0.0001 + j   -1.8277
    Zbus[3, 5] = -0.0005 + j   -1.6710
    Zbus[4, 5] = -0.0011 + j   -1.8407
    Zbus[5, 5] =  0.0046 + j   -1.6371
    Zbus[6, 5] =  0.0047 + j   -1.8154
    Zbus[7, 5] = -0.0047 + j   -1.8434

    Press ENTER key to DISPLAY next column.
  
```

```

          Y-bus :
          1 2 3 4 5 6 7 8 9 10
1 * *           * *
2 * *           *
3           * * *
4           * *           *
5           *   * *
6 * *           * * *
7 *           *   * *
8
9
10

          Z-bus :
          1 2 3 4 5 6 7 8 9 10
1 * * * * *
2 * * * * *
3 * * * * *
4 * * * * *
5 * * * * *
6 * * * * *
7 * * * * *
8
9
10

    POSITIVE SEQUENCE:
    Z Bus matrix is as follows:

    COLUMN 6 :

    Zbus[1, 6] = -0.0020 + j   -2.0093
    Zbus[2, 6] =  0.0010 + j   -1.9971
    Zbus[3, 6] = -0.0016 + j   -1.8461
    Zbus[4, 6] = -0.0031 + j   -2.0305
    Zbus[5, 6] =  0.0047 + j   -1.8154
    Zbus[6, 6] =  0.0064 + j   -1.9831
    Zbus[7, 6] = -0.0051 + j   -2.0209

    Press ENTER key to DISPLAY next column.
  
```

POSITIVE SEQUENCE:  
Z Bus matrix is as follows:

COLUMN 7 :

Zbus[1, 7] = -0.0037 + j -2.0120  
Zbus[2, 7] = -0.0070 + j -2.0254  
Zbus[3, 7] = -0.0034 + j -1.8426  
Zbus[4, 7] = -0.0029 + j -2.0121  
Zbus[5, 7] = -0.0047 + j -1.8434  
Zbus[6, 7] = -0.0051 + j -2.0209  
Zbus[7, 7] = 0.0233 + j -1.9496

Y-bus :  
1 2 3 4 5 6 7 8 9 10  
1 \* \* \* \* \* \* \*  
2 \* \* \* \* \* \* \*  
3 \* \* \* \* \* \* \*  
4 \* \* \* \* \* \* \*  
5 \* \* \* \* \* \* \*  
6 \* \* \* \* \* \* \*  
7 \* \* \* \* \* \* \*  
8 \* \* \* \* \* \* \*  
9 \* \* \* \* \* \* \*  
10 \* \* \* \* \* \* \*

Z-bus :  
1 2 3 4 5 6 7 8 9 10  
1 \* \* \* \* \* \* \*  
2 \* \* \* \* \* \* \*  
3 \* \* \* \* \* \* \*  
4 \* \* \* \* \* \* \*  
5 \* \* \* \* \* \* \*  
6 \* \* \* \* \* \* \*  
7 \* \* \* \* \* \* \*  
8 \* \* \* \* \* \* \*  
9 \* \* \* \* \* \* \*  
10 \* \* \* \* \* \* \*

Press ENTER key to DISPLAY next column.

Zbus matrix is stored under the name,  
KARRY.BUS

Ybus matrix is stored under the name,  
JARRY.BUS

SUMMARY:

There are totally 8 line(s),  
2 transformer(s), and 0 branch(es) in  
the network.

Press ENTER key to get to last page!

Exit to "DOS"

Press ENTER key to DISPLAY next column.

Y-bus :  
1 2 3 4 5 6 7 8 9 10  
1 \* \* \* \* \* \* \*  
2 \* \* \* \* \* \* \*  
3 \* \* \* \* \* \* \*  
4 \* \* \* \* \* \* \*  
5 \* \* \* \* \* \* \*  
6 \* \* \* \* \* \* \*  
7 \* \* \* \* \* \* \*  
8 \* \* \* \* \* \* \*  
9 \* \* \* \* \* \* \*  
10 \* \* \* \* \* \* \*

Z-bus :  
1 2 3 4 5 6 7 8 9 10  
1 \* \* \* \* \* \* \*  
2 \* \* \* \* \* \* \*  
3 \* \* \* \* \* \* \*  
4 \* \* \* \* \* \* \*  
5 \* \* \* \* \* \* \*  
6 \* \* \* \* \* \* \*  
7 \* \* \* \* \* \* \*  
8 \* \* \* \* \* \* \*  
9 \* \* \* \* \* \* \*  
10 \* \* \* \* \* \* \*

PART TWO

With this experiment we are to obtain the zero sequence Ybus only for the 7 bus power system of PART ONE.

C:\AUBURN>NET

Proceed through the initial steps until prompted to choose between A/I/B.

Choose "A"

Choose "Z" for zero sequence Ybus

Choose "K"

Input "Zero Sequence Line Data" in impedance (pu):-

Enter:

From node 1 to node 2  
R = 0.299  
X = 0.953  
Yc/2 = 0.018

Enter:

From node 1 to node 6  
R = 0.161  
X = 0.437  
Yc/2 = 0.009

Enter:

From node 1 to node 7  
R = 0.267  
X = 0.699  
Yc/2 = 0.057

Enter:

From node 2 to node 6  
R = 0.237  
X = 0.642  
Yc/2 = 0.013

Enter:

From node 2 to node 6  
R = 0.237  
X = 0.642  
Yc/2 = 0.013

Enter:

From node 3 to node 5  
R = 0.093  
X = 0.394  
Yc/2 = 0.134

Enter:

From node 4 to node 7  
R = 0.266  
X = 0.721  
Yc/2 = 0.014



Enter:

From node 6 to node 7  
R = 0.243  
X = 0.680  
Yc/2 = 0.014

Press "8" to move to TRANSFORMER DATA.

Enter: For TRANSFORMER NUMBER ONE:

From node 3 to node 4  
R = 0.001  
X = 0.053  
TAP = 1.1

$Z' = R' + j X'$  where:  $R' = R * T = 0.0011$   
 $X' = X * T = 0.0583$

From node 3 to ground:  
 $T * Z_t / (T - 1) = 0.0110 + j 0.5830$

From noede 4 to ground:  
 $T * T * Z_t / (1 - T) = -0.0121 + j -0.6413$

Press ENTER key to continue.

Enter: For TRANSFORMER NUMBER TWO:

From node 5 to node 6  
R = 0.001  
X = 0.026  
TAP = 1.1

Processed so far:  
All of Lines.  
From bus 3 to 4 (T)  
From bus 5 to 6 (T)

$Z' = R' + j X'$  where:  $R' = R * T = 0.0011$   
 $X' = X * T = 0.0286$

From node 5 to ground:  
 $T * Z_t / (T - 1) = 0.0110 + j 0.2860$

From noede 6 to ground:  
 $T * T * Z_t / (1 - T) = -0.0121 + j -0.3146$

Press ENTER key to continue.

Press "8" to complete and proceed to BRANCH DATA.

Choose "N" as no branch data.

Choose a name for stored data:

"GAR6"

Stored under GAR60.DAT

Names for :

Ybus = RARRY

Proceed to display results. The results are as follows:

ZERO SEQUENCE:		Y-bus :
Y Bus matrix is as follows:		1 2 3 4 5 6 7 8 9 10
		1 *
		2 *
		3
COLUMN 1 :		4
		5
Ybus[1, 1] = 1.5189 + j -4.1346		6 *
Ybus[2, 1] = -0.2997 + j 0.9553		7 *
Ybus[3, 1] = 0.0000 + j 0.0000		8
Ybus[4, 1] = 0.0000 + j 0.0000		9
Ybus[5, 1] = 0.0000 + j 0.0000	10	
Ybus[6, 1] = -0.7423 + j 2.0148		Z-bus :
Ybus[7, 1] = -0.4769 + j 1.2485		1 2 3 4 5 6 7 8 9 10
		1
		2
		3
		4
		5
		6
Press ENTER key to display next column.	7	
	8	
	9	
	10	

ZERO SEQUENCE:		Y-bus :
Y Bus matrix is as follows:		1 2 3 4 5 6 7 8 9 10
		1 * *
		2 * *
		3
COLUMN 2 :		4
		5
Ybus[1, 2] = -0.2997 + j 0.9553		6 * *
Ybus[2, 2] = 1.3119 + j -3.6529		7 *
Ybus[3, 2] = 0.0000 + j 0.0000		8
Ybus[4, 2] = 0.0000 + j 0.0000		9
Ybus[5, 2] = 0.0000 + j 0.0000	10	
Ybus[6, 2] = -1.0122 + j 2.7416		Z-bus :
Ybus[7, 2] = 0.0000 + j 0.0000		1 2 3 4 5 6 7 8 9 10
		1
		2
		3
		4
		5
		6
Press ENTER key to display next column.	7	
	8	
	9	
	10	

ZERO SEQUENCE:  
Y Bus matrix is as follows:

COLUMN 3 :

Ybus[1, 3] = 0.0000 + j 0.0000  
Ybus[2, 3] = 0.0000 + j 0.0000  
Ybus[3, 3] = 0.9234 + j -21.1314  
Ybus[4, 3] = -0.3235 + j 17.1466  
Ybus[5, 3] = -0.5675 + j 2.4041  
Ybus[6, 3] = 0.0000 + j 0.0000  
Ybus[7, 3] = 0.0000 + j 0.0000

Y-bus :

1 2 3 4 5 6 7 8 9 10  
1 \* \*  
2 \* \*  
3 \*  
4 \*  
5 \*  
6 \* \*  
7 \*  
8  
9  
10

Z-bus :

1 2 3 4 5 6 7 8 9 10  
1  
2  
3  
4  
5  
6  
7  
8  
9  
10

Press ENTER key to display next column.

```

                                Y-bus :
                                1 2 3 4 5 6 7 8 9 10
ZERO SEQUENCE:
Y Bus matrix is as follows :
                                1 * *
                                2 * *
                                3      * *
                                4      * *
                                5      *
                                6 * *
                                7 *      *
                                8
                                9
                                10
COLUMN 4 :
Ybus[ 1, 4] = 0.0000 + j 0.0000
Ybus[ 2, 4] = 0.0000 + j 0.0000
Ybus[ 3, 4] = -0.3235 + j 17.1466
Ybus[ 4, 4] = 0.7445 + j -16.7946
Ybus[ 5, 4] = 0.0000 + j 0.0000
Ybus[ 6, 4] = 0.0000 + j 0.0000
Ybus[ 7, 4] = -0.4504 + j 1.2208

                                Z-bus :
                                1 2 3 4 5 6 7 8 9 10
                                1
                                2
                                3
                                4
                                5
                                6
                                7
                                8
                                9
                                10
Press ENTER key to display next column.
```

```

                                Y-bus :
                                1 2 3 4 5 6 7 8 9 10
ZERO SEQUENCE:
Y Bus matrix is as follows :
                                1 * *
                                2 * *
                                3      * * *
                                4      * *
                                5      * *
                                6 * *      *
                                7 *      *
                                8
                                9
                                10
COLUMN 5 :
Ybus[ 1, 5] = 0.0000 + j 0.0000
Ybus[ 2, 5] = 0.0000 + j 0.0000
Ybus[ 3, 5] = -0.5675 + j 2.4041
Ybus[ 4, 5] = 0.0000 + j 0.0000
Ybus[ 5, 5] = 2.0446 + j -40.6748
Ybus[ 6, 5] = -1.3428 + j 34.9134
Ybus[ 7, 5] = 0.0000 + j 0.0000

                                Z-bus :
                                1 2 3 4 5 6 7 8 9 10
                                1
                                2
                                3
                                4
                                5
                                6
                                7
                                8
                                9
                                10
Press ENTER key to display next column.
```

ZERO SEQUENCE:  
Y Bus matrix is as follows :

COLUMN 6 :

$Y_{bus}[ 1, 6] = -0.7423 + j \quad 2.0148$   
 $Y_{bus}[ 2, 6] = -0.0122 + j \quad 2.7416$   
 $Y_{bus}[ 3, 6] = 0.0000 + j \quad 0.0000$   
 $Y_{bus}[ 4, 6] = 0.0000 + j \quad 0.0000$   
 $Y_{bus}[ 5, 6] = -1.3428 + j \quad 34.9134$   
 $Y_{bus}[ 6, 6] = 3.4412 + j \quad -37.7510$   
 $Y_{bus}[ 7, 6] = -0.4660 + j \quad 1.3041$

Y-bus :

	1	2	3	4	5	6	7	8	9	10
1	*	*				*				
2	*	*				*				
3			*	*	*					
4			*	*						
5			*		*	*				
6	*	*			*	*				
7	*			*		*				
8										
9										
10										

Z-bus :

	1	2	3	4	5	6	7	8	9	10
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Press ENTER key to display next column.

ZERO SEQUENCE:  
Y Bus matrix is as follows :

COLUMN 7 :

$Y_{bus}[ 1, 7] = -0.4769 + j \quad 1.2485$   
 $Y_{bus}[ 2, 7] = 0.0000 + j \quad 0.0000$   
 $Y_{bus}[ 3, 7] = 0.0000 + j \quad 0.0000$   
 $Y_{bus}[ 4, 7] = -0.4504 + j \quad 1.2208$   
 $Y_{bus}[ 5, 7] = 0.0000 + j \quad 0.0000$   
 $Y_{bus}[ 6, 7] = -0.4660 + j \quad 1.3041$   
 $Y_{bus}[ 7, 7] = -1.3933 + j \quad -3.6884$

Y-bus :

	1	2	3	4	5	6	7	8	9	10
1	*	*				*	*			
2	*	*				*				
3			*	*	*					
4			*	*			*			
5			*		*	*				
6	*	*			*	*	*			
7	*			*		*	*			
8										
9										
10										

Z-bus :

	1	2	3	4	5	6	7	8	9	10
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Press ENTER key to continue



EXPERIMENT FOUR 7 BUS SYSTEM EXPANDED TO A 12 BUS SYSTEM
---

C:\AUBURN>NET

Select 1 to build the Ybus.

Enter 12 buses, No Names.

Keep the reference the same.

Choose "A" as only Ybus matrix required.

Choose "P" for positive sequence.

Choose "F" to input DATA from an "EXISTING DATA FILE" (namely GAR4B.DAT) from EXPERIMENT THREE PART ONE".

Choose "I" as original data was "IMPEDANCE".

Enter: GAR4B.DAT (no extensions), therefore enter GAR4B.

You are then prompted as to whether you want to edit any BRANCH DATA., Choose "Y".

Do you want to change any BRANCH DATA value or Eliminate any branches,?

Enter "Y"

The screen shows:-

- COMMENTS :
1. The existing file --- GAR4B.DAT, contains the branch data, the number of branches and buses for the given network;
  2. Notation [GAR4B.DAT] = [GAR4B];
  3. All of input (R,X,G & B) are in P.U. and formated as F10.4
  4. If you want to eliminate a branch, enter 0 for both R & X

As we do not want to edit the existing data nor eliminate any branches, Choose "N".

Kindly note that this existing 7 bus power system already contains 30 branches.

The screen now prompts:-

Do you want to ADD any new branch(es) ? (Y/N)

Choose "Y".

Refer to Figure 8. As we wish to expand the 7 bus system to 12 buses, we will be increasing the number of branches by 5, namely:-

```

ADDITIONAL BRANCH BETWEEN NODE 5 AND 8
"      "      "      "      8      "      9
"      "      "      "      8      "      12
"      "      "      "      9      "      10
"      "      "      "      10     "      11

```

Enter these additional branches using the values provided in LINE/TRANSFORMER DATA (pu) IN EXPERIMENT THREE.

NB! The program only prompts for "R" and "X" for these additional branches. It does not prompt for Yc/2 nor does it prompt for TRANSFORMER DATA. It is thus not possible to add to a new branch which is a transformer, and when adding a new line as a branch the program does not prompt for 1/2 charging susceptances.

The program now confirms that there are 12 buses.

Choose a new name other than the original name:

Choose "GAR7"

This 12 bus data will thus be stored under:-

"GAR7B.DAT"

Give a name for the new Ybus:-

Choose "WARRY"

Proceed to display results:-

```

          POSITIVE SEQUENCE:
Y Bus matrix is as follows :
          *
          *
          Y - BUS :
          COLUMN 1 :
Ybus[ 1, 1] = 4.7972 + j -12.6942
Ybus[ 2, 1] = -0.8170 + j 3.2680 *
Ybus[ 3, 1] = 0.0000 + j 0.0000 *
Ybus[ 4, 1] = 0.0000 + j 0.0000
Ybus[ 5, 1] = 0.0000 + j 0.0000
Ybus[ 6, 1] = -2.2364 + j 5.9105
Ybus[ 7, 1] = -1.7438 + j 3.5997
Ybus[ 8, 1] = 0.0000 + j 0.0000
Ybus[ 9, 1] = 0.0000 + j 0.0000
Ybus[10, 1] = 0.0000 + j 0.0000
Ybus[11, 1] = 0.0000 + j 0.0000
Ybus[12, 1] = 0.0000 + j 0.0000

```



Press ENTER key to display next column.

POSITIVE SEQUENCE:			Y - BUS :
Y Bus matrix is as follows :			**
			**
COLUMN 2 :			
Ybus[ 1, 2] =	-0.8170 + j	3.2680	
Ybus[ 2, 2] =	3.9172 + j	-11.2920	**
Ybus[ 3, 2] =	0.0000 + j	0.0000	*
Ybus[ 4, 2] =	0.0000 + j	0.0000	
Ybus[ 5, 2] =	0.0000 + j	0.0000	
Ybus[ 6, 2] =	-3.1002 + j	8.0680	
Ybus[ 7, 2] =	0.0000 + j	0.0000	
Ybus[ 8, 2] =	0.0000 + j	0.0000	
Ybus[ 9, 2] =	0.0000 + j	0.0000	
Ybus[10, 2] =	0.0000 + j	0.0000	
Ybus[11, 2] =	0.0000 + j	0.0000	
Ybus[12, 2] =	0.0000 + j	0.0000	

Press ENTER key to display next column.

POSITIVE SEQUENCE:			Y - BUS :
Y Bus matrix is as follows :			**
			**
COLUMN 3 :			*
			*
			*
Ybus[ 1, 3] =	0.0000 + j	0.0000	
Ybus[ 2, 3] =	0.0000 + j	0.0000	**
Ybus[ 3, 3] =	1.2135 + j	-26.5068	*
Ybus[ 4, 3] =	-0.3235 + j	17.1466	
Ybus[ 5, 3] =	-0.8576 + j	7.7795	
Ybus[ 6, 3] =	0.0000 + j	0.0000	
Ybus[ 7, 3] =	0.0000 + j	0.0000	
Ybus[ 8, 3] =	0.0000 + j	0.0000	
Ybus[ 9, 3] =	0.0000 + j	0.0000	
Ybus[10, 3] =	0.0000 + j	0.0000	
Ybus[11, 3] =	0.0000 + j	0.0000	
Ybus[12, 3] =	0.0000 + j	0.0000	

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
                                Y - BUS :
                                **
                                **
                                **
                                **
                                *
                                **
                                * *
                                *

Ybus[ 1, 4] = 0.0000 + j 0.0000
Ybus[ 2, 4] = 0.0000 + j 0.0000
Ybus[ 3, 4] = -0.3235 + j 17.1466
Ybus[ 4, 4] = 1.6580 + j -19.1523
Ybus[ 5, 4] = 0.0000 + j 0.0000
Ybus[ 6, 4] = 0.0000 + j 0.0000
Ybus[ 7, 4] = -1.3639 + j 3.5785
Ybus[ 8, 4] = 0.0000 + j 0.0000
Ybus[ 9, 4] = 0.0000 + j 0.0000
Ybus[10, 4] = 0.0000 + j 0.0000
Ybus[11, 4] = 0.0000 + j 0.0000
Ybus[12, 4] = 0.0000 + j 0.0000

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
                                Y - BUS :
                                **
                                **
                                ***
                                **
                                * *
                                ** *
                                * *
                                *

Ybus[ 1, 5] = 0.0000 + j 0.0000
Ybus[ 2, 5] = 0.0000 + j 0.0000
Ybus[ 3, 5] = -0.8576 + j 7.7795
Ybus[ 4, 5] = 0.0000 + j 0.0000
Ybus[ 5, 5] = 12.2357 + j -145.0601
Ybus[ 6, 5] = -1.3428 + j 34.9134
Ybus[ 7, 5] = 0.0000 + j 0.0000
Ybus[ 8, 5] = -9.9010 + j 99.0099
Ybus[ 9, 5] = 0.0000 + j 0.0000
Ybus[10, 5] = 0.0000 + j 0.0000
Ybus[11, 5] = 0.0000 + j 0.0000
Ybus[12, 5] = 0.0000 + j 0.0000

```

Press ENTER key to display next column.

POSITIVE SEQUENCE:  
Y Bus matrix is as follows :

COLUMN 6 :

Ybus[ 1, 6]	=	-2.2364 + j	5.9105
Ybus[ 2, 6]	=	-3.1002 + j	8.0680
Ybus[ 3, 6]	=	0.0000 + j	0.0000
Ybus[ 4, 6]	=	0.0000 + j	0.0000
Ybus[ 5, 6]	=	-1.3428 + j	34.9134
Ybus[ 6, 6]	=	7.9680 + j	-49.3683
Ybus[ 7, 6]	=	-1.4107 + j	3.6993
Ybus[ 8, 6]	=	0.0000 + j	0.0000
Ybus[ 9, 6]	=	0.0000 + j	0.0000
Ybus[10, 6]	=	0.0000 + j	0.0000
Ybus[11, 6]	=	0.0000 + j	0.0000
Ybus[12, 6]	=	0.0000 + j	0.0000

Y - BUS :  
\*\* \*  
\*\* \*  
\*\*\*  
\*\*  
\* \*\*  
\*\* \*\*  
\* \* \*  
\*

Press ENTER key to display next column.

POSITIVE SEQUENCE:  
Y Bus matrix is as follows :

COLUMN 7 :

Ybus[ 1, 7]	=	-1.7438 + j	3.5997
Ybus[ 2, 7]	=	0.0000 + j	0.0000
Ybus[ 3, 7]	=	0.0000 + j	0.0000
Ybus[ 4, 7]	=	-1.3639 + j	3.5785
Ybus[ 5, 7]	=	0.0000 + j	0.0000
Ybus[ 6, 7]	=	-1.4107 + j	3.6993
Ybus[ 7, 7]	=	4.5184 + j	-10.7925
Ybus[ 8, 7]	=	0.0000 + j	0.0000
Ybus[ 9, 7]	=	0.0000 + j	0.0000
Ybus[10, 7]	=	0.0000 + j	0.0000
Ybus[11, 7]	=	0.0000 + j	0.0000
Ybus[12, 7]	=	0.0000 + j	0.0000

Y - BUS :  
\*\* \*\*  
\*\* \*  
\*\*\*  
\*\* \*  
\* \*\*  
\*\* \*\*\*  
\* \* \*\*  
\*

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :

    COLUMN 8 :

Ybus[ 1, 8] = 0.0000 + j 0.0000
Ybus[ 2, 8] = 0.0000 + j 0.0000
Ybus[ 3, 8] = 0.0000 + j 0.0000
Ybus[ 4, 8] = 0.0000 + j 0.0000
Ybus[ 5, 8] = -9.9010 + j 99.0099
Ybus[ 6, 8] = 0.0000 + j 0.0000
Ybus[ 7, 8] = 0.0000 + j 0.0000
Ybus[ 8, 8] = 13.3374 + j -107.0873
Ybus[ 9, 8] = -1.7241 + j 4.3103
Ybus[10, 8] = 0.0000 + j 0.0000
Ybus[11, 8] = 0.0000 + j 0.0000
Ybus[12, 8] = -1.7123 + j 3.7671

                                Y - BUS :
**      **
**      *
***
**      *
* ** *
**     ***
*  * **
      *  *
              *
              *
              *

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :

    COLUMN 9 :

Ybus[ 1, 9] = 0.0000 + j 0.0000
Ybus[ 2, 9] = 0.0000 + j 0.0000
Ybus[ 3, 9] = 0.0000 + j 0.0000
Ybus[ 4, 9] = 0.0000 + j 0.0000
Ybus[ 5, 9] = 0.0000 + j 0.0000
Ybus[ 6, 9] = 0.0000 + j 0.0000
Ybus[ 7, 9] = 0.0000 + j 0.0000
Ybus[ 8, 9] = -1.7241 + j 4.3103
Ybus[ 9, 9] = 3.4482 + j -8.3333
Ybus[10, 9] = -1.7241 + j 4.0230
Ybus[11, 9] = 0.0000 + j 0.0000
Ybus[12, 9] = 0.0000 + j 0.0000

                                Y - BUS :
**      **
**      *
***
**      *
* ** *
**     ***
*  * **
      * **
              **
              *
              *

```

Press ENTER key to display next column.

```
POSITIVE SEQUENCE:
Y Bus matrix is as follows :

COLUMN 10:

Ybus[ 1,10] = 0.0000 + j 0.0000
Ybus[ 2,10] = 0.0000 + j 0.0000
Ybus[ 3,10] = 0.0000 + j 0.0000
Ybus[ 4,10] = 0.0000 + j 0.0000
Ybus[ 5,10] = 0.0000 + j 0.0000
Ybus[ 6,10] = 0.0000 + j 0.0000
Ybus[ 7,10] = 0.0000 + j 0.0000
Ybus[ 8,10] = 0.0000 + j 0.0000
Ybus[ 9,10] = -1.7241 + j 4.0230
Ybus[10,10] = 3.2846 + j -7.2740
Ybus[11,10] = -1.5605 + j 3.2510
Ybus[12,10] = 0.0000 + j 0.0000
```

Y - BUS :

```
** **
** *
***
** *
* ** *
** ***
* * **
* **
***
**
*
*
```

Press ENTER key to display next column.

```
POSITIVE SEQUENCE:
Y Bus matrix is as follows :

COLUMN 11:

Ybus[ 1,11] = 0.0000 + j 0.0000
Ybus[ 2,11] = 0.0000 + j 0.0000
Ybus[ 3,11] = 0.0000 + j 0.0000
Ybus[ 4,11] = 0.0000 + j 0.0000
Ybus[ 5,11] = 0.0000 + j 0.0000
Ybus[ 6,11] = 0.0000 + j 0.0000
Ybus[ 7,11] = 0.0000 + j 0.0000
Ybus[ 8,11] = 0.0000 + j 0.0000
Ybus[ 9,11] = 0.0000 + j 0.0000
Ybus[10,11] = -1.5605 + j 3.2510
Ybus[11,11] = 1.5605 + j -3.2510
Ybus[12,11] = 0.0000 + j 0.0000
```

Y - BUS :

```
** **
** *
***
** *
* ** *
** ***
* * **
* **
***
***
**
*
```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :

    COLUMN 12:

Ybus[ 1,12] = 0.0000 + j 0.0000
Ybus[ 2,12] = 0.0000 + j 0.0000
Ybus[ 3,12] = 0.0000 + j 0.0000
Ybus[ 4,12] = 0.0000 + j 0.0000
Ybus[ 5,12] = 0.0000 + j 0.0000
Ybus[ 6,12] = 0.0000 + j 0.0000
Ybus[ 7,12] = 0.0000 + j 0.0000
Ybus[ 8,12] = -1.7123 + j 3.7671
Ybus[ 9,12] = 0.0000 + j 0.0000
Ybus[10,12] = 0.0000 + j 0.0000
Ybus[11,12] = 0.0000 + j 0.0000
Ybus[12,12] = 1.7123 + j -3.7671

```

```

      Y - BUS :
**  **
**  *
***
**  *
* ** *
** ***
* * **
      * ** *
          ***
              ***
                  **
                      *  *

```

Press ENTER key to display next column.

Ybus matrix is stored under the name,  
WARRY.BUS

Press ENTER key to get the last page !

```

      Y - BUS :
**  **
**  *
***
**  *
* ** *
** ***
* * **
      * ** *
          ***
              ***
                  **
                      *  *

```

Exit to "DOS".

NB! For certain repeated studies, elimination of some of the buses results in a reduced simplified system. Such a reduced matrix is called Yeq and its inverse is called Zeq.

b. EXPERIMENTATION USING GUNGOR PROGRAMS-ZYBUSB/ZBUSB

EXPERIMENT FIVE  
3 BUS POWER SYSTEM

INFORMATION AVAILABLE :

A one-line diagram of a 3 bus system is shown in FIGURE 9.

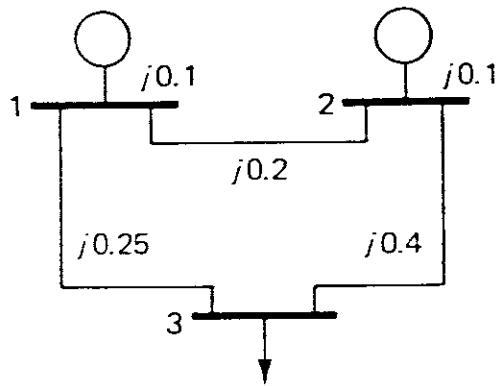


FIGURE 9

The power system contains no transformers and no line susceptances. The generator have reactances of  $j0.1$  and lines have reatances of  $j0.2$  (1 to 2),  $j 0.25$  (1 to 3) and  $j 0.4$  (2 to 3)

PART ONE - ZYBUS

C:\GUNGOR>ZYBUS

The screen shows:

Choose P = 0

The program prompts for:-

No. of BUSES = ? Press 3

No. of LINES = ? Press 3

No. of EQ.BUSES ( = NB for NO REDUCTION) = ? Press 3

NB ! With this experiment we do not wish to reduce the network therefore the number of equivalent buses = number of buses "NB". As EQ.BUSES = NB the results will not include  $Y_{eq}$  nor  $Z_{eq}$ .

ENTER LINE DATA AS : NS, NR, R, XL, BC

LINE 1

? 1, 2, 0, .2, - 10

LINE 2

? 1, 3, 0, .25, 0

LINE 3

? 2, 3, 0, .4, 0

NB! This program does not provide for entering Generator Impedances. Therefore these impedances entered as  $1/2$  charging susceptances. Therefore  $j0.1 = -j10$  and is entered as BC = -10 under LINE DATA. (See above).

To run program press "ENTER" and the following results are obtained:



YBUS		
Y( 1, 1)=	0.0000	-19.0000
Y( 1, 2)=	0.0000	5.0000
Y( 1, 3)=	0.0000	4.0000
Y( 2, 1)=	0.0000	5.0000
Y( 2, 2)=	0.0000	-17.5000
Y( 2, 3)=	0.0000	2.5000
Y( 3, 1)=	0.0000	4.0000
Y( 3, 2)=	0.0000	2.5000
Y( 3, 3)=	0.0000	-6.5000

As this program is able to invert the Ybus into a Zbus, Choose "y" to run program and to obtain its results:

ZBUS		
Z( 1, 1)=	0.0000	0.0717
Z( 1, 2)=	0.0000	0.0283
Z( 1, 3)=	0.0000	0.0550
Z( 2, 1)=	0.0000	0.0283
Z( 2, 2)=	0.0000	0.0717
Z( 2, 3)=	0.0000	0.0450
Z( 3, 1)=	0.0000	0.0550
Z( 3, 2)=	0.0000	0.0450
Z( 3, 3)=	0.0000	0.2050

PART TWO - ZBUS

We wish now to form the Zbus of PART ONE directly.

C:\GUNGOR>ZBUSB.

The screen shows:

PRINT OPTION:	P=0	FOR SCREEN OUTPUT ONLY
	P=1	FOR SCREEN & PRINTER OUTPUT
	P=2	FOR SCREEN & DISK OUTPUT (ZBUSB.OUT)

Choose P = 0

ENTER:-

NO.OF BUSES = 3  
NO. OF LINES = 3  
NO. OF GEN = 2

ENTER GENERATOR DATA AS : RG, XG

GENERATOR 1  
? 0, .1

GENERATOR 2  
? 0, .1

ENTER LINE DATA AS : NS, NR, R, XL

LINE 1  
? 1, 2, 0, .2

LINE 2  
? 1, 3, 0, .25

LINE 3  
? 2, 3, 0, .4

Press enter to obtain results:

ZBUS		
Z( 1, 1)=	0.0000	0.0717
Z( 1, 2)=	0.0000	0.0283
Z( 1, 3)=	0.0000	0.0550
Z( 2, 1)=	0.0000	0.0283
Z( 2, 2)=	0.0000	0.0717
Z( 2, 3)=	0.0000	0.0450
Z( 3, 1)=	0.0000	0.0550
Z( 3, 2)=	0.0000	0.0450
Z( 3, 3)=	0.0000	0.2050

It can be seen that the results are the same as was obtained in PART ONE except in this case they were formed directly.

EXPERIMENT SIX  
REDUCTION OF A  
5 BUS SYSTEM TO A  
SIMPLIFIED 3 BUS SYSTEM

INFORMATION AVAILABLE:

A one-line diagram of a 5 bus system is shown in FIGURE 10

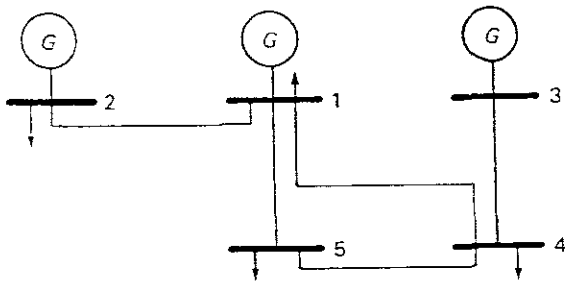


FIGURE 10

Line Data(pu)

Bus Code	Impedance	1/2 Charging Susceptance	Rating MVA
1-2	$0.030 + j0.103$	$j0.05$	60
1-4	$0.105 + j0.347$	$j0.01$	10
1-5	$0.080 + j0.262$	$j0.02$	20
3-4	$0.106 + j0.403$	$j0.01$	50
4-5	$0.033 + j0.118$	$j0.05$	15

The system contains no transformers but includes 1/2 charging susceptances. The generators have no impedances.

PART ONE - ZYBUSB

Run the program to reduce the above 5 bus system to a simplified 3 bus system and obtain  $Y_{eq}$  for this 3 bus system.

C:\GUNGOR>ZYBUSB

Choose P = 0

Enter the input data:

NO. OF BUSES	=	5
NO. OF LINES	=	5
NO. OF EQ.BUSES	=	3

LINE DATA				
NS	NR	R	XL	BC
1	2	.03	.103	.05
1	4	.105	.347	.01
1	5	.08	.262	.02
3	4	.105	.403	.01
4	5	.033	.118	.05

Run the program by pressing "ENTER"

YBUS		
Y( 1, 1)=	4.4716	-15.0009
Y( 1, 2)=	-2.6067	8.9495
Y( 1, 3)=	0.0000	0.0000
Y( 1, 4)=	-0.7989	2.6401
Y( 1, 5)=	-1.0660	3.4913
Y( 2, 1)=	-2.6067	8.9495
Y( 2, 2)=	2.6067	-8.8995
Y( 2, 3)=	0.0000	0.0000
Y( 2, 4)=	0.0000	0.0000
Y( 2, 5)=	0.0000	0.0000
Y( 3, 1)=	0.0000	0.0000
Y( 3, 2)=	0.0000	0.0000
Y( 3, 3)=	0.6054	-2.3137
Y( 3, 4)=	-0.6054	2.3237
Y( 3, 5)=	0.0000	0.0000
Y( 4, 1)=	-0.7989	2.6401
Y( 4, 2)=	0.0000	0.0000
Y( 4, 3)=	-0.6054	2.3237
Y( 4, 4)=	3.6024	-12.7536
Y( 4, 5)=	-2.1981	7.8599
Y( 5, 1)=	-1.0660	3.4913
Y( 5, 2)=	0.0000	0.0000
Y( 5, 3)=	0.0000	0.0000
Y( 5, 4)=	-2.1981	7.8599
Y( 5, 5)=	3.2641	-11.2811

The above is the Ybus matrix for a 5 bus system.

The program prompts:

"DO YOU WANT ZBUS"

Choose "N" and Yeq results are obtained:-

YEQ		
Y( 1, 1)=	3.0400	-10.3849
Y( 1, 2)=	-2.6066	8.9495
Y( 1, 3)=	-0.4339	1.6200
Y( 2, 1)=	-2.6066	8.9495
Y( 2, 2)=	2.6066	-8.8995
Y( 2, 3)=	0.0000	-0.0000
Y( 3, 1)=	-0.4339	1.6200
Y( 3, 2)=	0.0000	-0.0000
Y( 3, 3)=	0.4351	-1.5724

**SECTION D  
SIMULATED INDUSTRIAL APPLICATION**

**EXPERIMENT SEVEN  
5 BUS SYSTEM**

**INFORMATION AVAILABLE:**

A one-line diagram of the 5 bus system is shown in FIGURE 11.

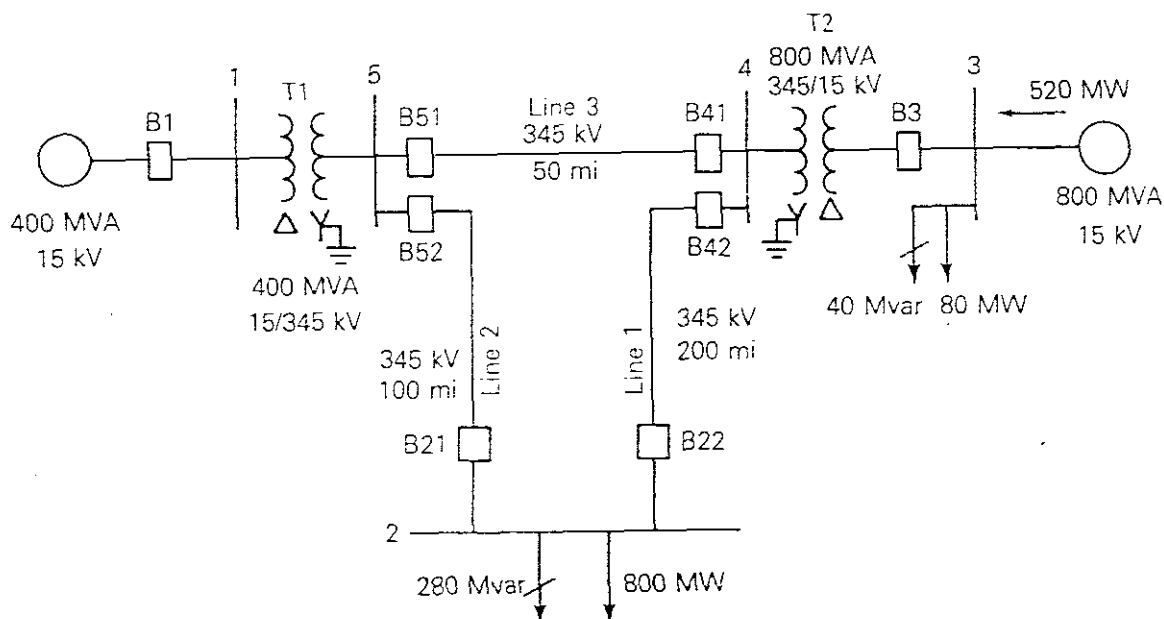


FIGURE 11

The following tables of DATA are supplied:

**A. BUS DATA:**

BUS	TYPE	V	$\delta$	PG	QG	PL	QL	QGmax	QGmin
		per unit	degrees	per unit	per unit	per unit	per unit	per unit	per unit
1	Swing	1.0	0	-	-	0	0	-	-
2	Load	-	-	0	0	2.0	0.7	-	-
3	Constant voltage	1.05	-	1.3	-	0.2	0.1	1.0	-0.7
4	Load	-	-	0	0	0	0	-	-
5	Load	-	-	0	0	0	0	-	-

Sbase = 400 MVA, Vbase = 15 kV at buses 1, 3 and 345 kV at buses 2, 4 and 5.

**B. LINE DATA:**

BUS-BUS	R'	X'	G'	B'	MAXIMUM MVA
	per unit	per unit	per unit	per unit	per unit
2-4	0.036	0.4	0	0.43	3.0
2-5	0.018	0.2	0	0.22	3.0
4-5	0.009	0.1	0	0.11	3.0

**C. TRANSFORMER DATA:**

BUS-BUS	R	X	Gc	Bm	MAXIMUM MVA
	per unit	per unit	per unit	per unit	per unit
1-5	0.006	0.08	0	0	1.5
3-4	0.003	0.04	0	0	2.5

**D. LOAD FLOW DATA:**

BUS	INPUT DATA	UNKNOWNNS
1	V1 = 1.0, $\delta_1 = 0$	P1, Q1
2	P2 = PG2 - PL2 = -2 Q2 = QG2 - QL2 = -0.7	V2, $\delta_2$
3	V3 = 1.05 P3 = PG3 - PL3 = 1.1	Q3, $\delta_3$
4	P4 = 0, Q4 = 0	V4, $\delta_4$
5	P5 = 0, Q5 = 0	V5, $\delta_5$

NB! Bus 1 is a swing bus, Bus 3 to which a generator and a load are connected is a voltage controlled bus. Buses 2,4 and 5 are load buses.

NB! The 5 bus power system includes transformers and  $\frac{1}{2}$  charging susceptances.

**EXPERIMENTAL REQUIREMENTS:**

- a. Compute the elements of the second row of the Positive Sequence Ybus.
- b. Compute the elements of the fifth row of the Positive Sequence Zbus.

EXPERIMENTAL STEPS

C:\AUBURN>NET  
Choose 1 to build Ybus/Zbus.  
Enter 5 buses, No Names.  
Keep reference the same at zero.  
Choose "B" for both Y/Z matrices.  
Choose "P" for positive sequence matrices.  
Choose "IY".  
Choose "K" for keyboard entry.  
Enter Line Data as impedances (pu):

Enter to read:-  
From node 2 to node 4  
R = 0.036  
X = 0.4  
YC = 0.43 = 0.215  
— ———  
2 2

Enter:  
From node 2 to node 5  
R = 0.018  
X = 0.2  
YC = 0.22 = 0.11  
— ———  
2 2

Enter:  
From node 4 to node 5  
R = 0.009  
X = 0.1  
YC = 0.11 = 0.055  
— ———  
2 2

Press 6 to end entering LINE DATA and to proceed to TRANSFORMER DATA.

Choose "Y" as there are two transformers.

Enter: (For T1)  
From node 1 to node 5  
R = 0.006  
X = 0.08  
TAP = 1 (assume as no tap setting given)

Enter: (For T2)  
From node 3 to node 4  
R = 0.003  
X = 0.04  
TAP = 1 (assume as no tap setting given)

Press 6 to end entering TRANSFORMER DATA and to proceed to BRANCH DATA.



As there is no BRANCH DATA choose "N".

Store this data under "GAR5" (namely GAR5B.DAT).

Let names for buses be:-

Ybus = NARRY

Zbus = ZARRY

Follow steps to display results:

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
                                *
                                Y - BUS :

    COLUMN 1 :

Ybus[ 1, 1] = 0.9323 + j   -12.4301   *
Ybus[ 2, 1] = 0.0000 + j    0.0000
Ybus[ 3, 1] = 0.0000 + j    0.0000
Ybus[ 4, 1] = 0.0000 + j    0.0000
Ybus[ 5, 1] = -0.9323 + j   12.4301

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
                                *
                                Y - BUS :
                                *
                                *
                                *
                                * *

    COLUMN 2 :

Ybus[ 1, 2] = 0.0000 + j    0.0000   * *
Ybus[ 2, 2] = 0.6696 + j   -7.1147
Ybus[ 3, 2] = 0.0000 + j    0.0000
Ybus[ 4, 2] = -0.2232 + j   2.4799
Ybus[ 5, 2] = -0.4464 + j   4.9598

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
                                *
                                Y - BUS :
                                *
                                *
                                * *
                                * *

    COLUMN 3 :

Ybus[ 1, 3] = 0.0000 + j    0.0000   * *
Ybus[ 2, 3] = 0.0000 + j    0.0000
Ybus[ 3, 3] = 1.8645 + j   -24.8602
Ybus[ 4, 3] = -1.8645 + j   24.8602
Ybus[ 5, 3] = 0.0000 + j    0.0000

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
    COLUMN 4 :
Ybus[ 1, 4] = 0.0000 + j      0.0000
Ybus[ 2, 4] = -0.2232 + j    2.4799
Ybus[ 3, 4] = -1.8645 + j    24.8602
Ybus[ 4, 4] = 2.9805 + j    -36.9898
Ybus[ 5, 4] = -0.8928 + j    9.9197
    Y - BUS :
*
* *
* *
* * *
* * *
```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Y Bus matrix is as follows :
    COLUMN 5 :
Ybus[ 1, 5] = -0.9323 + j    12.4301
Ybus[ 2, 5] = -0.4464 + j    4.9598
Ybus[ 3, 5] = 0.0000 + j     0.0000
Ybus[ 4, 5] = -0.8928 + j    9.9197
Ybus[ 5, 5] = 2.2715 + j   -27.1446
    Y - BUS :
*
* * *
* *
* * * *
* * * *
```

Press ENTER key to display Zbus matrix

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows :
    COLUMN 1 :
Zbus[ 1, 1] = 0.0102 + j    -1.1896
Zbus[ 2, 1] = -0.0024 + j   -1.3420
Zbus[ 3, 1] = 0.0003 + j    -1.3124
Zbus[ 4, 1] = 0.0003 + j    -1.3124
Zbus[ 5, 1] = 0.0042 + j    -1.2696
    Z - BUS :
*
*
*
*
*
```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows :
    COLUMN 2 :
Zbus[ 1, 2] = -0.0024 + j    -1.3420
Zbus[ 2, 2] =  0.0044 + j    -1.2685
Zbus[ 3, 2] = -0.0038 + j    -1.3566
Zbus[ 4, 2] = -0.0038 + j    -1.3566
Zbus[ 5, 2] = -0.0024 + j    -1.3420
    Z - BUS :
    * *
    * *
    * *
    * *
    * *

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows :
    COLUMN 3 :
Zbus[ 1, 3] =  0.0003 + j    -1.3124
Zbus[ 2, 3] = -0.0038 + j    -1.3566
Zbus[ 3, 3] =  0.0073 + j    -1.2287
Zbus[ 4, 3] =  0.0043 + j    -1.2687
Zbus[ 5, 3] =  0.0003 + j    -1.3124
    Z - BUS :
    * * *
    * * *
    * * *
    * * *
    * * *

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows :
    COLUMN 4 :
Zbus[ 1, 4] =  0.0003 + j    -1.3124
Zbus[ 2, 4] = -0.0038 + j    -1.3566
Zbus[ 3, 4] =  0.0043 + j    -1.2687
Zbus[ 4, 4] =  0.0043 + j    -1.2687
Zbus[ 5, 4] =  0.0003 + j    -1.3124
    Z - BUS :
    * * * *
    * * * *
    * * * *
    * * * *
    * * * *

```

Press ENTER key to display next column.

```

    POSITIVE SEQUENCE:
Z Bus matrix is as follows :
    COLUMN 5 :
Zbus[ 1, 5] =  0.0042 + j    -1.2696
Zbus[ 2, 5] = -0.0024 + j    -1.3420
Zbus[ 3, 5] =  0.0003 + j    -1.3124
Zbus[ 4, 5] =  0.0003 + j    -1.3124
Zbus[ 5, 5] =  0.0042 + j    -1.2696
    Z - BUS :
    * * * * *
    * * * * *
    * * * * *
    * * * * *
    * * * * *

```

Press ENTER key to continue.

Zbus matrix is stored under the name, ZARRY.BUS

Ybus matrix is stored under the name, NARRY.BUS

SUMMARY:

There are totally 3 line(s), 2 transformer(s)

and no branch(es) in the network.

Press ENTER key to get the last page!

EXPERIMENTAL RESULTS

a.	Y21	=	0.0000 + j 0.0000
	Y22	=	0.6696 - j 7.1147
	Y23	=	0.0000 + j 0.0000
	Y24	=	-0.2232 + j 2.4799
	Y25	=	-0.4464 + j 4.9598

b.	Z51	=	0.0042 - j 1.2696
	Z52	=	-0.0024 - j 1.3420
	Z53	=	0.0003 - j 1.3124
	Z54	=	0.0003 - j 1.3124
	Z55	=	0.0042 - j 1.2696

SECTION E  
SELF EXPERIMENTATION ON A SIMULATED INDUSTRIAL  
APPLICATION

EXPERIMENT EIGHT  
3 BUS POWER SYSTEM

INFORMATION AVAILABLE:

A one-line diagram of a 3 Bus power system is shown in FIGURE 12.

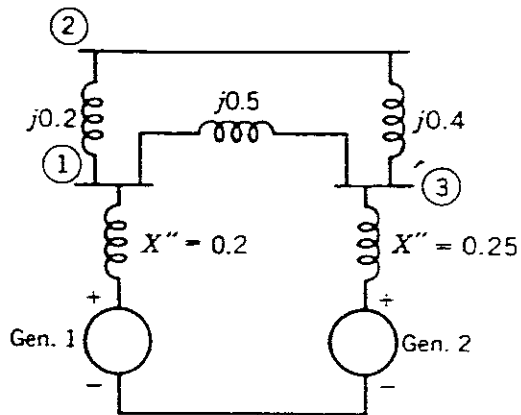


FIGURE 12

Both generators are Y-connected. Transformers are at the ends of each transmission line in the system and are Y-Y with grounded neutrals except that the transformers connecting the lines to bus 3 are Y-delta with the neutral of the Y solidly grounded. The delta sides of the Y-delta transformers are connected to bus 3. All line reactances shown in Figure 12 between buses include the reactances of the transformers. Zero-sequence reactance values for these lines including transformers are 2.0 times those shown in Figure 12. Zero-sequence reactances of generators connected to buses 1 and 3 are 0.04 and 0.08 per unit, respectively. The neutral of the generator at bus 1 is connected to ground through a reactor of 0.02 per unit, and the neutral of the generator at bus 3 is not connected to ground.

**EXPERIMENTAL REQUIREMENTS:**

- a. Compute the Zero-Sequence Zbus for FIGURE 12. (NB! Bus 3 is not included, Store Data = Gar9, Ybus = XARRY and Zbus = WARRY).
- b Compute the elements Z12, Z21 and Z23 for the Positive-Sequence Zbus. (NB! Bus 3 is included)

**EXPERIMENTAL RESULTS**

$$\text{a. Zbus } -0 = \begin{vmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{vmatrix} = \begin{vmatrix} j0.0845 & j0.0563 \\ j0.0563 & j0.3042 \end{vmatrix}$$

$$\text{b. Zbus } -1 = \begin{vmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{32} \\ Z_{31} & Z_{32} & Z_{33} \end{vmatrix} = \begin{vmatrix} j0.145 & j0.119 & j0.069 \\ j0.119 & j0.247 & j0.1006 \\ j0.069 & j0.1006 & j0.1635 \end{vmatrix}$$

SECTION F  
COMPARISON OF THE PROGRAMS

COMPARISON TABLE

PACKAGE AUBURN	PACKAGE GUNGOR
<p>1. The package only includes one program - NETWORK MATRICES.</p> <p>2. Builds both Ybus/Zbus for multiport systems.</p> <p>3. Can build both simultaneously or separately.</p> <p>4. Can build Positive and Zero Sequence Ybus and Zbus matrices.</p> <p>5. Results can be displayed.</p> <p>6. Input Data LINE DATA either in Impedance or Admittance. Transformer Data - Tap Setting. BRANCH DATA: Max Buses = 20. Keyboard/ Existing Data File Input. STORING DATA Data can be stored in Data File for recurrent experimentation. UPDATING DATA - No short cut to update data or to extend/decrease an existing power system. One has to proceed through the program step by step from its beginning until prompted for EXISTING DATA FILE input, which can then be used and system updated. OUTPUT DATA A column of a matrix is displayed at a time. Printing of results is achieved by the PRINT SCREEN key only.</p>	<p>1. The package includes among others two programs, ZYBUS and ZBUS.</p> <p>2. ZYBUS a. This program forms Ybus and then inverts it to form Zbus. b. Network reduction is possible and buses can be eliminated resulting in Yeq.</p> <p>3. ZBUS a. This forms the Zbus directly.</p> <p>4. INPUT DATA a. ZYBUS PRINT OPTION. SYSTEM DATA. LINE DATA: The program does not provide for entering generator impedances, these having to be entered as 1/2 charging susceptances.</p> <p>b. ZBUS PRINT OPTION - options other than print screen are available. SYSTEM DATA. LINE DATA: The program allows for generator impedances to be entered which therefore do not need to be treated as 1/2 charging susceptances. The program however does not provide for entering 1/2 susceptances for lines.</p> <p>UPDATING DATA Neither ZYBUS/ZBUS programs provide facilities for updating data. One has to reset before a new run.</p> <p>STORING DATA Neither ZYBUS/ZBUS provide storage nor can input be done from DATA FILES.</p> <p>OUTPUT DATA Results can be displayed in the screen and hard copies can be obtained using the PRINT OPTION.</p>

SECTION G

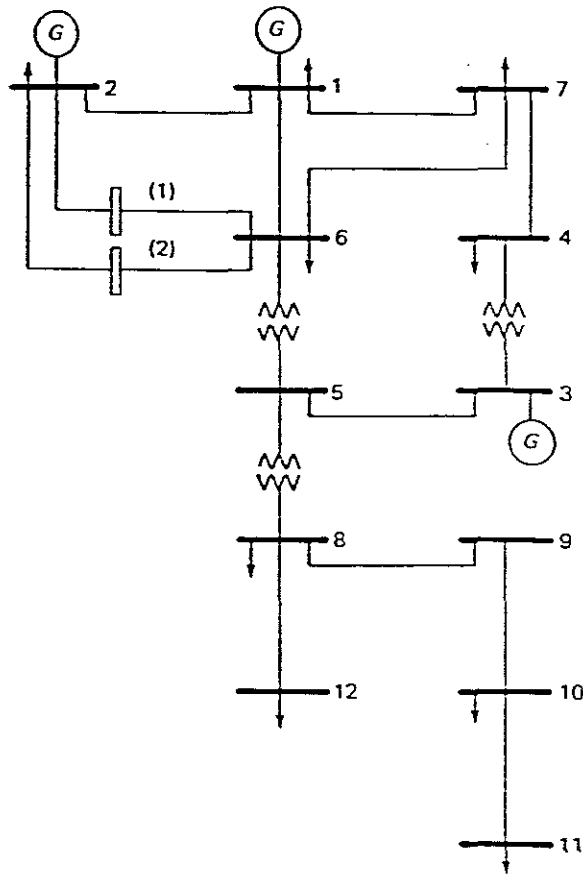
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- b. GUNGOR - POWER SYSTEMS.
- c. GLOVER - POWER SYSTEM ANALYSIS AND DESIGN.
- d. STEVENSON - ELEMENTS OF POWER SYSTEM ANALYSIS.

----- END -----



THE USE OF GUNGOR'S COMPUTER PROGRAMS ACPF1B, ACPF2B  
 AND DCPFB FOR EXPERIMENTATION ON LOAD FLOW  
 ON MULTI-BUS POWER SYSTEMS



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GUNGOR'S PROGRAMS ON LOAD FLOW ON MULTI-BUS POWER SYSTEMS

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        (3) EXPERIMENT A3 - 5 BUS POWER SYSTEM - - - - - 51

    b. PROGRAM ACPF2B:

        (1) EXPERIMENT A4 - 3 BUS POWER SYSTEM - - - - - 54

        (2) EXPERIMENT A5 - 3 BUS POWER SYSTEM - - - - - 62

        (3) EXPERIMENT A6 - 5 BUS POWER SYSTEM - - - - - 65

    c. PROGRAM DCPFB:

        (1) EXPERIMENT A7 - 3 BUS POWER SYSTEM - - - - - 74

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## INTRODUCTION

A load study is the determination of the voltage, current, active and reactive power and power factor at various points in an electric network under existing or contemplated conditions of normal operation. Load studies are essential in planning the future development of a system because satisfactory operation of the system depends on knowing the effects of interconnections with other power systems, of new loads, new generating stations and new transmission lines before they are installed.

Before the development of computers, load flow studies were done by hand. This was time consuming and tedious. Today however computer programs may handle 1500 buses, 2500 lines, 500 transformers with tap changing under load and can include a number of phase shifting transformers. Complete results are printed quickly and economically.

In the operation of power systems any appreciated drop in voltage makes it desirable to change the tap setting on transformers to maintain proper voltage at the load. Voltages usually have to be maintained between 1.05 and 0.95 pu limits.

A list of line loading is also provided as well as electrical losses which are important in economically dispatching generation.

Load flow is the name given to a network solution that shows currents, voltages and power flows at every bus in the system. It is normally assumed that the system is balanced and the common use of the term load flow implies a positive sequence solution only.

Load flow is not a single calculation such as  $E = IR$  or  $E = [Z]I$  involving circuit analysis. In load flow we are given a non-linear relationship between voltage and current at each bus and we must solve for all voltages and currents such that these non-linear relationships are met. The non-linear relationships involve, for example, the real and reactive power consumption at a bus, or the generated real power and scheduled voltage magnitude at a generator bus. As such, the load flow gives us the electrical response to a particular set of loads and generator unit outputs.

In power flow studies the input data for loads is normally given in terms of power. Also generators are considered as power sources, not voltages or current sources. The power flow problem is therefore formulated as a set of non-linear algebraic equations suitable for computer solution.

Because of the non-linearity of the power equations in load flow solutions, the solution is obtained by an iterative method. Gauss-Seidel, iterative solutions was introduced in the late 1950's and found widespread application. Experience with the Gauss-Seidel method of solution usually requires many number of iterations before the voltage corrections are within an acceptable precision index. Multipliers are used to accelerate convergence and are called acceleration factors. For any system however optimum values for acceleration factors exist and a poor choice may result in less rapid convergence or make convergence impossible.

The Newton-Raphson iterative technique was introduced to overcome the slowness of the Gauss-Seidel method.

The power flow problem is a solution of non-linear equations containing knowns and unknowns. These are given in the following table:

BUS TYPE	KNOWNS	UNKNOWNNS
Swing (Slack) generator	$V, \delta = 0$	$P, Q$
Voltage controlled (generator) bus	$P, V$	$Q, \delta$
Load buses	$P, Q$	$V, \delta$

TABLE.1

SWING BUS - Usually numbered bus 1 and is the reference bus for which  $V/\delta = 1/0^\circ$  pu. The power flow program computes  $P_1$  and  $Q_1$ . A generator station is assigned to take up the slack in the system, that is, to supply in addition to its own share, the system transmission losses. Hence it is called the swing (slack) generator. The voltage becomes the reference point for other voltages of the system. The unknowns at the swing bus are the real and reactive generations.

VOLTAGE CONTROLLED BUS - At the generator (voltage controlled) buses, the real power outputs of the generator and the voltage magnitudes are specified, since voltage regulators keep the terminal voltage constant and the output powers are regulated by their prime movers. Thus the reactive generation and voltage angle become the unknowns. Examples of these types of buses are buses to which generators, switched shunt capacitors, or static var systems are connected. Another example is a bus to which a tap changing transformer is connected. The power flow program then computes the tap setting.

From a power flow standpoint, the addition of a shunt capacitor bank to a load bus corresponds to the addition of a negative reactive load since a capacitor absorbs negative reactive power increasing bus voltage. Likewise the addition of a shunt reactor corresponds to the addition of a positive reactive load decreasing the voltage magnitude of a load bus. Tap changing and voltage regulating transformers are used to control bus voltages as well as reactive power flows on lines to which they are connected. Similarly, phase-angle regularity transformers are used to control bus angles as well as real power flows on lines to which they are connected.

Another important feature of load flow analysis is to determine pre-fault voltages which exist due to the load flow. These pre-fault voltages at specific buses are available for short circuit calculations as part of fault studies.

The power flow program can thus be used to investigate the effect of switching in or out lines, transformers, loads and generators. Proposed future changes to meet future load growth by adding new lines, transformers and generators can be investigated. Engineering judgement can then be made until the desired loading and voltage profiles are obtained.

LOAD BUS - At load buses, the real and reactive powers of loads are specified, thus the unknowns are the voltages. Most buses in a typical power flow program are load buses.

Successful power system generation requires the following:

1. Generation supplies the demand (load) plus losses.
2. Bus voltages magnitudes remain close to the rated values.
3. Generators operate within specified real and reactive power limits.
4. Transmission lines and transformers are not overloaded.

SECTION A

1. EXPLANATION OF THE USAGE OF PACKAGE GUNGOR

a. PROGRAM AC POWER FLOW - GAUSS - SEIDEL (ACPF1B)

This ACPF1B program follows the Gauss-Seidel iterative procedure with Ybus. This program will provide an AC Power Flow solution of a power system using Gauss-Seidel iterations with voltage controlled generator buses.

INPUT DATA

Input data for the program consists of :

- (1) Print option (see below for further details)
- (11) System data requesting?
  - Number of Buses = ?
  - Number of Lines = ?
  - Numbers of Generators = ?
  - Base MVA = ?
  - Tolerance (pu) = ?
  - Maximum number of iterations = ?
- (111) Line data and each line is entered under the heading NS, NR, R, XL, Bc ("Commas" important)
  - where NS = Sending end bus number
  - NR = Receiving end bus number
  - R = Resistance (pu)
  - XL = Induction Reactance (pu)
  - Bc = 1/2 Charging Susceptance (pu)
  - If R and Bc = 0 enter "0".

The line data, for example, will thus be:

NS	NR	R	XL	Bc
1	2	0.05	.2	.01
1	3	.1	.5	.02
2	3	.04	.25	.01

- (iv) Bus data and each bus is entered under the heading V, PG, PL, QL ("Commas" important)
  - where V = Bus Voltage (pu). Unknown voltages are entered as "1".
  - PG = Real Power Generation in MW.
  - PL = Load Real Power in MW.
  - QL = Load Reactive Power in MVAR.

NB! Unknown variables, except voltages, are entered as a "0".

The bus data, for example, will be:

V	PG	PL	QL
BUS 1.			
1.02	0	50	10
BUS 2.			
1	60	0	0
BUS 3.			
1	0	100	20

NB! The program does not provide for entering generator impedances.

STORING DATA

The program provides no facilities for storing entered data except under the printing option below.

UPDATING DATA

The program provides no facilities for updating data and one has to reset before a new run.

RUNNING THE PROGRAM

On completion of the Input Data, enter is pressed to run the program and the results are displayed on the screen.

PRINTING

The program prompts at its beginning a "PRINT OPTION" as follows:

P = 0 FOR SCREEN OUTPUT ONLY  
P = 1 FOR SCREEN & PRINTED OUTPUT  
P = 2 FOR SCREEN & DISK OUTPUT e.g (ACPF1B.OUT)

P=0 merely enables the output data to be displayed on the screen.  
P=1 option prints a printer output as the input data is entered step by step and once the program is run the printer then simultaneously prints the results as a hard copy.  
P=2 option lists the output data on the screen and simultaneously stores the results in the ACPF1B.OUT file for example.

To print the output, enter:

C:\GUNGOR>TYPE ACPF1B. OUT.

The data is once again displayed on the screen and the "PRINT SCREEN" key can be pressed to obtain an output. The "PAUSE" key is operated to stop the listing at the desired point.

Alternatively, enter:

C:\GUNGOR>MORE<ACPF1B.OUT.

where this command replaces the necessity to use the "PAUSE" key. To print the file ACPF1B.OUT enter:

C:\GUNGOR>PRINT ACPF1B.OUT.

and then press "enter" after being prompted by the words:

NAME OF LIST DEVICE[PRN]:

OUTPUT DATA

The Output Data lists:

(1) The Ybus if required, for example:

Y-BUS		
Y (1,1)	=	0.0000 -7.0000
Y (1,2)	=	0.0000 2.0000
Y (1,3)	=	0.0000 5.0000
Y (2,1)	=	0.0000 2.0000
Y (2,2)	=	0.0000 -6.0000
Y (2,3)	=	0.0000 4.0000
Y (3,1)	=	0.0000 5.0000
Y (3,2)	=	0.0000 4.0000
Y (3,3)	=	0.0000 -9.0000

NB! The Ybus being formed as certain of its elements are used in formulæ as part of the iterative process.

(11) The results of each iteration if required, is for example:

(NB! A major shortcoming of the program is that it fails to define or explain the meaning of the iteration headings. It was necessary to run a computer experiment first, then compare its results to a hand calculated example, and in this way determine the definition and meaning of these symbols. For example, what does DE mean ?).

ITERATION = 1						
BUS	QC	VR	VI	DQ	DE	DF
2	0.0000	0.9950	0.0995	0.0000	-0.0050	-0.0995
3	0.0000	0.9224	-0.0472	0.0000	-0.0776	0.0472



the findings were:

- (a) Bus = Bus number
- (b) QC = Reactive Power at a certain bus calculated from the formula: (See Gungor p.207 and p.214)

$$Q_i = - \operatorname{Im} \left[ (Y_{ii} V_i + \sum_{k=1}^N Y_{ik} V_k) V_i^* \right] \quad [k = i]$$

NB! Im means imaginary part of, N = Number of buses and k = bus number.

For example at Bus 2,

$$Q_2 = -\operatorname{Im} \left[ (Y_{22} V_2 + Y_{21} V_1 + Y_{23} V_3) V_2^* \right] \quad \begin{array}{l} i=2 \\ k=1 \text{ and } 3 \end{array}$$

$$= Q_c$$

- (c) VR and VI = Real and Imaginary components of the voltage at a certain bus calculated from the formula: (See Gungor p.207 and 214).

$$V_i = \frac{1}{Y_{ii}} \left[ \frac{P_i - jQ_i}{V_i^*} - \sum_{k=1}^N Y_{ik} V_k \right] \quad k = i$$

For example at Bus 2,

$$V_2 = \frac{1}{Y_{22}} \left[ \frac{P_2 - jQ_2}{V_2^*} - Y_{21} V_1 + Y_{23} V_3 \right] \quad \begin{array}{l} i = 2 \\ k = 1 \text{ \& } 3 \end{array}$$

$$= V_R + jV_I$$

NB! VR and jVI having been obtained by first substituting  $1/\_0^\circ$  for V2 is then re-substituted for V2\* and V2 is re-calculated giving VR + jVI. Two successive calculations of V2 (the second being like the first except for the correction of V2\*) are recommended at each bus before proceeding to the next one. As the corrected voltage is found at each bus, it is used in calculating the corrected voltage at the next. The process is repeated at each bus consecutively throughout the network except at the swing bus to complete the first iteration. Then the entire process is carried out again and again until the amount of correction in voltage at every bus is less than some precision index (tolerance).

(d) DQ = Is the change in QC from the previous to the current iteration, using the values of the VR + jVI obtained above.

(e) DE and DF = Is the real and reactive components of the voltage (VR\* + jVI) as calculated above minus the previous voltage used for V2\* .

Also, the final iteration of the solution is listed but with the following headings, for example:

SOLUTION IN 3 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.000	0.000	18.386	40.193	0.000	0.000
2	0.998	0.064	60.000	34.998	0.000	0.000
3	0.920	-0.063	0.000	0.000	80.000	60.000

Where:

(f) VR and VI = Real and imaginary components of the voltage of a bus.

(g) PG = Real component of the power generation at a bus.

(h) QG = Reactive component of the power generation at a bus.

(i) PL = Real component of the power of the load at a bus.

(j) QL = Reactive component of the power of the load at a bus.

NB! This final iteration shows the number of iterations taken to provide a solution within the required tolerance.

(111) The results of the line flows (MW and MVAR), are for example:

LINE FLOWS (MW, MVAR)			
1	2	-12.872	0.415
1	3	31.257	39.778
2	1	12.872	0.415
2	3	48.649	34.195
3	1	-31.257	-34.660
3	2	-48.649	-25.355

NB! The program does not include graphics, therefore a one-line diagram cannot be obtained from the computer. One has to draw one's own representation.

(iv) The results of the Systems Totals, are for example:

SYSTEM TOTALS			
P GENERATION	=	78.386	
Q GENERATION	=	75.191	
P LOAD	=	80.000	
Q LOAD	=	60.000	
P LOSS	=	-1.614	
Q LOSS	=	15.191	

NB! The program does not give the mismatch value at a bus. This has to be hand calculated.

To make the above more clearer the following hand calculated load flow solution is given by way of an example.

#### EXAMPLE 1

A one line diagram of a three bus power system with generator reactances omitted is as follows:

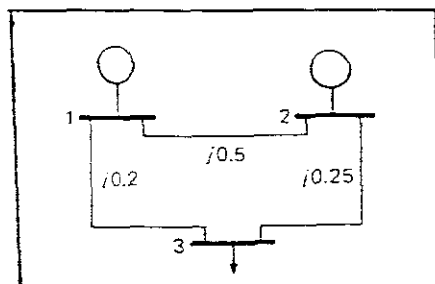


FIGURE.1

The reactances of the lines are given in pu on a 100 MVA base.  
Let:

$V_1 = 1.0/\underline{0^\circ}$ pu
$V_2 = 1.0$ p.u, $P_2 = 60$ MW
$P_3 = -80$ MW, $Q_3 = -60$ Mvar (lag)

Six knowns

NB! Power drawn by a load is negative power into a system.

Using the Gauss-Seidel iteration with Ybus procedure, obtain the power flow solution of this system within a tolerance of 0.01 pu.

The six unknowns are:

$P_1, Q_1$
$\delta_2, Q_2$
$V_3, \delta_3$

The step by step solution procedure is as follows:

**STEP 1** Form Ybus, namely:

$Y_{bus} \text{ pu} = -j \begin{bmatrix} 7 & -2 & -5 \\ -2 & 6 & -4 \\ -5 & -4 & 9 \end{bmatrix}$
---

**STEP 2** Assume the following initial values:

$$\text{Let } \delta_2 = 0, V_3 = 1.0 \text{ pu, } \delta_3 = 0$$

**ITERATION 1**

**STEP 3** Calculate  $Q_2$  and  $V_R + jV_I$  for bus 2 and 3

FOR BUS 2

$$\begin{aligned} Q_2 &= -\text{Im}[(Y_{22} V_2 + Y_{21} V_1 + Y_{23} V_3) V_2^*] \\ &= [ \{ (-j6)(1/\underline{0^\circ}) + (j2)(1/\underline{0^\circ}) + (j4)(1/\underline{0^\circ}) \} 1/\underline{0^\circ} ] = 0 \end{aligned}$$

i.e.  $Q_C = 0$  for iteration 1 for Bus 2

$$V_2 = \frac{1}{Y_{22}} \left[ \frac{P_2 - jQ_2}{V_2^*} - Y_{21} V_1 - Y_2 V_3 \right]$$

$$= \frac{1}{-j6} \left[ \frac{0.6 + j0}{1/_0^\circ} - (j2)(1/_0^\circ) - (j4)(1/_0^\circ) \right]$$

$$= 1 /_{-5.71^\circ}$$

Repeat using  $1 /_{-5.71^\circ}$  for  $V_2^*$

$$V_2 = 0.99005 + j0.0995 = 0.995 /_{-5.74^\circ}$$

$$= 1 /_{-5.74^\circ} \text{ (Rounded off)}$$

$$= 0.995 + j0.1 = V_R + jV_I$$

i.e. $V_R = 0.995$	for Iteration 1
$V_I = 0.1$	and bus 2

$$V_3 = \frac{1}{Y_{33}} \left[ \frac{P_3 - jQ_3}{V_3^*} - Y_{31} V_1 - Y_{32} V_2 \right]$$

$$= \frac{1}{-j9} \left[ \frac{-0.8 + j.06}{1/_0^\circ} - (j5)(1/_0^\circ) - (j4)(0.995 + j0.1) \right]$$

$$= 0.9322 /_{-2.74^\circ}$$

Repeat using  $0.9322 /_{-2.74^\circ}$  as  $V_3^*$

i.e. $V_R = 0.9218$	for Iteration 1
$V_I = 0.0474$	and bus 3

<b>STEP 4</b>	Determine DQ for Iteration 1
---------------	------------------------------

As DQ is the change in the Q from the previous to the current iteration  $DQ = 0$  as we are busy with Iteration 1.

i.e. $DQ = 0$	for Bus 2
---------------	-----------

STEP 5

Determine DE and DF for Buses 2 and 3

$$\begin{aligned} dV2 &= (0.995 + j0.1) - (1.0 - j0) \\ &= -0.005 + j0.1 \\ &= DE + jDF \end{aligned}$$

i.e. DE = -0.005 for Iteration 1  
DF = 0.1 and Bus 2

$$\begin{aligned} dV3 &= (0.9218 - j0.0474) - (1-j0) \\ &= -0.0782 - j0.0474 \\ &= DE + jDF \end{aligned}$$

i.e. DE = -0.0782 for Iteration 1  
DF = -0.0474 and Bus 3

The larger DF of the two is then stored as  $x_{max}$ , namely 0.1

i.e.  $dx_{max} = 0.1$

ITERATION 2

STEP 6

Calculate  $Q2$  and  $VR + jVI$  for Bus 2 and 3

$$\begin{aligned} Q2 &= -\text{Im}[(-j6)(0.995+j0.1) + (j2)(1/_0^\circ) \\ &\quad + (j4)(0.9218-j0.0474)](0.995-j0.1) \\ &= 0.36\text{pu} \end{aligned}$$

NB! Previously calculated  $VR + jVI$  for buses 2 and 3 being used for  $V2$  and  $V3$  in the above equation for  $Q2$ .

i.e  $QC = 0.36$  for Iteration 2 for bus 2

$$\begin{aligned} V2 &= \frac{1}{-j6} \left[ \frac{0.6-j0,36}{1/_5.74^\circ} - (j2)(1/_0^\circ) - (j4)(0.9218-j0.0474) \right] \\ &= 1 /_{-4.24^\circ} = 0.9973 + j0,0739 \end{aligned}$$

Repeat by substituting for  $1 /_{-4.24^\circ}$  for  $V2^*$

$$V2 = 1 /_{-4.15^\circ} = 0,9974 + j0.0723 = VR + jVI$$

i.e. VR = 0,9974 for Iteration 2  
VI = 0,0723 for bus 2

In a similar manner for V3:

$$V3 = 0.9205 - j0.059 = 0.9224 /_{-3.68^\circ}$$

i.e. VR = 0.9205 for Iteration 2  
VI = -0.059 and Bus 3

STEP 7 Determine DQ for Iteration 2.

$$DQ = 0.36 - 0 = 0.36$$

( It is the change in Q from the previous to the current iteration).

i.e. DQ = 0.36 for Bus 2

STEP 8 Determine DE and DF for Buses 2 and 3.

Checking to see by how much the change is:

$$\begin{aligned} dV2 &= (0.9974 + j0.0723) - (0.995 + j0.1) \\ &= 0.0024 - j0.0277 \\ &= DE - jDF \end{aligned}$$

i.e. DE = 0.0024 for Iteration 2  
DF = -0.0277 and Bus 2

$$\begin{aligned} dV3 &= (0.9205 - j0.0592) - (0.9218 - j0.0474) \\ &= -0.0013 - j0.0118 \\ &= DE - jDF \end{aligned}$$

i.e. DE = -0.0013 for Iteration 2  
DF = -0.0118 and Bus 3

The larger DF of the two is then stored as:

$$dxmax = 0,028$$

It is still not within desired tolerance of 0.01.

ITERATION 3

The third iteration, following the same procedure, results in the following solution within the desired tolerance.

$$\begin{aligned} V_2 &= 1 \angle 3.5^\circ = 0.9981 + j0.0610 \\ V_3 &= 0.923 \angle -4.0^\circ = 0.9208 - j0.0644 \end{aligned}$$

Checking:

$$\begin{aligned} dV_2 &= 0.9981 + j0.0610 \\ \text{minus } &0.9974 + j0.0723 \\ \hline &0.0007 - j0.01 = 0.01 \angle -85.9^\circ \end{aligned}$$

$$\begin{aligned} dV_3 &= 0.9208 - j0.0644 \\ \text{minus } &0.9205 - j0.059 \\ \hline &0.0003 + j0.0054 = 0.0054 \angle 86.8^\circ \end{aligned}$$

$$dx_{\max} = 0.01 \text{ which is within tolerance.}$$

From the above it can be seen that the procedure converges in 3 iterations.

The Line Flows are now calculated using the following equations:  
(See Gungor p.166 and 167)

$$P_S = \frac{A}{B} V_S^2 \cos(\beta - \alpha) - \frac{V_S V_r}{B} \cos(\beta + \delta)$$

$$Q_S = \frac{A}{B} V_S^2 \sin(\beta - \alpha) - \frac{V_S V_r}{B} \sin(\beta + \delta)$$

$$P_r = \frac{V_S V_r}{B} \cos(\beta - \delta) - \frac{A V_r^2}{B} \cos(\beta - \alpha)$$



$$Q_r = \frac{V_s V_r}{B} \sin(\beta - \delta) - \frac{AV_r^2}{B} \sin(\beta - \alpha)$$

where:

- $P_s, P_r$  = Real Power at Sending and Receiving-ends of a line.
- $Q_s, Q_r$  = Reactive Power at Sending and Receiving ends of a line.
- $V_s, V_r$  = Voltages at Sending and Receiving ends of a line.
- $\delta$  = Phase angle between  $V_s$  and  $V_r$ .
- ABCD = ABCD parameters for a two part representation of a transmission line, given that:

$$A = \frac{A}{\alpha} = D$$

$$B = \frac{B}{\beta}$$

and since no shunt branches are present in this example, the transmission parameters of each line (like a short line) are:

$$A = D = 1/_0^\circ \quad \text{i.e. } \alpha = 0^\circ$$

$$B = Z = jX = X/_90^\circ \quad \text{i.e. } \beta = 90^\circ$$

$$C = 0$$

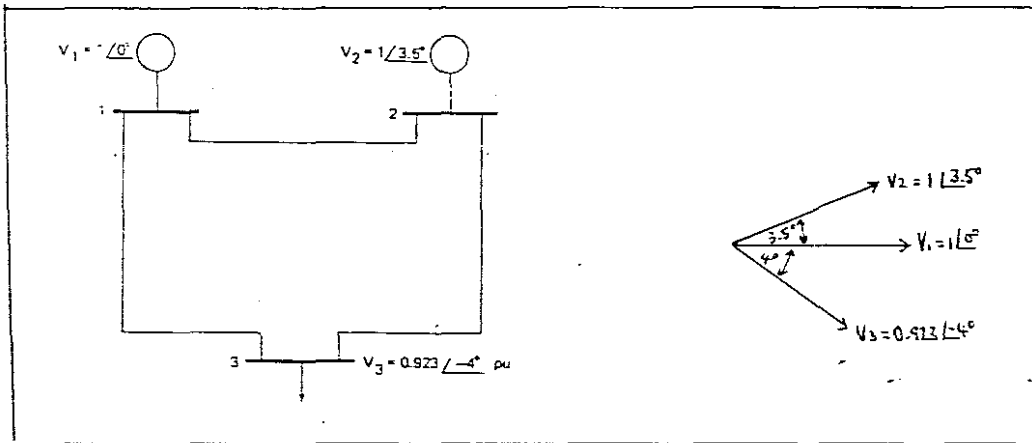


FIGURE.2

FIGURE.3

Hence for Line 1-2, let  $V_r = V_2 /_0^\circ$  and  $V_s = V_1 /_-3.5^\circ$ , we have

$$P_{12s} = \frac{1}{0,5} (1)^2 \cos 90^\circ - \frac{(1)(1)}{0,5} \cos(90^\circ - 3.5^\circ) = -0.1221 \text{ pu} = -12.2 \text{ MW}$$

$$Q_{12s} = \frac{1}{0,5} (1)2 \sin 90^\circ - \frac{(1)(1)}{0,5} \sin(90^\circ - 3.5^\circ) = 0.0037\text{pu} = 0.4\text{MVAR}$$

$$P_{12R} = \frac{(1)(1)}{0,5} \cos(90^\circ + 3.5^\circ) - \frac{(1)^2}{0,5} \cos 90^\circ = -0.1221\text{pu} = -12.2\text{MW}$$

$$Q_{12R} = \frac{(1)(1)}{0,5} \sin(90^\circ + 3.5^\circ) - \frac{(1)^2}{0,5} \sin 90^\circ = 0.0037\text{pu} = -0.4\text{MVAR}$$

Hence for Line 1-3, Let  $V_R = V_3 / \_0^\circ$  and  $V_S = V_1 / \_4^\circ$ , we have

$$\begin{aligned} P_{13s} &= 32,2\text{MW}, Q_{13s} = 39,7 \text{ MVAR} \\ P_{13r} &= 32,\text{MW} \quad Q_{13r} = 34.4 \text{ MVAR} \end{aligned}$$

Hence for Line 2-3 Let  $V_R = V_3 / \_0^\circ$  and  $V_S = V_2 / \_7.5^\circ$ , we have

$$\begin{aligned} P_{23s} &= 48.2\text{MW} \quad Q_{23s} = 34 \text{ MVAR} \\ P_{23r} &= 48.2\text{MW} \quad Q_{23r} = 25.3 \text{ MVAR} \end{aligned}$$

These results are tabulated in the power flow diagram as follows:

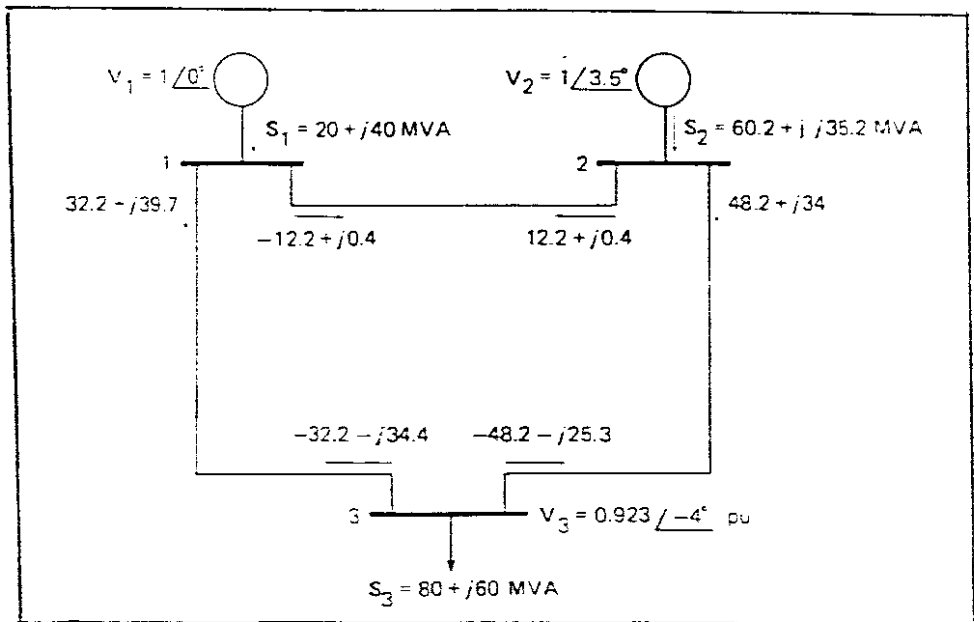


FIGURE 4

The generator powers are obtained by summing up the line flows at the generator buses. The difference between the calculated values and the sum is called the mismatch. Note also that the calculated value of  $P_2 = 60,2\text{MW}$ , is a little more than the scheduled power of 60MW. This difference is due to the coarse accuracy of hand calculations. Computer solutions will generate more accurate results.

b. PROGRAM AC POWER FLOW - NEWTON RAPHSON (ACPF2B)

This ACPF2B program follows the Newton-Raphson iterative procedure with Ybus.

INPUT DATA

Input data for the program consists of:

- (1) Print option. (Follow the same steps as is provided by "PRINTING" under Program ACPF1B for ACPF2B, however when using P=2 use ACPF2B.OUT.)
- (11) System Data requesting:
  - Number of buses = ?
  - Number of Lines = ?
  - Number of Generators = ?
  - Base MVA = ?
  - Tolerance (pu) = ?
  - Maximum number of Iterations = ?
- (111) Line Data and each line is entered under the headings NS, NR, R, XL, Bc ("Commas" important)
  - where NS = Sending end bus number
  - NR = Receiving end bus number
  - R = Resistance (pu)
  - XL = Inductive Reactance (pu)
  - Bc =  $\frac{1}{2}$  Charging Susceptance (pu)

NB! If Bc = 0 enter "0". It is found that if "0" is entered for resistance, i.e. the lines are purely reactive, the Jacobian becomes singular, hence no solution. To overcome this difficulty very small values must be used for resistances. It was found that 0.000001 could be used. Smaller values than these resulted in no solution.

The line data, for example, will thus be:

NS	NR	R	XL	Bc
1	2	0.05	.2	.01
1	3	.1	.5	.02
2	3	.04	.25	.01

(1V) Bus data and each bus is entered under the headings V, PG, PL, QL ("Commas" important).  
where V = Bus voltage (pu). Unknown voltages are entered as "1".  
PG = Real Power Generation in MW  
PL = Load Real Power in MW  
QL = Load Reactive Power in MVAR.

NB! Unknown variables, except voltages, are entered as a "0".

The bus data, for example, will thus be:

V	PG	PL	QL
BUS 1			
1.02	0	0	0
BUS 2			
1	60	0	0
BUS 3			
1	0	100	20

NB! The program does not provide for entering generator impedances.

STORING DATA

The program provides no facilities for storing entered data except under the printing option below.

UPDATING DATA

The program provides no facilities for updating data and one has to reset before a new run.

RUNNING THE PROGRAM

On completion of the Input Data, enter is pressed to run the program and the results are displayed on the screen.

OUTPUT DATA

The Output Data lists:

(1) The Ybus if required, for example:

Y-BUS	
Y(1.1)	= 0.0000 -7.0000
Y(1.2)	= 0.0000 2.0000
Y(1.3)	= 0.0000 5.0000
Y(2.1)	= 0.0000 2.0000
Y(2.2)	= 0.0000 -6.0000
Y(2.3)	= 0.0000 4.0000
Y(3.1)	= 0.0000 5.0000
Y(3.2)	= 0.0000 4.0000
Y(3.3)	= 0.0000 -9.0000

NB!  
The Ybus being formed as certain of its elements are used in formuli as part of the iterative process

(11) The JACOBIAN matrix if required, for example:

J-MATRIX	
J(1.1)	= 0.00002
J(1.2)	= -0.00002
J(1.3)	= 6.00000
J(1.4)	= -4.00000
J(2.1)	= -0.00002
J(2.2)	= 0.00004
J(2.3)	= -4.00000
J(2.4)	= 9.00000
J(3.1)	= 6.00000
J(3.2)	= -4.00000
J(3.3)	= -0.00002
J(3.4)	= 0.00002
J(4.1)	= -4.00000
J(4.2)	= 9.00000
J(4.3)	= 0.00002
J(4.4)	= -0.00004

The Jacobian (J) consists of partial derivatives of P and Q with respect of the Variables appearing in each of their formula.

The above Jacobian matrix is for a system of only 3 buses. If the swing bus is number 1, bus 2 is started with since voltage magnitude and angle are specified at the swing bus. Its matrix form for a 3 bus system is:

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \dots \\ \Delta Q_2 \\ \Delta Q_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial \delta_3} & \dots & \frac{\partial P_2}{\partial |V_2|} & \frac{\partial P_2}{\partial |V_3|} \\ \frac{\partial P_3}{\partial \delta_2} & \frac{\partial P_3}{\partial \delta_3} & \dots & \frac{\partial P_3}{\partial |V_2|} & \frac{\partial P_3}{\partial |V_3|} \\ \dots & \dots & \dots & \dots & \dots \\ \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial \delta_3} & \dots & \frac{\partial Q_2}{\partial |V_2|} & \frac{\partial Q_2}{\partial |V_3|} \\ \frac{\partial Q_3}{\partial \delta_2} & \frac{\partial Q_3}{\partial \delta_3} & \dots & \frac{\partial Q_3}{\partial |V_2|} & \frac{\partial Q_3}{\partial |V_3|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2 \\ \Delta \delta_3 \\ \dots \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix}$$

or

$$\begin{bmatrix} dP \\ dQ \end{bmatrix} = \begin{bmatrix} J \end{bmatrix} \begin{bmatrix} d\delta \\ dV \end{bmatrix}$$

The superscripts which would indicate the number of the iteration are omitted because they change with each iteration. The elements of the Jacobian are found by taking the partial derivatives of the expressions for P and Q and substituting therein the voltages assumed for the first iteration or calculated in the last previous iteration. The Jacobian is partitioned to emphasise the different general types of partial derivatives appearing in each submatrix.

(111) The Jacobian Inverse Matrix, for example:

J. INVERSE		
Jl(1.1)	=	-0.00020
Jl(1.2)	=	0.00086
Jl(1.3)	=	0.23121
Jl(1.4)	=	0.10558
Jl(2.1)	=	0.00117
Jl(2.2)	=	0.00325
Jl(2.3)	=	0.10276
Jl(2.4)	=	0.15837
Jl(3.1)	=	0.23684
Jl(3.2)	=	0.10526
Jl(3.3)	=	-0.00000
Jl(3.4)	=	-0.00000
Jl(4.1)	=	0.10526
Jl(4.2)	=	0.15789
Jl(4.3)	=	-0.00000
Jl(4.4)	=	-0.00000

It is necessary to invert the Jacobian to solve for  $\delta$  and V, namely:

$$\begin{bmatrix} d\delta \\ dV \end{bmatrix} = \begin{bmatrix} -1 \\ J \end{bmatrix} \begin{bmatrix} dP \\ dQ \end{bmatrix}$$

The values found for dV and d $\delta$  are added to the previous values of voltage magnitude and angle to obtain new values for P and Q for starting the next iteration.

The process is repeated until the precision index (pre-selected tolerance) is satisfied. That is dV and d $\delta$  are less than the chosen precision index.

(iv) The results of each iteration if required, for example:

(NB! The program fails to define or explain the meaning of the symbols used as iteration headings. It was necessary to run a computer experiment first, then compare its results to a hand calculated example, and in this way determine the definition and meaning of these symbols. For example what does DF mean?).

ITERATION = 1								
BUS	PC	QC	DP	DQ	VR	VI	DE	DF
2	0.00	0.00	0.60	0.00	0.935	0.057	-0.064	0.057
3	0.00	0.00	-0.80	-0.60	0.903	-0.063	-0.096	-0.063

It was found that,

- (a) BUS = BUS Number
- (b) PC = Real Power calculated at a certain bus from the formula : (See Gungor p.207 and 225)

$$P_i = \sum_{k=1}^N (D_i G_{ik} + D_i B_{ik} F_k - F_i B_{ik} D_k + F_i G_{ik} F_k)$$

Where N = total number of buses in system, i = Bus number of which power is sought.

D<sub>i</sub> and F<sub>i</sub> = real and reactive components of voltage from bus i to ground, namely,

$$V_i = D_i + jF_i$$

G<sub>ik</sub> and B<sub>ik</sub> = real and reactive parts of admittance as part of Y<sub>bus</sub>

D<sub>k</sub> and F<sub>k</sub> = real and reactive parts of voltage of V<sub>bus</sub>

Values are then substituted and P<sub>2</sub> is calculated.

therefore  $PC = P_2$  as calculated

This is then done for each bus.

(c) QC = Reactive Power calculated at a certain bus from the formula: (see Gungor p207 and p226)

$$Q_i = \sum_{k=1}^N (D_i B_{ik} D_k - D_i G_{ik} F_k + F_i G_{ik} D_k + F_i B_{ik} F_k)$$

where each unknown has the same meaning as defined for P<sub>c</sub>.

Values are then substituted and Q2 is calculated.

therefore  $QC = Q2$  as calculated

This is then done for each bus.

(d) DP = Real Power Difference as calculated at a certain bus:

$$DP = P_{spec} - P_{calc}$$

where:

$P_{spec}$  = Real Power specified at a bus before commencement of specific iteration.

$P_{calc}$  = Real Power calculated as PC and as part of an iteration.

DP = Real Power difference between  $P_{spec}$  and  $P_{calc}$ .

(e) DQ = Reactive Power Difference as calculated at a certain bus:

$$DQ = Q_{spec} - Q_{calc}$$

where:

$Q_{spec}$  = Reactive Power specified at a bus before commencement of specific iteration.

$Q_{calc}$  = Reactive Power calculated as QC and as part of an iteration.

DQ = Reactive Power difference between  $Q_{spec}$  and  $Q_{calc}$ .

(f) VR and VI = Calculated real and reactive components of a voltage at a certain bus as derived from the application of the Jacobian and its inverse, for a given iteration, namely:

$$\begin{bmatrix} d\delta \\ dV \end{bmatrix} = \begin{bmatrix} -1 \\ J \end{bmatrix} \begin{bmatrix} dP \\ dQ \end{bmatrix}$$

(g) DE and DF = Voltage difference between the real and reactive components of the voltage as calculated as VR and VI minus the initial or previous value of the voltage at a certain bus.

For example, if the initial value of the voltage at bus 2 was  $1/\_0^\circ = 1 + j0$  and if VR and VI equals 0.9358 and 0.0579 then

$$DE = 1 - 0.9358 = 0.0642$$

$$DF = 0.0579 - 0 = 0.0579$$

These are then the corrected values of the voltage which are added to the previous values of voltage to obtain new values for PC and QC and for starting the next iteration. The process is repeated in a number of iterations until the pre-selected tolerance is satisfied.



Also, the final iteration of the solution is listed, but with the following headings, for example:

SOLUTION IN 3 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.000	0.000	20.000	79.552	0.000	0.000
2	0.910	0.065	60.000	-0.002	0.000	0.000
3	0.877	-0.066	0.000	0.000	80.000	60.000

where:

- (f) VR and VI = Real and Imaginary components of the voltage at a bus.
- (g) PG = Real component of the Power Generation at a bus.
- (h) QG = Reactive component of the Power Generation at a bus.
- (i) PL = Real component of the Power of the load at a bus.
- (j) QL = Reactive component of the Power of the load at a bus.

NB! This final iteration shows the number of iterations taken to provide a solution within the required tolerance.

(v) The results of the line flows (MW and MVARs), for example:

LINE	FLWS	(MW, MVAR)
1.2	-13.047	17.985
1.3	33.047	61.566
2.1	13.047	-15.517
2.3	46.942	15.515
3.1	-33.047	-51.801
3.2	-46.942	-8.175

NB! The program does not include graphics, therefore a one-line diagram cannot be obtained from the computer. One has to draw one's own representation.

(vi) The results of the Systems Totals, are for example:

SYSTEM TOTALS			
P	GENERATION	=	80.000
Q	GENERATION	=	79.550
P	LOAD	=	80.000
Q	LOAD	=	60.000
P	LOSS	=	0.000
Q	LOSS	=	19.550

NB! The program does not give the mismatch value at a bus. This has to be hand calculated.

SUMMARY OF THE GENERAL PRINCIPLES OF THE NEWTON RAPHSON METHOD

1. Determine values of P and Q flowing into the system at every bus for the specified or estimated values of voltage magnitudes and angles for the first iteration or the most recently determined voltages for subsequent iterations.
2. Calculate dP and dQ.
3. Calculate values for the Jacobian using estimated or specified values of voltage magnitude and angle in the equations for partial derivatives determined by differentiation.
4. Invert the Jacobian and calculate voltage corrections  $d\delta$  and  $dV$  at every bus.
5. Calculate new values of  $\delta$  and V by adding  $d\delta$  and  $dV$  to previous values.
6. Return to step 1 and repeat the process using the most recently determined values of voltage magnitudes and angles until either all values of dP and dQ or all values of  $d\delta$  and  $dV$  are less than a chosen pre-selected tolerance.

NB! Gungor and his program ACPF2B follow the above general method but use specific equations. To make this more clearer the following example is given.

EXAMPLE 2

The basic information for this example is the same as for EXAMPLE 1. In this example however, only one complete Newton Raphson iteration will be shown as hand calculated and the balance of the solution will be illustrated as results obtained from a computer. The results obtained confirm those of EXAMPLE 1.

A one-line diagram of a three bus power system with generator reactances omitted is as follows:

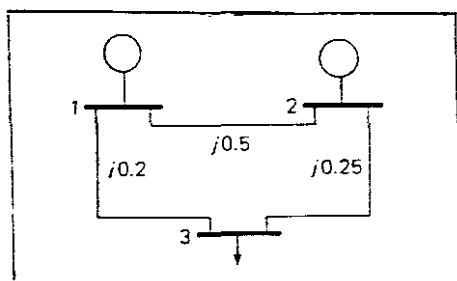


FIGURE .5

The reactances of the lines are given in pu on a 100 MVA base. Let:

SIX KNOWNS

$V_1$	$=$	$1. / \underline{0}^\circ$	pu
$V_2$	$=$	$1.0$ pu,	$P_2 = 60$ MW
$P_3$	$=$	$-80$ MW,	$Q_3 = -60$ MVAR (lag)

NB! Power drawn by a load is negative power into a system.

The step by step solution procedure is as follows:

STEP 1 From Ybus, namely:

$$Y_{bus} \text{ pu} = -j \begin{bmatrix} 7 & -2 & -5 \\ -2 & 6 & -4 \\ -5 & -4 & 9 \end{bmatrix}$$

STEP 2 Let :

$$\begin{aligned} D2^\circ &= 1.0, & F2^\circ &= 0 \\ D3 &= 1.0, & F3^\circ &= 0 \end{aligned}$$

where:

$D2^\circ, F2^\circ, D3^\circ, F3^\circ$  = Real and imaginary components of voltages at buses 2 and 3. These being the initial values used for the first iteration.

STEP 3 Calculate P and Q using the following equations:

$$P_2 = \sum_{k=1}^3 (D_2 G_{2k} D_k + D_2 B_{2k} F_k - F_2 B_{2k} D_k + F_2 G_{2k} F_k)$$

As the lines are reactive  $G_{2k} = 0$ , therefor:

$$P_2 = \sum_{k=1}^3 (D_2 B_{2k} F_k - F_2 B_{2k} D_k)$$

$$\begin{aligned} P_2 &= \text{The following expansion} \\ &= (D_2^\circ B_{21} F_1^\circ + D_2^\circ B_{22} F_2^\circ + D_2^\circ B_{23} F_3^\circ) \\ &\quad - (F_2^\circ B_{21} D_1^\circ + F_2^\circ B_{22} D_2^\circ \\ &\quad \quad + F_2^\circ B_{23} D_3^\circ) \end{aligned}$$

Now from Ybus,  $B_{21} = -2$ ,  $B_{22} = 6$  and  $B_{23} = -4$ , therefor

$$\begin{aligned}
 &= 1[(-2)(0) + (6)(0) + (-4)(0)] - 0[(-2)(0) + (6)(1) + (-4)(1)] \\
 &= 1[0] - 0 \\
 &= 0
 \end{aligned}$$

i.e.  $PC = 0$  for bus 2

$$P_3 = \sum_{k=1}^3 (D_3 G_{3k} D_k + D_3 B_{3k} F_k - F_3 B_{3k} D_k + F_3 G_{3k} F_k)$$

$$\begin{aligned}
 &= D_3^\circ (B_{31}F_1^\circ + B_{32}F_2^\circ + B_{33}F_3^\circ) - F_3^\circ (B_{31}D_1^\circ + B_{32}D_2^\circ + B_{33}D_3^\circ) \\
 &= 0
 \end{aligned}$$

i.e.  $PC = 0$  for bus 3

$$Q_3 = \sum_{k=1}^3 (D_3 B_{3k} D_k - D_3 G_{3k} F_k - F_3 G_{3k} D_k + F_3 B_{3k} F_k)$$

$$\begin{aligned}
 &= D_3^\circ (B_{31}D_1^\circ + B_{32}D_2^\circ + B_{33}D_3^\circ) + F_3^\circ (B_{31}F_1^\circ + B_{32}F_2^\circ + B_{33}F_3^\circ) \\
 &= 1[(-5)(1) + (-4)(1) + (9)(1)] + 0 \\
 &= 0
 \end{aligned}$$

i.e.  $QC = 0$  for bus 3

STEP 4 Calculate  $dP$ ,  $dQ$  and  $dV$  given that:

$$\begin{aligned}
 dP_{k1} &= P_{ks} - P_{k1} \\
 dQ_{k1} &= Q_{ks} - Q_{k1} \\
 dV_{112} &= V_{ks2} - V_{k12}
 \end{aligned}$$

$$dP_2 = P_{2s} - P_2 = 0.6 - 0 = 0.6 \quad 60\text{MW} = 0.6\text{pu}$$

$P_{2s}$  = specified power at bus 2, namely 60MW.

i.e.  $DP = 0.6$  for bus 2

$$dP3 = P3s - P3^1 = (-0.8 - 0) = -0.8 \quad -80MW = -0.8pu$$

P3s = specified power at bus 3, namely -80MW.

$$\text{i.e. } DP = -0.8 \text{ for bus 3}$$

$$dQ3 = Q3s - Q3^1 = (-0.6 - 0) = -0.6 \quad -60MW = -0.6pu$$

Q3s = specified reactive power at bus 3, namely -60MW.

$$\text{i.e. } DQ = -0.6 \text{ for bus 3}$$

$$dV2^2 = V2s^2 - (V2^0)^2 = (1)^2 - (1)^2 = 0 \quad i = 1 \text{ for first iteration}$$

V2s = specified voltage at bus 2, namely 1.0pu

Therefore from the above dxmax = 0.8 which is the largest.

STEP 5

Calculate the bus currents given that:

$$I_{bus}^1 = Y_{bus} V_{bus}^0$$

$$I_{bus} = \begin{bmatrix} -j7 & j2 & j5 \\ j2 & -j6 & j4 \\ j5 & j4 & -j9 \end{bmatrix} \begin{bmatrix} 1+j0 \\ 1+j0 \\ 1+j0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + j \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

STEP 6

Calculate the Jacobian matrix given that,

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \\ \Delta Q_1 \\ \Delta Q_2 \\ \Delta V_1^2 \\ \Delta V_2^2 \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & \dots & J_{1n} & J_{1n+1} & \dots & J_{1n+m} & J_{1n+m+1} & \dots & J_{1n+m+l} \\ J_{21} & J_{22} & \dots & J_{2n} & J_{2n+1} & \dots & J_{2n+m} & J_{2n+m+1} & \dots & J_{2n+m+l} \\ \vdots & \vdots & \dots & \vdots & \vdots & \dots & \vdots & \vdots & \dots & \vdots \\ J_{n1} & J_{n2} & \dots & J_{nn} & J_{n,n+1} & \dots & J_{n,n+m} & J_{n,n+m+1} & \dots & J_{n,n+m+l} \\ \hline J_{n+1,1} & J_{n+1,2} & \dots & J_{n+1,n} & J_{n+1,n+1} & \dots & J_{n+1,n+m} & J_{n+1,n+m+1} & \dots & J_{n+1,n+m+l} \\ \vdots & \vdots & \dots & \vdots & \vdots & \dots & \vdots & \vdots & \dots & \vdots \\ J_{n+m,1} & J_{n+m,2} & \dots & J_{n+m,n} & J_{n+m,n+1} & \dots & J_{n+m,n+m} & J_{n+m,n+m+1} & \dots & J_{n+m,n+m+l} \\ \hline J_{n+m+1,1} & J_{n+m+1,2} & \dots & J_{n+m+1,n} & J_{n+m+1,n+1} & \dots & J_{n+m+1,n+m} & J_{n+m+1,n+m+1} & \dots & J_{n+m+1,n+m+l} \\ \vdots & \vdots & \dots & \vdots & \vdots & \dots & \vdots & \vdots & \dots & \vdots \\ J_{n+m+l,1} & J_{n+m+l,2} & \dots & J_{n+m+l,n} & J_{n+m+l,n+1} & \dots & J_{n+m+l,n+m} & J_{n+m+l,n+m+1} & \dots & J_{n+m+l,n+m+l} \end{bmatrix} \begin{bmatrix} \Delta D_1 \\ \Delta D_2 \\ \Delta D_3 \\ \Delta F_1 \\ \Delta F_2 \\ \Delta F_3 \end{bmatrix}$$

or

$$\begin{bmatrix} dP1 \\ dQ1 \\ dV12 \end{bmatrix} = \begin{bmatrix} J11 & J21 \\ J31 & J41 \\ J51 & J61 \end{bmatrix} \begin{bmatrix} dD1 \\ dF1 \end{bmatrix}$$

where the elements of the Jacobian matrix are given in the following table:

Elements of the Jacobian Matrix	$J_{1kk} = \frac{\partial P_k}{\partial D_k} = D_k G_{kk} - F_k B_{kk} + A_k$	$k = 2, 3, \dots, N$ $j = 2, 3, \dots, N$ $k \neq j$	(Diagonals)
	$J_{1kj} = \frac{\partial P_k}{\partial D_j} = D_k G_{kj} - F_k B_{kj}$		(Off diagonals)
	$J_{2kk} = \frac{\partial P_k}{\partial F_k} = D_k B_{kk} + F_k G_{kk} + C_k$	$k = 2, 3, \dots, N$ $j = 2, 3, \dots, N$ $k \neq j$	
	$J_{2kj} = \frac{\partial P_k}{\partial F_j} = D_k B_{kj} + F_k G_{kj}$		
	$J_{3kk} = \frac{\partial Q_k}{\partial D_k} = D_k B_{kk} + F_k G_{kk} - C_k$	$k = G + 1, G + 2, \dots, N$ $j = 2, 3, \dots, N$ $k \neq j$	
	$J_{3kj} = \frac{\partial Q_k}{\partial D_j} = D_k B_{kj} + F_k G_{kj}$		
	$J_{4kk} = \frac{\partial Q_k}{\partial F_k} = F_k B_{kk} - D_k G_{kk} + A_k$	$k = G + 1, G + 2, \dots, N$ $j = 2, 3, \dots, N$ $k \neq j$	
	$J_{4kj} = \frac{\partial Q_k}{\partial F_j} = F_k B_{kj} - D_k G_{kj}$		
	$J_{5kk} = \frac{\partial V_k^2}{\partial D_k} = 2D_k$	$k = 2, 3, \dots, G$ $j = 2, 3, \dots, N$ $k \neq j$	
	$J_{5kj} = \frac{\partial V_k^2}{\partial D_j} = 0$		
	$J_{6kk} = \frac{\partial V_k^2}{\partial F_k} = 2F_k$	$k = 2, 3, \dots, G$ $j = 2, 3, \dots, N$ $k \neq j$	
	$J_{6kj} = \frac{\partial V_k^2}{\partial F_j} = 0$		

TABLE.2

The non-zero Jacobian elements, by TABLE 2, for this example are:

$$\begin{aligned}
 J_{222} &= \frac{1}{\delta F_2} \delta P_2 = D_2 B_{22} + F_2 G_{22} + C_2 = 0 \\
 J_{223} &= \frac{1}{\delta F_3} \delta P_2 = D_2 B_{23} + F_2 G_{23} = -4 \\
 J_{232} &= \frac{1}{\delta F_2} \delta P_3 = D_3 B_{32} + F_3 G_{32} = -4 \\
 J_{233} &= \frac{1}{\delta F_3} \delta P_3 = D_3 B_{33} + F_3 G_{33} = 9 \\
 J_{332} &= \frac{1}{\delta D_2} \delta Q_3 = D_3 B_{32} + F_3 G_{32} = -4 \\
 J_{333} &= \frac{1}{\delta D_3} \delta Q_3 = D_3 B_{33} + F_3 G_{33} = 9 \\
 J_{522} &= \frac{1}{\delta D_2} \delta V_2^2 = 2D_2 = 2
 \end{aligned}$$

Therefore the Jacobian is:

$$J = \begin{matrix} & & 2 & 3 & 2 & 3 \\ \begin{matrix} 2 \\ 3 \\ 3 \\ 2 \end{matrix} & = & \begin{bmatrix} 0 & 0 & 6 & -4 \\ 0 & 0 & -4 & 9 \\ -4 & 9 & 0 & 0 \\ 2 & 0 & 0 & 0 \end{bmatrix} \end{matrix}$$

$$dJ = -684$$

**STEP 7** Obtain by matrix inversion the corrections

dDk1, Fk1 from

$$\begin{bmatrix} dD1 \\ dF1 \end{bmatrix} = [J]^{-1} \begin{bmatrix} dP1 \\ dQ1 \\ dV12 \end{bmatrix}$$

Therefore:

$$J^{-1} = \frac{-1}{-684} \begin{bmatrix} 0 & 0 & 0 & 342 \\ 0 & 0 & 76 & 152 \\ 162 & 72 & 0 & 0 \\ 72 & 108 & 0 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0.5000 \\ 0 & 0 & 0.1111 & 0.2222 \\ 0.2368 & 0.1053 & 0 & 0 \\ 0.1053 & 0.1599 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} dD21 \\ dD31 \\ dF21 \\ dF31 \end{bmatrix} = J^{-1} \begin{bmatrix} dP2 \\ dP3 \\ dQ3 \\ dV22 \end{bmatrix} = J^{-1} \begin{bmatrix} 0.6 \\ -0.8 \\ -0.6 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ -0.0666 \\ 0.0578 \\ -0.0631 \end{bmatrix}$$

**STEP 8** Calculate the new bus voltages.

(a) At voltage controlled buses, where:

$$D_{k1+1} = V_{ks} \cos \delta_{k1}$$

$$F_{k1+1} = V_{ks} \sin \delta_{k1}$$

given that

$$\delta_{k1} = \tan^{-1} (F_{k1}/D_{k1})$$

(b) At the remaining buses, where:

$$D_{k1+1} = D_{k1} + D_{k1}$$

$$F_{k1+1} = F_{k1} + F_{k1}$$

Therefore:

$$(a) \delta_2^1 = \tan^{-1} (0,0578 \div 1) = 3.31^\circ$$

$$\text{i.e. } D_2^1 = 1 \cos 3.31 = 0.9983, F_2^1 = 1 \sin 3.31 = 0.0578$$

$$\text{i.e. } V_R = 0,9983 \text{ and } V_I = 0.0578 \text{ for bus 2}$$

$$(b) D_3^1 = 1 - 0.0666 = 0.9334$$

$$F_3^1 = 0 - 0.0631 = -0.0631$$

$$\text{i.e. } V_R = 0.9334 \text{ and } V_I = -0.0631 \text{ for bus 3}$$

$$\begin{bmatrix} D_{21} \\ D_{31} \\ F_{21} \\ F_{31} \end{bmatrix} = \begin{bmatrix} 0.9983 \\ 0.9334 \\ 0.0578 \\ -0.0631 \end{bmatrix}$$

For Bus 2

$$\text{i.e. } DE = 1 - 0.9983 = 0.0017$$

$$DF = 0.0578 - 0 = 0.0578$$

For Bus 3

$$DE = 1 - 0.9334 = 0.0667$$

$$DF = 0,0631 - 0 = 0.0631$$



This is the end of the first iteration and can be written in the same form as which the computer prints results, namely:

ITERATION = 1								
BUS								
2	0.0000	0.0000	0.6000	0.0000	0.9983	0.0578	0.0017	0.0578
3	0.0000	0.0000	-0.8000	-0.6000	0.9334	-0.0631	0.0667	0.0631

Note now that the F's are non zero. For the next iteration, the P's and Q's would be non zero and the Jacobian will have more non zero terms, requiring a computer inversion.

For the second iteration the computer produced the following Jacobian and iteration results:

JACOBIAN MATRIX			
0.252	-0.252	5.733	-3.733
0.231	-0.231	-3.993	8.993
1.996	0.000	0.115	0.000
-3.733	7.806	0.252	-1.368

ITERATION = 2								
BUS	PC	QC	DP	DQ	VR	VI	DE	DF
2	0.5836	0.2909	0.0164	0.0	0.9983	0.0591	0.0	0.0013
3	-0.7833	-0.5033	-0.0967	-0.0967	0.9206	-0.0647	-0.0127	-0.0016

Which hereafter gives a solution in 3 iterations:

SOLUTION IN 3 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.000	0.000	20.540	40.050	0.000	0.000
2	0.998	0.059	60.000	34.290	0.000	0.000
3	0.92	-0.064	0.000	0.000	80.000	60.000

$$V_1 = 1/\_0^\circ \text{pu}, V_2 = 1/\_+3.39^\circ = 0.998 + j0.059, V_3 = 0.923/\_-4^\circ = 0.92 - j0.064$$

LINE	FLAWS	(MW, MVAR)
1,2	11.82	0.35
1,3	-32.36	34.66
2,1	-11.82	0.35
2,3	-47.6	-25.39
3,1	32.36	39.7
3,2	47.6	33.94

SYSTEMS TOTALS		
P	GENERATION	= 80.540
Q	GENERATION	= 74.34
P	LOAD	= 80.000
Q	LOAD	= 60.000
P	LOSS	= 0.54
Q	LOSS	= 14.34

It can be seen that the above results are comparable with those of EXAMPLE 1, which confirm that Gauss-Seidal and Newton Raphson methods can be used for Load flow solutions.

C. PROGRAM LINEARISED (DC) POWER FLOW -(DCPFB)

This DCPFB program will provide a D.C. Linearised Power Flow solution for a power system.

As the resistances of transmission lines are rather small compared with the reactances of those lines, for certain types of operations (e.g. fault studies and transient stability studies) the resistances are neglected to simplify the solutions. Such a Load Flow system, with its resistances neglected, is often referred to as a DC Load Flow System. It is a widely used approximation of the AC Load Flow and is linearised as it converts the AC solution into a single linear circuit analysis problem. The DC Load Flow is useful for rapid calculations of real power flows. Because the equations used are linear, the load flow solution does not use iterations as was the case with AC Flow systems.

INPUT DATA

Input data for the program consists of:

(I) PRINT OPTION. (Follow the same steps as is provided by "PRINTING" under PROGRAM ACPFIB for DCPFB, however when using P=2 use DCPFB.OUT).

(II) SYSTEMS DATA:

(NB! The buses must be so numbered that the last bus is the reference bus, for which no power is specified. The reference bus can be any bus in the system and need not necessarily be bus 1.)

Number of buses (NB) = ?  
Number of lines (NL) = ?  
Base MVA = ?

The program does not request a pre-selection tolerance.

(III) LINE DATA:

Line Data and each line is entered under the headings NS, NR, XL(pu) ("Commas" important)  
where NS = Sending End Bus number.  
NR = Receiving End Bus number.  
XL(pu) = Inductive Reactance (pu).

The line data, for example, will thus be:

NS	NR	XL
1	2	0.25
1	3	0.2
2	3	0.5

Enter line data from 1 to NL.

(IV) BUS DATA:

NB! The bus is entered as (1 to NB-1) in ascending order. The buses must be so numbered that the last bus is the reference bus, for which no power is specified. The reference bus can be any bus in the system and need not necessarily be bus 1. Only NB-1 buses are requested to be entered. No information about the reference bus need be entered. The program takes it into account.

Bus data is entered under the headings, for example:

BUS DATA	
NO.	POWER (MW)
1	-80
2	60

"Power drawn by a load is negative power into a system"

This bus data is for a 3 bus power system having the following configuration:

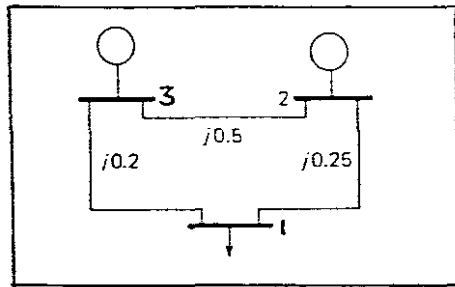


FIGURE.6

It can be seen that only NB-1 buses are entered as input bus data. The reference bus becomes bus 3 and is the bus for which no power is specified. No information about the reference bus is entered as program takes it into account. The bus data must also be in ascending order, Bus 1 = -80MW and Bus 2 = 60MW.

NB! The program does not provide for entering generator impedances.

STORING AND UPDATING DATA

The program provides no facilities except under the printing option.

RUNNING THE PROGRAM

On completion of the Input data, enter is pressed to run the program and results are displayed on the screen.



i.e. For  $\delta \ll 1$  radian,  $\sin \delta \approx \delta$ , Hence, in general the line flows become,

$$P_{ik} = \frac{V_i V_r}{X_{ik}} \delta_{ik}$$

where:  
 $\delta_{ik} = \delta_i - \delta_k$

As all bus voltages are around 1pu, let

$$V_i = V_r = 1pu$$

and

$$B_{ik} = \frac{-1}{X_{ik}}$$

which is consistent with the definition of  $Y_{bus}$ , then

$$P_{ik} = -b_{ik} \delta_{ik} = \frac{\delta_i - \delta_k}{X_{ik}}$$

Now the bus power at any bus is the sum of the power flows in the lines connected to that bus, Hence

$$P_i = \sum_{k=1}^N P_{ik} = \sum_{k=1}^N (-b_{ik} \delta_{ik}) \quad i = 1, 2, \dots, N$$

or in matrix form

$$\begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ \vdots \\ \vdots \\ P_N \end{bmatrix} = - \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1N} \\ b_{21} & b_{22} & \dots & b_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ b_{N1} & b_{N2} & \dots & b_{NN} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \vdots \\ \vdots \\ \delta_N \end{bmatrix}$$

which can be abbreviated as

$$\begin{bmatrix} P \end{bmatrix} = \begin{bmatrix} b \end{bmatrix} \begin{bmatrix} \delta \end{bmatrix}$$

where the matrix [b] is the imaginary part of Ybus and appears as output data as follows, for example:

B - MATRIX		
B (1,1)	=	9.0000
B (1,2)	=	-4.0000
B (1,3)	=	-5.0000
B (2,1)	=	-4.0000
B (2,2)	=	6.0000
B (2,3)	=	-2.0000
B (3,1)	=	-5.0000
B (3,2)	=	-2.0000
B (3,3)	=	7.0000

B MATRIX FOR A 3 BUS POWER SYSTEM

The program then inverts the B-matrix and it appears as output data as follows, for example:

B - INVERSE		
X (1,1)	=	0.1579
X (1,2)	=	0.1053
X (2,1)	=	0.1053
X (2,2)	=	0.2368

FOR A 3 BUS POWER SYSTEM

(c) The solution for [ $\delta$ ] matrix is therefore

$$[\delta] = [b]^{-1} [P]$$

and this appears as output data as follows, for example:

ANGLES (IN RADIANS) ARE		
THETA (1)	=	-0.0632
THETA (2)	=	0.0579
THETA (3)	=	0.0000

(2) THE LINE FLOWS (MW), are for example:

LINE FLOWS (MW)		
P (1,2)	=	-48.4211
P (1,3)	=	-31.5790
P (2,3)	=	11.5789

(3) THE POWER AT THE REFERENCE BUS, is for example:

P(3)	=	20.0000MW
------	---	-----------

NB! The program does not draw a one-line diagram nor does it give mismatches. These have to be done by hand.

To make this more clearer, the following hand calculated example is given:

**EXAMPLE 3**

(See Gungor p.231)

The basic information for this example is the same as for EXAMPLE 1.

A one-line diagram of a three bus power system with generator reactances omitted is as follows:

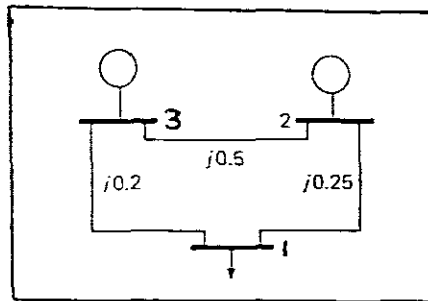


FIGURE. 7

The reactances of the lines are given in pu on a 100 MVA base. Let:

$P_1$	$=$	$-80\text{MW}$
$P_2$	$=$	$60\text{MW}$

KNOWN

Power drawn by a load is negative power into the system.

**STEP 1** Form SUSCEPTANCE MATRIX [b], that is:

$$Y = \frac{1}{Z}, \text{ but as } Z = jX, Y = \frac{1}{jX} = B \text{ (Susceptance)}$$

Therefore, from FIGURE. 7:

$$B_{11} = \frac{1}{j0,25} + \frac{1}{j0,2} = -j4 -j5 = -j9$$



$$B_{12} = \frac{-1}{j0,25} = +j4, \quad B_{13} = \frac{-1}{j0,2} = +j5$$

$$B_{21} = +j4, \quad B_{22} = \frac{1}{j0,25} + \frac{1}{j0,5} = -j4 -j2 = -j6$$

$$B_{23} = \frac{-1}{j0,5} = +j2, \quad B_{31} = \frac{-1}{j0,2} = +j5$$

$$B_{32} = \frac{-1}{j0,5} = +j2, \quad B_{33} = \frac{1}{j0,2} + \frac{1}{j0,5} = -j5 -j2 = -j7$$

$$[b] = \begin{bmatrix} -j9 & +j4 & +j5 \\ +j4 & -j6 & +j2 \\ +j5 & +j2 & -j7 \end{bmatrix}$$

$$[b] = -j \begin{bmatrix} 9 & -4 & -5 \\ -4 & 6 & -2 \\ -5 & -2 & 7 \end{bmatrix}$$

**STEP 2** Invest the susceptance matrix:

$$[b]^{-1} = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} = \begin{bmatrix} 0.1579 & 0.1053 \\ 0.1053 & 0.2368 \end{bmatrix}$$

**STEP 3** Determine bus angles from the general equation.

$$[\delta] = [b]^{-1} [P]$$

namely:

$$\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} = [b]^{-1} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}$$

where:  $P_1 = -80\text{MW} (-0.8\text{pu})$  and  $P_2 = 60\text{MW} (0.6\text{pu})$

$$\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} = \begin{bmatrix} 0.1579 & 0.1053 \\ 0.1053 & 0.2368 \end{bmatrix} \begin{bmatrix} -0.8 \\ 0.6 \end{bmatrix}$$

$$\begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} = \begin{bmatrix} -0.0632 \\ 0.0579 \end{bmatrix} \text{ RADIANS}$$

Therefore the bus angles in radians and degrees are:

THETA (1)	=	-0.0632 Radians	=	-3.62 degrees
THETA (2)	=	0.0579 Radians	=	3.31 degrees
THETA (3)	=	0.0000 Radians	=	0.0 degrees

Theta (3) being the angle for the reference, bus 3.

**STEP 4** Determine the line flows from the general formula:

$$P_{ik} = \frac{\delta_i - \delta_k}{X_{ik}} = -b_{ik} (\delta_i - \delta_k)$$

$$P_{12} = -b_{12}(\delta_1 - \delta_2) = -(-4)(-0.0632 - 0.0579) = -0.484 = -48.4211 \text{ MW}$$

$$P_{13} = -b_{13}(\delta_1 - \delta_3) = -(-5)(-0.0632 - 0) = -0.31579 = -31.579 \text{ MW}$$

$$P_{23} = -b_{23}(\delta_2 - \delta_3) = -(-2)(0.0579 - 0) = 0.11578 = 11.5789 \text{ MW}$$

**STEP 5** Determine the power at the reference bus 3 and at the other buses to find any mismatch.

$$P_3 = P_{13} + P_{23} \qquad P_2 = P_{21} + P_{23} \qquad P_1 = P_{12} + P_{13}$$

$$P_3 = -31.579 + 11.579 \quad P_2 = 48.4211 + 11.5789 \quad P_1 = -48.4211 - 31.579$$

$$P_3 = 20 \text{ MW}$$

$$P_2 = 60 \text{ MW}$$

$$P_1 = -80 \text{ MW}$$

**STEP 6** Draw the one-line power flow diagram for this solution, namely:

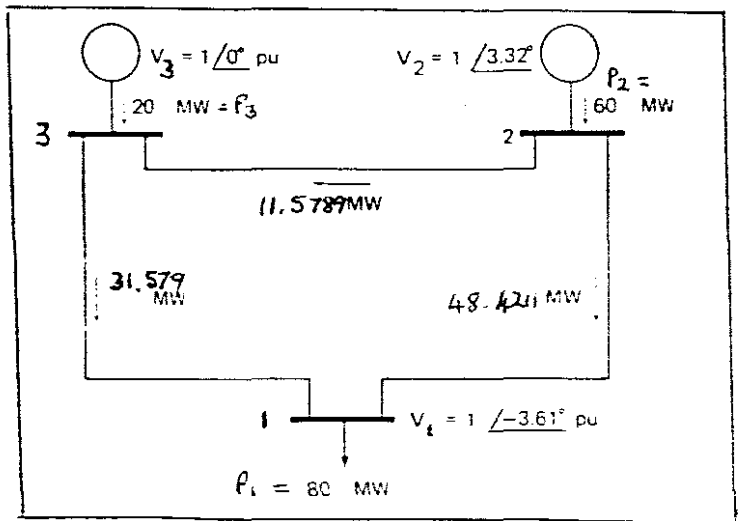


FIGURE. 8

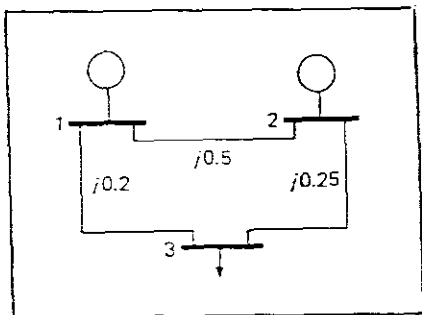
**2. EXPERIMENTATION USING THE PROGRAMS**

**a. PROGRAM ACPF1B - GAUSS SEIDEL**

**EXPERIMENT A1  
3 BUS POWER SYSTEM  
R = 0, Bc = 0**

**INFORMATION AVAILABLE:**

A one-line diagram of a three bus system with generator reactances omitted is shown in Figure 9.



**FIGURE.9**

The reactances of the power system are given in pu on a 100 MVA base. The system contains no transformers and no line resistances nor susceptances. The lines have reactances of  $j0.5$  (1 to 2),  $j0.2$  (1 to 3) and  $j0.25$  (2 to 3).

Let:

$V1 = 1/\_0^\circ$ pu,
$V2 = 1.0$ pu, $P2 = 60$ MW
$P3 = -80$ MW, $Q3 = -60$ MVAR (lag)

**EXPERIMENTAL REQUIREMENTS:**  
Use the program ACPF1B (Gauss-Seidel) and obtain the Ybus, all of the iterations, the line flows and the system totals. Tabulate the results in a power-flow diagram and analyse and comment thereon.

SOLUTION

C:\GUNGOR\ACPFIB  
The screen shows

```
PRINT OPTION: P = 0 FOR SCREEN OUTPUT ONLY
                P = 1 FOR SCREEN AND PRINTED OUTPUT
                P = 2 FOR SCREENS AND DISK OUTPUT
P = ?
```

Select "0"

The program then prompts for System Data:

No. of buses = ?, Enter 3  
No. of lines = ?, Enter 3  
No. of generators = ?, Enter 2  
Base MVA = ?, Enter 100  
Tolerance = ?, Enter 0.01  
Max. No. of iterations = ?, Enter 10

The program next prompts for Line Data:

It requests that line data be entered under the headings, NS, NR, R, XL, BC for each line (NB! "Commas")  
Enter the data as:

LINE 1  
? 1, 2, 0, 0.5, 0 press enter

LINE 2  
? 1, 3, 0, 0.2, 0 press enter

LINE 3  
? 2, 3, 0, 0.25, 0 press enter

The program then prompts for the Bus Data:

It requests that the bus data be entered under the headings, V, PG, PL, QL for each bus (NB! "Commas")  
Enter data as:

BUS 1  
? 1, 0, 0, 0 press enter

BUS 2  
? 1, 60, 0, 0 press enter

BUS 3  
? 1, 0, 80, 60 press enter

This completes the Input Data.

The computer now prompts for:

"DO YOU WANT Y-BUS LISTED ? (Y/N)?"

Select Y and the YBus is displayed as follows:

YBUS		
Y(1,1)	= 0.00000	-7.00000
Y(1,2)	= 0.00000	2.00000
Y(1,3)	= 0.00000	5.00000
Y(2,1)	= 0.00000	2.00000
Y(2,2)	= 0.00000	-6.00000
Y(2,3)	= 0.00000	4.00000
Y(3,1)	= 0.00000	5.00000
Y(3,2)	= 0.00000	4.00000
Y(3,3)	= 0.00000	-9.00000

It then prompts:

"DO YOU WANT RESULTS OF EACH ITERATION LISTED? (Y/N)?"

Select Y and the number of iterations are listed:

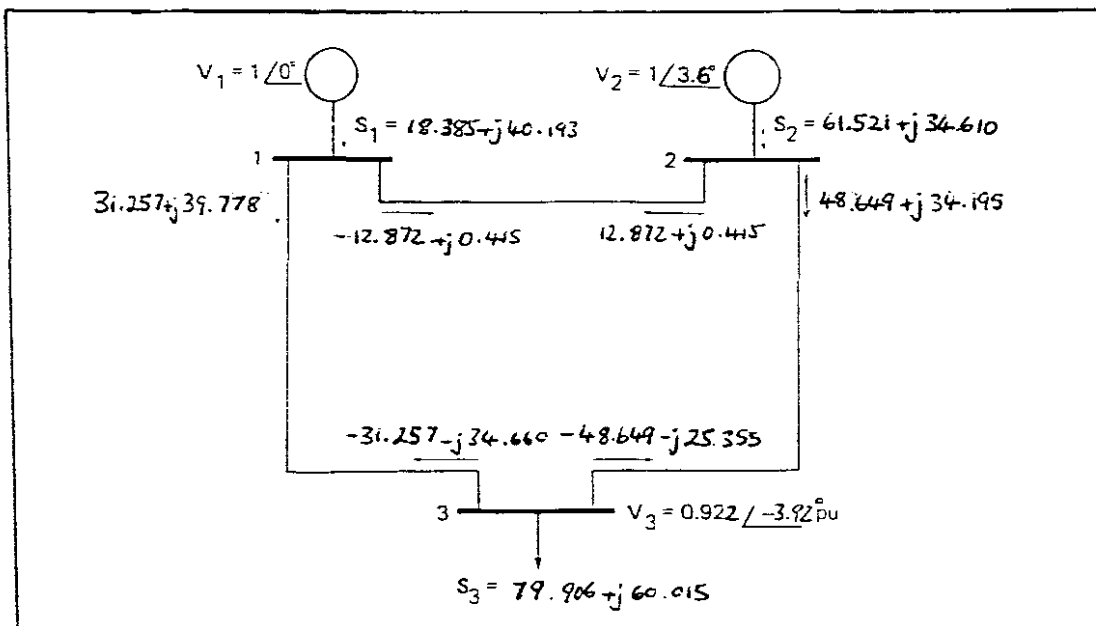
ITERATION = 1						
BUS	-QC	VR	VI	DQ	DE	DF
2	0.0000	0.9950	0.0995	0.0000	-0.0050	-0.0995
3	0.0000	0.9224	-0.0472	0.0000	-0.0776	0.0472
ITERATION = 2						
BUS	-QC	VR	VI	DQ	DE	DF
2	0.3575	0.9974	0.0728	-0.3575	0.0023	0.0268
3	0.0000	0.9206	-0.0589	0.0000	-0.0018	0.0116
SOLUTIONS IN 3 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.000	0.000	18.386	40.193	0.000	0.000
2	0.998	0.064	60.000	34.998	0.000	0.000
3	0.920	-0.063	0.000	0.000	80.000	60.000

Simultaneously the line flows and system totals are also listed:

LINE FLOWS (MW,MVAR)			
1	2	-12.872	0.415
1	3	31.257	39.778
2	1	12.872	0.415
2	3	48.649	34.195
3	1	-31.257	-34.660
3	2	-48.649	-25.355

SYSTEM TOTALS	
P GENERATION=	78.386
Q GENERATION=	75.191
P LOAD	= 80.000
Q LOAD	= 60.000
P LOSS	= -1.614
Q LOSS	= 15.191

The program is unable to provide a one-line diagram. The results are tabulated in a one-line power flow diagram as follows:



POWER FLOW DIAGRAM  
FIGURE 10

$$\begin{aligned}
 V_1 &= 1 / \underline{0}^\circ \text{ puV}, & V_2 &= 0.998 + j0.064 = 1 / \underline{3.66}^\circ \text{ pu V} \\
 V_3 &= 0.92 - j0.063 = 0.922 / \underline{-3.92} \text{ pu V} \\
 S_1 &= (31.257 + 39.778) + (-12.872 + j0.415) \\
 &= 18.385 + j40.193 \text{ MVA} \\
 S_2 &= (12.872 + j0.415) + (48.649 + j34.195) \\
 &= 61.521 + j34.610 \text{ MVA} \\
 S_3 &= (-31.257 - j34.660) + (-48.649 - j 25.355) \\
 &= -79.906 - j60.015 \text{ negative power into the system equals} \\
 &\quad \text{positive power to load, therefore:} \\
 &= 79.906 + j 60.015 \text{ MVA to the load.}
 \end{aligned}$$

COMMENTS

NB! The difference between the calculated values and the sum is called the mismatch.

COMMENT ONE

From Iteration 3, the sum of the PG's at Buses 1 and 2 = 18.386 + 60 = 78.386 MW. However from Figure 10 the PG sum = 18.385 + 61.521 = 79.906 MW giving a difference of 1.52 MW.

Likewise the sum of the QG's = 40.193 + 34.998 = 75.191MVAR, however from figure 10 the QG sum = 40.193 + 34.61 = 74.803 MVAR giving a difference of -0.388 MVAR

Also from Iteration 3, PL = 80 and QL = 60, however from Figure 10, PL = 79.906 and QL = 60.015 giving 0.094 and 0.015 differences respectively.

COMMENT TWO

From the Systems Totals the P LOSS to the system is (-80 + 78.386) = 1.614MW and the Q LOSS = (75.161 - 60) = 15.161 MVAR.

There are no active power losses across the lines, namely:

Line 1 to 2	-12.872
Line 2 to 1	12.872
	<hr/>
	0.000
	<hr/>

Line 1 to 3	31.257
Line 3 to 1	-31.257
	<hr/>
	0.000
	<hr/>

Line 2 to 3	48.649
Line 3 to 2	-48.649
	<hr/>
	0.000
	<hr/>

From Figure 10 the Q LOSS is:

Line 1 to 2	0.415
Line 2 to 1	0.415
	<hr/>
	0.830
	<hr/> <hr/>
	Absorbed by line

Line 1 to 3	39.778	
Line 3 to 1	-34.660	
	<u>5.118</u>	Absorbed by line

Line 2 to 3	34.195	
	-25.355	
	<u>8.84</u>	Absorbed by line

Therefore Q LOSS = 14.788 MVAR giving a difference of 0.373 MVAR.



EXPERIMENT A2  
3 BUS POWER SYSTEM  
 $R \neq 0$  ,  $Bc \neq 0$

INFORMATION AVAILABLE :

A three bus system with its generator reactances omitted has the following data:

LINE DATA				
NS	NR	R	XL	BC
1	2	.05	.2	.01
2	3	.1	.5	.02
3	3	.04	.25	.01

BUS DATA				
BUS	V	PG	PL	QL
1	1.02	0	50	10
2	1	60	0	0
3	1	0	100	20

EXPERIMENTAL REQUIREMENTS

If the base MVA = 100, the tolerance = 0.01 and the maximum number of iterations = 10, use program ACPF1B to determine:

- (a)  $Y_{23}$  and  $Y_{32}$ . What do you notice about these admittances and why is it necessary for the program to formulate a  $Y_{bus}$  ?  
What elements of the  $Y_{bus}$  are necessary for formulating  $Q_C$  at bus 2 for iteration 1 and what are their values?.
- (b)  $V_R$  and  $V_I$  at bus 2 for iteration 1 and show therefrom how the values of  $DE$  and  $DF$  are obtained?.
- (c) The power flow diagram, showing thereon the line flows, the voltages at each bus and the  $P$  and  $Q$  generation totals at generator buses. How are these values obtained,
- (d) What are the  $P$  LOSSES on lines 1 to 2, 1 to 3, and 2 to 3 ?.
- (e) Is the reactor in line 1 to 2 supplying or absorbing reactive power ?.
- (f) What is the difference between the total  $P$  GENERATION and the TOTAL LOAD ?.

SOLUTION

C:\GUNGOR\ACPF1B

The same steps are prompted by the program as in EXPERIMENT A1. Follow these steps except add Resistance and Susceptance into the line data. The Output Data results are as follows:

Y-BUS		
Y(1,1) =	1.56109	-6.59896
Y(1,2) =	-1.17647	4.70588
Y(1,3) =	-0.38462	1.92308
Y(2,1) =	-1.17647	4.70588
Y(2,2) =	1.80050	-8.58604
Y(2,3) =	-0.62402	3.90016
Y(3,1) =	-0.38462	1.92308
Y(3,2) =	-0.62402	3.90016
Y(3,3) =	1.00864	-5.79323

ITERATION= 1						
BUS	-QC	VR	VI	DQ	DE	DF
2	-0.1141	0.9976	0.0695	0.1141	-0.0024	-0.0695
3	0.0000	0.9264	-0.1112	0.0000	-0.0736	0.1112

ITERATION= 2						
BUS	-QC	VR	VI	DQ	DE	DF
2	0.0307	0.9998	0.0178	-0.1449	0.0023	0.0517
3	0.0000	0.9177	-0.1469	0.0000	-0.0087	0.0357

ITERATION= 3						
BUS	-QC	VR	VI	DQ	DE	DF
2	0.0953	1.0000	0.0002	-0.0646	0.0002	0.0176
3	0.0000	0.9153	-0.1594	0.0000	-0.0023	0.0124

ITERATION= 4						
BUS	-QC	VR	VI	DQ	DE	DF
2	0.1164	1.0000	-0.0059	-0.0210	-0.0000	0.0061
3	0.0000	0.9145	-0.1637	0.0000	-0.0008	0.0044

SOLUTION IN 5 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.020	0.000	92.821	29.792	50.000	10.000
2	1.000	-0.008	60.000	12.386	0.000	0.000
3	0.914	-0.165	0.000	0.000	100.000	20.000

LINE FLOWS (MW, MVAR)			
1	2	6.258	7.611
1	3	36.562	12.180
2	1	-6.204	-9.433
2	3	66.853	22.085
3	1	-35.082	-8.585
3	2	-64.852	-11.443
SYSTEM TOTALS			
P	GENERATION=	152.821	
Q	GENERATION=	42.178	
P	LOAD	=	150.000
Q	LOAD	=	30.000
P	LOSS	=	2.821
Q	LOSS	=	12.178

- (a)  $Y_{23} = -0.62402 + j 3.90016 = Y_{32}$ . (They are both the same as the admittance from bus 2 to 3 must be equal to the admittance from bus 3 to 2.)  
 A  $Y_{bus}$  has to be formulated as some of its elements are used in formulæ as part of the iterative process.

$Y_{22}$ ,  $Y_{21}$  and  $Y_{23}$  are the elements used to determine  $Q_C$  at bus 2 for iteration 1. Likewise for iteration 2 etc. Their values are  $1.80050 - j8.58604$ ,  $-1.7647 + j4.70588$  and  $-0.62402 + j3.90016$ .

- (b)  $VR = 0.9976$ ,  $VI = 0.0695$  for iteration 1 and 2.  
 $DE + jDF = (0.9976 + j0.0695) - (1 + j0) = -0.0024 + j0.0695$

(c)

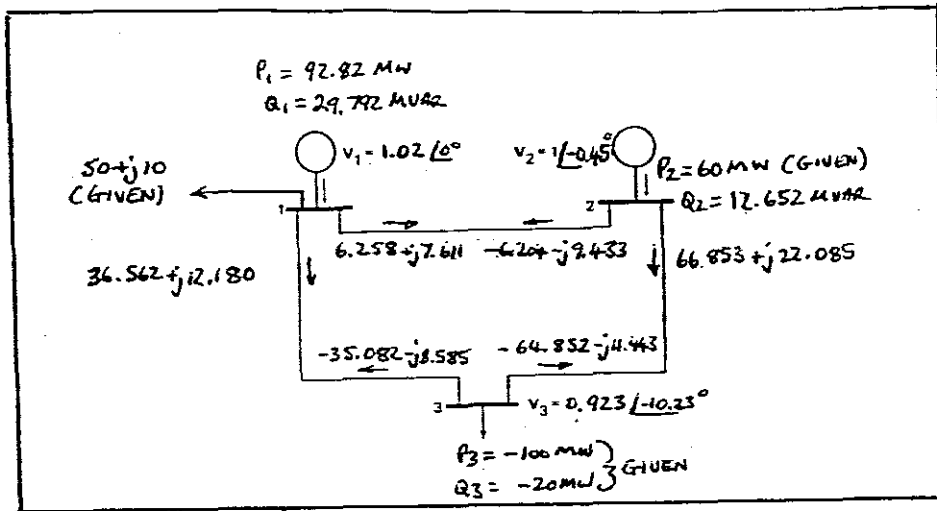


FIGURE.11

$$P1 \text{ GEN} = 36.562 + 6.258 + 50 = 92.82 \text{ MW}$$

$$P2 \text{ GEN} = 66.853 - 6.204 = 60.649 \text{ MW}$$

$$\text{TOTAL P GEN} = 153.469 \text{ MW AS AGAINST } 152.821 \text{ MW}$$

$$Q1 \text{ GEN} = 12.18 + 7.611 + 10 = 29.791 \text{ MVAR}$$

$$Q2 \text{ GEN} = 22.085 - 9.433 = 12.652 \text{ MVAR}$$

$$\text{TOTAL QGEN} = 42.443 \text{ MVAR AS AGAINST } 42.178 \text{ MVAR.}$$

(d) P LOSSES:

$$\text{LINE 1 to 2} = 6.258 - 6.204 = 0.054 \text{ MW}$$

$$1 \text{ to } 3 = 36.562 - 35.082 = 1.48 \text{ MW}$$

$$2 \text{ to } 3 = 66.853 - 64.852 = 2.001 \text{ MW}$$

$$\text{TOTAL P LOSS} = 3.535 \text{ MW}$$

which is similar to:

$$153.409 - 3.535 = 149.874 \approx 150 \text{ MW TOTAL P LOAD.}$$

$$(e) \text{ Q from 1 to 2} = 7.611$$

$$\text{Q from 2 to 1} = -9.433$$

Therefore  $9.433 - 7.611 = 1.822 \text{ MVAR Supplying.}$

Also  $Q2 \text{ GEN} = 22.085 - 9.433 = 12.652 \text{ MVAR}$  showing that MVARs are being supplied by line 1 to 2 towards bus 2.

$$\begin{aligned} (f) \text{ TOTAL P GENERATION} - \text{TOTAL P LOAD} &= 153.469 - 149.874 \\ &= 3.535 \text{ MW} \\ &= \text{P LOSS.} \end{aligned}$$

EXPERIMENT A 3  
5 BUS POWER SYSTEM  
3 GENERATORS  
R ≠ 0, Bc ≠ 0

INFORMATION AVAILABLE:

A five bus system having three generators with their reactances omitted has the following data:

No. of buses = 5  
No. of lines = 5  
No. of generators = 3  
Base MVA = 100  
Tolerance = 0.01  
Max. Iteration = 10

Line Data:

NS	NR	R	XL	BC
1	2	.03	.103	.05
1	4	.105	.347	.01
1	5	.08	.262	.02
3	4	.106	.403	.01
4	5	.033	.11	.05

Bus Data:

BUS	V	PG	PL	QL
1	.98	0	46.8	5.8
2	1.015	93	86	20
3	.953	51.5	0	0
4	1	0	36.2	-4.2
5	1	0	17.4	-1.0

EXPERIMENTAL REQUIREMENTS:

Use ACPFIB to determine:

- The load flow solution values for VR, VI, PG, QG, PL and QL for buses 1, 2, 3, 4 and 5.
- Sketch a one-line diagram and represent the power flow solution thereon.
- What PG does the swing bus deliver to the system?
- What is the QG for the swing bus? Does the swing bus deliver or absorb reactive power. Explain your answer with reference to the summation of reactive powers at the swing bus.
- Is generator 3 delivering or absorbing reactive power.

SOLUTION

C:\GUNGOR\ACPFIB

The same steps are prompted by the program as in the EXPERIMENT A1. Follow these steps and enter the Input Data. The Output Data results are as follows:

SOLUTION IN 5 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	0.980	0.000	44.766	-28.705	46.800	5.800
2	1.015	-0.003	93.000	47.303	86.000	20.000
3	0.924	0.231	51.500	-11.665	0.000	0.000
4	0.968	0.005	0.000	0.000	36.200	-4.200
5	0.973	-0.012	0.000	0.000	17.400	-1.000

LINE-FLOWS (MW, MVAR)			
1	2	-6.679	-36.155
1	4	-0.287	2.533
1	5	4.932	-0.884
2	1	7.000	27.303
3	4	51.691	-11.464
4	1	0.300	-4.386
4	3	-48.442	21.970
4	5	12.569	-13.016
5	1	-4.911	-2.862
5	4	-12.489	3.862
SYSTEM TOTALS			
P	GENERATION=	189.266	
Q	GENERATION=	6.933	
P	LOAD	= 186.400	
Q	LOAD	= 20.600	
P	LOSS	= 2.866	
Q	LOSS	= -13.667	

b)

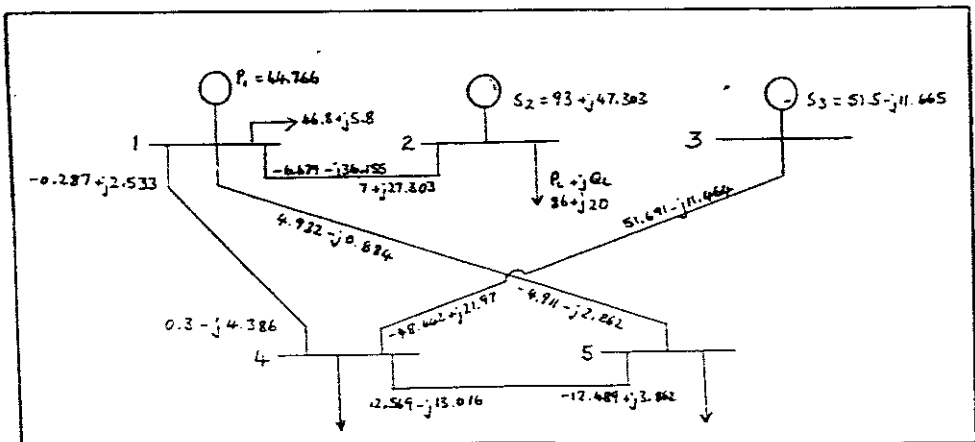


FIGURE 12.

- c)  $P_G = 44.766$  MW, this value being obtained from the results in "a" above or from:

$$P_1 = 46.8 - 6.679 + 4.932 - 0.287 = 44.776 \text{ MW}$$

- d)  $Q_G = -36.155$  (towards bus 1) -  $0.884$  (towards bus 1) +  $2.533$  (away from bus 1) +  $5.8$  (away from bus 1)

$Q_G = -28.705$  (towards bus 1). It is therefore absorbing reactive power.

- e) It is absorbing  $11.665$  MVAR. This being received from line 4 to 3.

b. PROGRAM ACPF2B - NEWTON RAPHSON

EXPERIMENT A 4  
3 BUS POWER SYSTEM  
 $R \neq 0, Bc \neq 0$

INFORMATION AVAILABLE:

A one line diagram of a three bus system with generator reactances omitted is shown in Figure 13.

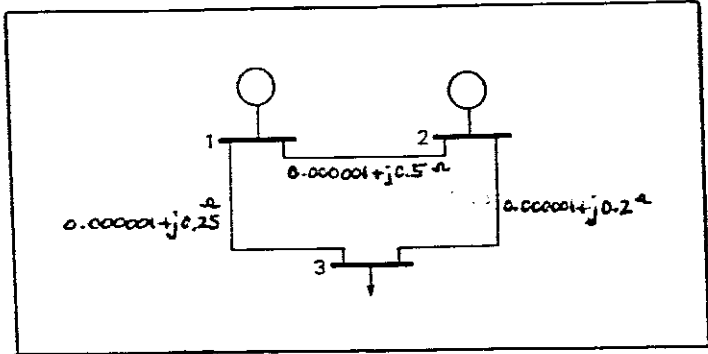


FIGURE.13

The impedances of the lines are given in pu on a 100 MVA base. The system contains no transformers or line susceptances. The lines have impedances of  $0.000001 + j0.5$  (line 1 to 2),  $0.000001 + j0.2$  (line 1 to 3) and  $0.000001 + j0.25$  (line 2 to 3).

Let:  $V1 = 1/_0^\circ$  pu,  
 $V2 = 1.0$  pu,  $P2 = 60$  MW  
 $P3 = -80$  MW,  $Q3 = -60$  MVAR (lag)

**EXPERIMENTAL REQUIREMENTS:**  
Use the program ACPF2B (Newton Raphson) and obtain the Ybus, the Jacobian Matrices and their inverses, all of the iterations, the line flows and the system totals. Tabulate the results in a power flow diagram and analyse and comment thereon.



SOLUTION

C:\GUNGOR\ACPF2B

Select "0" for screen output only.

The program then prompts for System Data:

No. of buses = ? Enter 3

No. of lines = ? Enter 3

No. of generators = ? Enter 2

Base MVA = ? Enter 100

Tolerance = ? Enter 0.01

Max. No. of iterations = ? Enter 10

The program next prompts for Line Data:

It requests that line data be entered under the headings, NS, NR, R, XL, BC for each line (NB! "Commas" and "R" must have some value otherwise Jacobian is singular).

Enter the data as:

LINE 1

? 1, 2, 0.000001, 0.5, 0 press enter

LINE 2

? 1, 3, 0.000001, 0.2, 0 press enter

LINE 3

? 2, 3, 0.000001, 0.25, 0 press enter

The program then prompts for the Bus Data:

It requests that the bus data be entered under the headings, V, PG, PL, QL for each bus (NB! "Commas")

Enter data as:

BUS 1

? 1, 0, 0, 0 press enter

BUS 2

? 1, 60, 0, 0 press enter

BUS 3

? 1, 0, 80, 60 press enter

This completes the Input Data.

The computer then prompts for:

"DO YOU WANT Y-BUS LISTED? (Y/N)?"

Select Y and the Ybus is displayed as follows:

YBUS		
Y(1,1)	=	0.00003 -7.00000
Y(1,2)	=	-0.00000 2.00000
Y(1,3)	=	-0.00002 5.00000
Y(2,1)	=	-0.00000 2.00000
Y(2,2)	=	0.00002 -6.00000
Y(2,3)	=	-0.00002 4.00000
Y(3,1)	=	-0.00002 5.00000
Y(3,2)	=	-0.00002 4.00000
Y(3,3)	=	0.00004 -9.00000

As "R" is small we can assume that the real component of each of the elements of the Ybus above are zero.

It then prompts:

"DO YOU WANT THE JACOBIAN LISTED? (Y/N)?"

Select Y and the Jacobian is listed:

JACOBIAN MATRIX	
J(1,1)=	0.00002
J(1,2)=	-0.00002
J(1,3)=	6.00000
J(1,4)=	-4.00000
J(2,1)=	-0.00002
J(2,2)=	0.00004
J(2,3)=	-4.00000
J(2,4)=	9.00000
J(3,1)=	6.00000
J(3,2)=	-4.00000
J(3,3)=	-0.00002
J(3,4)=	0.00002
J(4,1)=	-4.00000
J(4,2)=	9.00000
J(4,3)=	0.00002
J(4,4)=	-0.00004

As "R" was small we can assume that J11, J12, J21, J22, J33, J34, J43, J44 are zero.

It then prompts:

"DO YOU WANT J - INVERSE LISTED? (Y/N) ?"

Select Y and J - INVERSE is listed:

JACOBIAN INVERSE	
JI(1,1)=	-0.00020
JI(1,2)=	0.00086
JI(1,3)=	0.23121
JI(1,4)=	0.10558
JI(2,1)=	0.00117
JI(2,2)=	0.00325
JI(2,3)=	0.10276
JI(2,4)=	0.15837
JI(3,1)=	0.23684
JI(3,2)=	0.10526
JI(3,3)=	-0.00000
JI(3,4)=	-0.00000
JI(4,1)=	0.10526
JI(4,2)=	0.15789
JI(4,3)=	-0.00000
JI(4,4)=	-0.00000

It then prompts:

"DO YOU WANT RESULTS OF THIS ITERATION PRINTED? (Y/N)?"  
Select Y and iteration is listed:

ITERATION= 1									
BUS	PC	QC	DP	DQ	VR	VI	DE	DF	
2	0.0000	0.0000	0.6000	0.0000	0.9358	0.0579	-0.0642	0.0579	
3	0.0000	0.0000	-0.8000	-0.6000	0.9031	-0.0632	-0.0969	-0.0632	

It then prompts:

"DO YOU WANT RESULTS OF THIS ITERATION? (Y/N)?"  
Select Y for iteration 2

ITERATION= 2									
BUS	PC	QC	DP	DQ	VR	VI	DE	DF	
2	0.5613	0.0373	0.0387	-0.0373	0.9172	0.0630	-0.0186	0.0051	
3	-0.7613	-0.5055	-0.0387	-0.0945	0.8842	-0.0652	-0.0189	-0.0020	

It then prompts:

"DO YOU WANT JACOBIAN LISTED? (Y/N)?"

Select Y for JACOBIAN

JACOBIAN MATRIX	
J(1,1)=	0.26079
J(1,2)=	0.25191
J(1,3)=	5.53677
J(1,4)=	-3.66878
J(2,1)=	-0.26078
J(2,2)=	-0.25189
J(2,3)=	-3.53677
J(2,4)=	8.66877
J(3,1)=	5.46957
J(3,2)=	-3.66878
J(3,3)=	1.01652
J(3,4)=	-0.25191
J(4,1)=	-3.53677
J(4,2)=	7.24668
J(4,3)=	0.26078
J(4,4)=	-1.42542

It then prompts:

"DO YOU WANT J - INVERSE LISTED? (Y/N) "

Select Y for J - INVERSE

JACOBIAN INVERSE	
JI(1,1)=	-0.05300
JI(1,2)=	-0.00236
JI(1,3)=	0.29773
JI(1,4)=	0.14279
JI(2,1)=	-0.01614
JI(2,2)=	0.02638
JI(2,3)=	0.14697
JI(2,4)=	0.20898
JI(3,1)=	0.24993
JI(3,2)=	0.10390
JI(3,3)=	-0.01637
JI(3,4)=	-0.01283
JI(4,1)=	0.10003
JI(4,2)=	0.15844
JI(4,3)=	0.00655
JI(4,4)=	0.00513

It then prompts:

"DO YOU WANT RESULTS OF THIS ITERATION? (Y/N)?"

Select Y and as this is the last iteration it not only lists iteration 3, it also lists the solution in 3 iterations, the line flows and the systems totals:

ITERATION= 3								
BUS	PC	QC	DP	DQ	VR	VI	DE	DF
2	0.5879	0.0094	0.0121	-0.0094	0.9101	0.0652	-0.0071	0.0023
3	-0.7879	-0.5740	-0.0121	-0.0260	0.8769	-0.0661	-0.0073	-0.0009

SOLUTION IN 3 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.000	0.000	20.000	79.552	0.000	0.000
2	0.910	0.065	60.000	-0.002	0.000	0.000
3	0.877	-0.066	0.000	0.000	80.000	60.000

LINE FLOWS (MW, MVAR)			
1	2	-13.047	17.985
1	3	33.047	61.566
2	1	13.047	-15.517
2	3	46.942	15.515
3	1	-33.047	-51.801
3	2	-46.942	-8.175

SYSTEM TOTALS		
P GENERATION=		80.000
Q GENERATION=		79.550
P LOAD	=	80.000
Q LOAD	=	60.000
P LOSS	=	0.000
Q LOSS	=	19.550

The one-line diagram with the power solution thereof is:

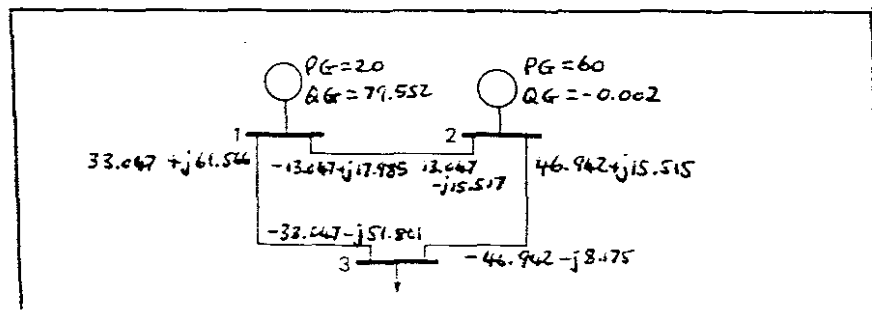


FIGURE 14.

**ANALYSIS AND COMMENTS:**

(a) The Jacobian matrix is for a system of only 3 buses. It is necessary to invert the Jacobian to solve for  $\delta$  and  $V$ , namely:

$$\begin{bmatrix} d\delta \\ dV \end{bmatrix} = \begin{bmatrix} & -1 \\ J & \end{bmatrix}^{-1} \begin{bmatrix} dP \\ dQ \end{bmatrix}$$

but before this can be solved  $dP$  (DP) and  $dQ$  (DQ) is calculated by the program for a bus.

For iteration 1,  $DP = 0.6$ ,  $DQ = 0$  for bus 2 and  $DP = -0.8$ ,  $DQ = -0.6$  for bus 3. These are the power differences between the specified and the calculated values.

(b) The program next calculates  $VR$  and  $VI$  for a iteration at a certain bus using the above matrix equation.  
 $VR = 0.9358$ ,  $VI = 0.0579$  for bus 2 and  $VR = 0.9031$  and  $VI = -0.0632$  for bus 3 for iteration 1. The program takes 3 iterations to obtain a solution, this giving the  $VR$  and  $VI$  for each bus the power flows:

$$\begin{aligned} VR &= 1, VI = 0.000, \text{ therefore } V1 = 1/\underline{0^\circ} \text{ pu V (bus 1)} \\ VR &= 0.91, VI = 0.065, \text{ therefore } V2 = 0.9/\underline{+0.001^\circ} \text{ pu (bus 2)} \\ VR &= 0.877, VI = -0.066, \text{ therefore } V3 = 0.88/\underline{-4.3^\circ} \text{ pu (bus 3)} \end{aligned}$$

(c) The program also calculates  $DE$  and  $DF$  for each iteration and for each bus, for iteration 1,  $DE = 0.0642$ ,  $DF = 0.0579$ , these being the voltage differences between the voltages calculated as  $VR$  and  $VI$  minus the initial or previous value of the voltage. These then being the corrected values of the voltage which are added to the previous values to obtain new values for  $PC$  and  $QC$  and for starting the next iteration.

(d) The program lists the solution and gives  $PG$ ,  $QG$ ,  $PL$  and  $QL$  for each bus for the power flows. (See one-line diagram)  
 $PG = 20 \text{ MW}$  for bus 1. This being the summation of the real power at bus 1, namely:

$$PG \text{ (bus 1)} = 33.047 - 13.047 = 20 \text{ MW}$$

$QG = 79.552 \text{ MVAR}$  for bus 1, namely:

$$QG \text{ (bus 1)} = 61.566 + 17.985 = 79.552 \text{ MVAR}$$

Likewise for bus 2

$$PG = 46.942 + 13.047 = 60 \text{ MW}$$

$$QG = 15.515 - 15.517 = -0.002 \text{ MVAR}$$

Likewise for bus 3

$$PL = +33.047 + 46.942 = 80 \text{ MW}$$

$$QL = 51.801 + 8.175 = 60 \text{ MVAR}$$

(e) The program also lists the System Totals :

P GENERATION	=	20 + 60	=	80MW
Q GENERATION	=	79.552 - 0.002	=	79.550 MVAR
P LOAD	=	80		MW
Q LOAD	=	60		MVAR
P LOSS	=	0	(This is due to the small "R" assumed for each line)	
Q LOSS	=	79.550 - 60	=	19.55 MVAR

EXPERIMENT A 5  
3 BUS POWER SYSTEM  
R ≠ 0 Bc ≠ 0

INFORMATION AVAILABLE:

The information is the same as EXPERIMENT A2 but is repeated here for convenience:

NO.OF BUSES= 3  
NO.OF LINES= 3  
NO.OF GEN = 2  
BASE MVA = 100  
TOLERANCE = .01  
MAX. ITER. = 10

LINE DATA

NS	NR	R	XL	BC
1	2	.05	.2	.01
1	3	.1	.5	.02
2	3	.04	.25	.01

BUS DATA

BUS	V	PG	PL	QL
1	1.02	0	50	10
2	1	60	0	0
3	1	0	100	20

EXPERIMENTAL REQUIREMENTS:

Use program ACPF2B.

- (a) Determine the Ybus and compare it with the Ybus results obtained in EXPERIMENT A2.
- (b) Determine the number of iterations taken by ACPF2B and compare them to the number of iterations taken by ACPF1B in EXPERIMENT A2.
- (c) Determine the value of voltages at each bus (VR and VI) and compare to VR and VI's obtained for EXPERIMENT A2
- (d) Determine the PG and QG for bus 1 and 2, show how each is made up by the summation of powers at each bus, then compare to EXPERIMENT A2.
- (e) Compare the system totals for this Experiment and Experiment A2.
- (f) What is your conclusion ?.



SOLUTION

C:\ GUNGOR \ ACPF2B

The same steps are prompted by the program as in EXPERIMENT A4. Follow the steps and obtain the Output Data results required, namely:

(a)

EXPERIMENT A5		
Y-BUS		
Y(1,1)=	1.56109	-6.59896
Y(1,2)=	-1.17647	4.70588
Y(1,3)=	-0.38462	1.92308
Y(2,1)=	-1.17647	4.70588
Y(2,2)=	1.80050	-8.58604
Y(2,3)=	-0.62402	3.90016
Y(3,1)=	-0.38462	1.92308
Y(3,2)=	-0.62402	3.90016
Y(3,3)=	1.00864	-5.79323

Programs ACPF1B and ACPF2B both produce the same Y bus

EXPERIMENT A2		
Y-BUS		
Y(1,1)=	1.56109	-6.59896
Y(1,2)=	-1.17647	4.70588
Y(1,3)=	-0.38462	1.92308
Y(2,1)=	-1.17647	4.70588
Y(2,2)=	1.80050	-8.58604
Y(2,3)=	-0.62402	3.90016
Y(3,1)=	-0.38462	1.92308
Y(3,2)=	-0.62402	3.90016
Y(3,3)=	1.00864	-5.79323

(b) The number of iterations taken by ACPF2B = 3 ITERATIONS  
The number taken by ACPF1B = 5 ITERATIONS.

(c)

EXPERIMENT A5						
SOLUTION IN 3 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.020	0.000	93.847	44.030	50.000	10.000
2	0.978	-0.004	60.000	0.001	0.000	0.000
3	0.898	-0.165	0.000	0.000	100.000	20.000

EXPERIMENT A2						
SOLUTION IN 5 ITERATIONS						
BUS	VR	VI	PG	QG	PL	QL
1	1.020	0.000	92.821	29.792	50.000	10.000
2	1.000	-0.008	60.000	12.386	0.000	0.000
3	0.914	-0.165	0.000	0.000	100.000	20.000

EXPERIMENT A5			EXPERIMENT A2	
BUS	VR	VI	VR	VI
1	1.02	0.00	1.02	0.00
2	0.978	-0.004	1.0	-0.008
3	0.898	-0.165	0.914	-0.165

It can be seen that there are slight discrepancies.  
(d)

EXPERIMENT A5				
LINE-FLOWS (MW, MVAR)				
1	2	6.722	18.565	
1	3	37.125	15.465	
2	1	-6.516	-19.737	
2	3	66.510	19.738	
3	1	-35.504	-11.108	
3	2	-64.482	-8.853	

EXPERIMENT A2				
LINE-FLOWS (MW, MVAR)				
1	2	6.258	7.611	
1	3	36.562	12.180	
2	1	-6.204	-9.433	
2	3	66.853	22.085	
3	1	-35.082	-8.585	
3	2	-64.852	-11.443	

PG (bus 1) = 6.722 + 37.125 + 50 = 93.847 as compared to 92.821 MW for Experiment A2.

PG (bus 2) = -6.516 + 66.510 = 60 MW which is the same for Experiment A2.

QG (bus 1) = 18.565 + 15.465 + 10 = 44.03 MVAR as compared to 29.792 MVAR for experiment A2.  
(Quite a large discrepancy).

QG (bus 2) = -19.737 + 19.738 = 0.001 MVAR as compared to 12.386 MVAR for Experiment A2 (Quite a large discrepancy).

EXPERIMENT A5	
SYSTEM TOTALS	
P GENERATION	= 153.847
Q GENERATION	= 44.032
P LOAD	= 150.000
Q LOAD	= 30.000
P LOSS	= 3.847
Q LOSS	= 14.032

EXPERIMENT A2	
SYSTEM TOTALS	
P GENERATION	= 152.821
Q GENERATION	= 42.178
P LOAD	= 150.000
Q LOAD	= 30.000
P LOSS	= 2.821
Q LOSS	= 12.178

P GENERATION	= 153.847 MW as compared to 152.821 MW
Q GENERATION	= 44.032 MVAR as compared to 42.178 MVAR
P LOAD	= 150.000 MW as compared to 150.000 MW
Q LOAD	= 30.000 MVAR as compared to 30.000 MVAR
P LOSS	= 3.847 MW as compared to 2.821 MW
Q LOSS	= 14.032 MVAR as compared to 12.178 MVAR

f) From the above there is a reasonable correlation between the results obtained from the two different iterative process programs. The Newton Raphson method however used only 3 iteration.

EXPERIMENT A 6  
5 BUS POWER SYSTEM  
R ≠ 0    Bc ≠ 0

INFORMATION AVAILABLE:

The information is the same as EXPERIMENT A3 but is repeated here for convenience:

NO. OF BUSES=	5
NO. OF LINES=	5
NO. OF GEN =	3
BASE MVA	= 100
TOLERANCE	= .01
MAX. ITER.	= 10

LINE DATA				
NS	NR	R	XL	BC
1	2	.03	.103	.05
1	4	.105	.347	.01
1	5	.08	.262	.02
3	4	.106	.403	.01
4	5	.033	.11	.05

BUS DATA				
BUS	V	PG	PL	QL
1	.98	0	46.8	5.8
2	1.015	93	86	20
3	.953	51.5	0	0
4	1	0	36.2	-4.2
5	1	0	17.4	-1

NB! The object of this experiment is to show how the program saves time and provides an accurate solution which would otherwise have been a very long hand calculation and may have included a number of errors.

**EXPERIMENTAL REQUIREMENTS**

Use program ACPF2B to determine all the results that can be provided by this program, namely Ybus, J-matrix, J-inverse matrix, iteration 1, iteration 2, J-matrix, J-inverse matrix, iteration 3, solution in 3 iterations, line flows and system totals.

Compare the System Totals obtained by this program to the System Totals obtained by experiment A3 to prove the accuracy of the two programs. Make a short comparison of the iteration methods.

SOLUTION

C:\GUNGOR\ACPF2B

The same steps are prompted by the program as in EXPERIMENT A4. Follow the steps and obtain the Output Data results required, namely:

Y-BUS		
Y(1,1)	=	4.47158 -15.00091
Y(1,2)	=	-2.60666 8.94952
Y(1,3)	=	0.00000 0.00000
Y(1,4)	=	-0.79888 2.64011
Y(1,5)	=	-1.06604 3.49129
Y(2,1)	=	-2.60666 8.94952
Y(2,2)	=	2.60666 - 8.89952
Y(2,3)	=	0.00000 0.00000
Y(2,4)	=	0.00000 0.00000
Y(2,5)	=	0.00000 0.00000
Y(3,1)	=	0.00000 0.00000
Y(3,2)	=	0.00000 0.00000
Y(3,3)	=	0.61044 - 2.31083
Y(3,4)	=	-0.61044 2.32083
Y(3,5)	=	0.00000 0.00000
Y(4,1)	=	-0.79888 2.640110
Y(4,2)	=	0.00000 0.00000
Y(4,3)	=	-0.61044 2.32083
Y(4,4)	=	3.91141 -13.23122
Y(4,5)	=	-2.50208 8.34028
Y(5,1)	=	-1.06604 3.49129
Y(5,2)	=	0.00000 0.00000
Y(5,3)	=	0.00000 0.00000
Y(5,4)	=	-2.50208 8.34028
Y(5,5)	=	3.56813 -11.76157

JACOBIAN MATRIX

J(1,1)= 2.73699  
J(1,2)= 0.00000  
J(1,3)= 0.00000  
J(1,4)= 0.00000  
J(1,5)= 8.77053  
J(1,6)= 0.00000  
J(1,7)= 0.00000  
J(1,8)= 0.00000  
J(2,1)= 0.00000  
J(2,2)= 0.55306  
J(2,3)= -0.58175  
J(2,4)= 0.00000  
J(2,5)= 0.00000  
J(2,6)= 2.32083  
J(2,7)= -2.21175  
J(2,8)= 0.00000  
J(3,1)= 0.00000  
J(3,2)= -0.61044  
J(3,3)= 3.95607  
J(3,4)= -2.50208  
J(3,5)= 0.00000  
J(3,6)= -2.32083  
J(3,7)= 13.13934  
J(3,8)= -8.34028  
J(4,1)= 0.00000  
J(4,2)= 0.00000  
J(4,3)= -2.50208  
J(4,4)= 3.58945  
J(4,5)= 0.00000  
J(4,6)= 0.00000  
J(4,7)= -8.34028  
J(4,8)= 11.76174  
J(5,1)= 9.29549  
J(5,2)= 0.00000  
J(5,3)= 0.00000  
J(5,4)= 0.00000  
J(5,5)= -2.55452  
J(5,6)= 0.00000  
J(5,7)= 0.00000  
J(5,8)= 0.00000  
J(6,1)= 0.00000  
J(6,2)= 2.08361  
J(6,3)= -2.21175  
J(6,4)= 0.00000  
J(6,5)= 0.00000  
J(6,6)= -0.61044  
J(6,7)= 0.58175  
J(6,8)= 0.00000  
J(7,1)= 0.00000  
J(7,2)= -2.32083  
J(7,3)= 13.32310  
J(7,4)= -8.34028  
J(7,5)= 0.00000  
J(7,6)= 0.61044  
J(7,7)= -3.86674  
J(7,8)= 2.50208

J(8,1) 0.00000  
J(8,2) 0.00000  
J(8,3) -8.34028  
J(8,4) 11.76139  
J(8,5) 0.00000  
J(8,6) 0.00000  
J(8,7) 2.50208  
J(8,8) -3.54681

JACOBIAN INVERSE

JI (1,1)= 0.02886  
JI (1,2)= 0.00000  
JI (1,3)= 0.00000  
JI (1,4)= 0.00000  
JI (1,5)= 0.09908  
JI (1,6)= 0.00000  
JI (1,7)= 0.00000  
JI (1,8)= 0.00000  
JI (2,1)= 0.00000  
JI (2,2)= 0.18320  
JI (2,3)= 0.05933  
JI (2,4)= 0.04221  
JI (2,5)= 0.00000  
JI (2,6)= 0.66665  
JI (2,7)= 0.19568  
JI (2,8)= 0.13850  
JI (3,1)= 0.00000  
JI (3,2)= 0.06146  
JI (3,3)= 0.05592  
JI (3,4)= 0.03978  
JI (3,5)= 0.00000  
JI (3,6)= 0.20552  
JI (3,7)= 0.18446  
JI (3,8)= 0.13056  
JI (4,1)= 0.00000  
JI (4,2)= 0.04371  
JI (4,3)= 0.03978  
JI (4,4)= 0.05178  
JI (4,5)= 0.00000  
JI (4,6)= 0.14547  
JI (4,7)= 0.13056  
JI (4,8)= 0.17026  
JI (5,1)= 0.10501  
JI (5,2)= 0.00000  
JI (5,3)= 0.00000  
JI (5,4)= 0.00000  
JI (5,5)= -0.03092  
JI (5,6)= 0.00000  
JI (5,7)= 0.00000  
JI (5,8)= 0.00000  
JI (6,1)= 0.00000  
JI (6,2)= 0.57566  
JI (6,3)= 0.17328  
JI (6,4)= 0.12264  
JI (6,5)= 0.00000  
JI (6,6)= -0.16378  
JI (6,7)= -0.05544  
JI (6,8)= -0.03988  
JI (7,1)= 0.00000  
JI (7,2)= 0.18157  
JI (7,3)= 0.18195  
JI (7,4)= 0.12878  
JI (7,5)= 0.00000  
JI (7,6)= -0.05922  
JI (7,7)= -0.05776  
JI (7,8)= -0.04155

J(8,1) 0.00000  
J(8,2) 0.12849  
J(8,3) 0.12878  
J(8,4) 0.16900  
J(8,5) 0.00000  
J(8,6) -0.04267  
J(8,7) -0.04156  
J(8,8) -0.05365

ITERATION= 1

BUS	PC	QC	DP	DQ	VR	VI	DE	DF
2	0.0926	0.2664	-0.0226	-0.4664	0.9681	0.0120	-0.0469	0.0120
3	-0.0273	-0.1130	0.5423	0.1130	1.0870	0.2016	0.1340	0.2016
4	0.0447	0.0919	-0.4067	-0.0499	1.0182	-0.0049	0.0182	-0.0049
5	0.0213	-0.0002	-0.1953	0.0102	1.0091	-0.0190	0.0091	-0.0190

ITERATION= 2

BUS	PC	QC	DP	DQ	VR	VI	DE	DF
2	0.0761	-0.1792	-0.0061	-0.0208	0.9659	0.0121	-0.0022	0.0000
3	0.5599	0.1294	-0.0449	-0.1294	0.9923	0.1987	-0.0947	-0.0029
4	-0.3697	0.0431	0.0077	-0.0011	0.9886	-0.0036	-0.296	0.0013
5	-0.1756	0.0138	0.0016	-0.0038	0.9879	-0.0177	-0.0212	0.0013

JACOBIAN MATRIX

J(1,1)= 2.48098  
J(1,2)= 0.00000  
J(1,3)= 0.00000  
J(1,4)= 0.00000  
J(1,5)= 8.83336  
J(1,6)= 0.00000  
J(1,7)= 0.00000  
J(1,8)= 0.00000  
J(2,1)= 0.00000  
J(2,2)= 0.61626  
J(2,3)= -0.14456  
J(2,4)= 0.00000  
J(2,5)= 0.00000  
J(2,6)= 2.53918  
J(2,7)= -2.42414  
J(2,8)= 0.00000  
J(3,1)= 0.00000  
J(3,2)= -0.61181  
J(3,3)= 3.56016  
J(3,4)= -2.50350  
J(3,5)= 0.00000  
J(3,6)= -2.29221  
J(3,7)= 13.02439  
J(3,8)= -8.23634  
J(4,1)= 0.00000  
J(4,2)= 0.00000  
J(4,3)= -2.61971  
J(4,4)= 3.56135  
J(4,5)= 0.00000  
J(4,6)= 0.00000  
J(4,7)= -8.19481  
J(4,8)= 11.54915

NB! The Jacobian is continued  
on the next page up to J(8,8)

J(5,1)=	8.42144
J(5,2)=	0.00000
J(5,3)=	0.00000
J(5,4)=	0.00000
J(5,5)=	-2.34001
J(5,6)=	0.00000
J(5,7)=	0.00000
J(5,8)=	0.00000
J(6,1)=	0.00000
J(6,2)=	2.28926
J(6,3)=	-2.42414
J(6,4)=	0.00000
J(6,5)=	0.00000
J(6,6)=	0.32315
J(6,7)=	0.14456
J(6,8)=	0.00000
J(7,1)=	0.00000
J(7,2)=	-2.29221
J(7,3)=	13.10866
J(7,4)=	-8.23634
J(7,5)=	0.00000
J(7,6)=	0.61181
J(7,7)=	-4.26846
J(7,8)=	2.50350
J(8,1)=	0.00000
J(8,2)=	0.00000
J(8,3)=	-8.19481
J(8,4)=	11.56229
J(8,5)=	0.00000
J(8,6)=	0.00000
J(8,7)=	2.61971
J(8,8)=	-3.90568



JACOBIAN INVERSE

JI(1,1)= 0.02918  
JI(1,2)= 0.00000  
JI(1,3)= 0.00000  
JI(1,4)= 0.00000  
JI(1,5)= 0.11015  
JI(1,6)= 0.00000  
JI(1,7)= 0.00000  
JI(1,8)= 0.00000  
JI(2,1)= 0.00000  
JI(2,2)= -0.11898  
JI(2,3)= 0.02721  
JI(2,4)= 0.02430  
JI(2,5)= 0.00000  
JI(2,6)= 0.70159  
JI(2,7)= 0.22518  
JI(2,8)= 0.15881  
JI(3,1)= 0.00000  
JI(3,2)= -0.02135  
JI(3,3)= 0.05924  
JI(3,4)= 0.04647  
JI(3,5)= 0.00000  
JI(3,6)= 0.21752  
JI(3,7)= 0.19569  
JI(3,8)= 0.13791  
JI(4,1)= 0.00000  
JI(4,2)= -0.01298  
JI(4,3)= 0.04430  
JI(4,4)= 0.06106  
JI(4,5)= 0.00000  
JI(4,6)= 0.15399  
JI(4,7)= 0.13848  
JI(4,8)= 0.17592  
JI(5,1)= 0.10501  
JI(5,2)= 0.00000  
JI(5,3)= 0.00000  
JI(5,4)= 0.00000  
JI(5,5)= -0.03094  
JI(5,6)= 0.00000  
JI(5,7)= 0.00000  
JI(5,8)= 0.00000  
JI(6,1)= 0.00000  
JI(6,2)= 0.59934  
JI(6,3)= 0.17031  
JI(6,4)= 0.11910  
JI(6,5)= 0.00000  
JI(6,6)= -0.21647  
JI(6,7)= -0.10052  
JI(6,8)= -0.07141  
JI(7,1)= 0.00000  
JI(7,2)= 0.18629  
JI(7,3)= 0.18178  
JI(7,4)= 0.12816  
JI(7,5)= 0.00000  
JI(7,6)= -0.06136  
JI(7,7)= -0.05971  
JI(7,8)= -0.04265

NB! The Jacobian Inverse is continued on the next page.

JI(8,1)=	0.00000
JI(8,2)=	0.13134
JI(8,3)=	0.12876
JI(8,4)=	0.16923
JI(8,5)=	0.00000
JI(8,6)=	-0.04168
JI(8,7)=	-0.04068
JI(8,8)=	-0.05323

ITERATION= 3

BUS	PC	QC	DP	DQ	VR	VI	DE	DF
2	0.0706	-0.1981	-0.0006	-0.0019	0.9657	0.0121	-0.0002	0.0000
3	0.4909	-0.0307	0.0241	0.0307	1.0103	0.2040	0.0181	0.0053
4	-0.3500	0.0429	-0.0120	-0.0009	0.9937	-0.0036	0.0051	-0.0001
5	-0.1700	0.0095	-0.0040	0.0005	0.9915	-0.0181	0.0036	-0.0003

SOLUTION IN 3 ITERATIONS

BUS	VR	VI	PG	QG	PL	QL
1	0.980	0.000	44.743	4.116	46.800	5.800
2	0.966	0.012	93.000	0.000	86.000	20.000
3	1.010	0.204	51.500	0.059	0.000	0.000
4	0.994	-0.004	0.000	0.000	36.200	-4.200
5	0.991	-0.018	0.000	0.000	17.400	-1.000

LINE FLOWS (MW, MVAR)

1	2	-6.909	10.849
1	4	-0.133	-4.803
1	5	4.985	-7.730
2	1	7.000	-20.000
3	4	51.523	0.059
4	1	0.149	2.908
4	3	-48.873	7.965
4	5	12.518	-6.674
5	1	-4.936	4.002
5	4	-12.465	-3.002

COMPARISON OF SYSTEM TOTALS		COMPARISON OF SYSTEM TOTALS	
EXPERIMENT A6		EXPERIMENT A3	
SYSTEM TOTALS		SYSTEM TOTALS	
P GENERATION=	189.243	P GENERATION=	189.266
Q GENERATION=	4.175	Q GENERATION=	6.933
P LOAD	= 186.400	P LOAD	= 186.400
Q LOAD	= 20.600	Q LOAD	= 20.600
P LOSS	= 2.843	P LOSS	= 2.866
Q LOSS	= -16.425	Q LOSS	= -13.667

CONCLUSION:

The results correlate with slight discrepancies proving the accuracy of the results and that both iterative methods lead to similar results. The above also shows just how much work is involved for only a 5 bus system.

SHORT COMPARISON OF GAUSS-SEIDEL AND NEWTON RAPHSON:

- a. The number of iterations required by the Newton-Raphson method using bus admittances is practically independent of the number of buses.
- b. The time for the Gauss-Seidel bus admittance method increases almost directly with the number of buses.
- c. On the otherhand, computing the elements of the JACOBIAN is time consuming and the time per iteration is considerably longer for the Newton-Raphson method.
- d. The advantage of shorter computer time for a solution of the same accuracy is in favour of the Newton-Raphson method for all but very small systems.

C.PROGRAM DCPFB-LINEARISED (DC) POWER FLOW

EXPERIMENT A7  
3 BUS POWER SYSTEM  
 $R = 0$   $B_c = 0$   $XL \neq 0$

INFORMATION AVAILABLE:

This information is similar to EXPERIMENT A1.

A one-line diagram of a three bus system with generator reactances omitted is shown in Figure 15.

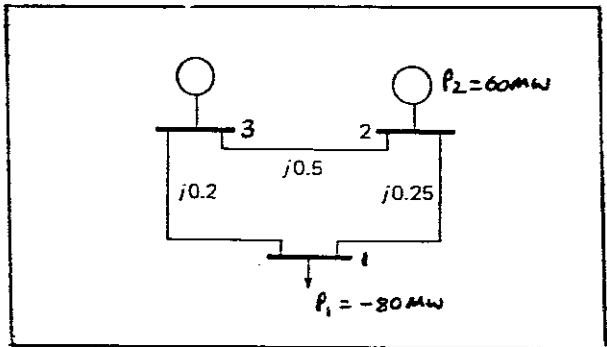


FIGURE 15

The reactances of the power system are given in pu on a 100 MVA base. The system contains no transformers, no line resistance nor susceptances. The lines have reactances of  $j0.25$  (1 to 2),  $j0.2$  (1 to 3) and  $j0.5$  (2 to 3). These being different to EXPERIMENT A1.

**EXPERIMENTAL REQUIREMENTS**

Use the program DCPFB to determine:

- The B-matrix. What is the B-matrix ?. Show how B11 is obtained.
- The B-inverse matrix. Why is it needed ?.
- The bus angles in radians and degrees.
- The line flows and the power delivered by the swing bus to the system. Show that  $P_2 + P_3 = P_1$ . Why are there no P Losses in the system ?.

SOLUTION

C:\GUNGOR\DCPFB.

The screen shows

```

PRINT OPTION:  P = 0  FOR SCREEN OUTPUT ONLY
                P = 1  FOR SCREEN & PRINTED OUTOUT
                P = 2  FOR SCREEN & DISK OUTPUT (DCPFB.OUT)
P = ?

```

Select "0"

The program then prompts for System Data:

No. of buses = ?, Enter 3

No. of lines = ?. Enter 3

Base MVA = ?, Enter 100

The program next prompts for Line Data:

It requests that line data be entered under the headings, NS, NR, XL(pu)

Enter the data as:

LINE 1

? 1, 2, 0.25 ("Commas" important) press enter

LINE 2

? 1, 3, 0.2 press enter

LINE 3

? 2, 3, 0.5 press enter

The program next prompts for the Bus Data:

It requests that the bus data be entered as P(MW), namely:

BUS 1

P(MW) (-FOR LOAD) = ?, Enter - 80 (load on bus 1)

BUS 2

P(MW) (-FOR LOAD) = ?, Enter 60 (generation on bus 2)

NB! The bus data is entered in ascending order and the swing bus becomes bus 3

The program next prompts:

"WANT B-MATRIX LISTED ? (Y/N)"

Select Y, press enter and B-matrix is displayed as follows:

```

a)  B MATRIX
     B(1,1)= 9.0000
     B(1,2)= -4.0000
     B(1,3)= -5.0000

     B(2,1)= -4.0000
     B(2,2)= 6.0000
     B(2,3)= -2.0000

     B(3,1)= -5.0000
     B(3,2)= -2.0000
     B(3,3)= 7.0000

```

$$B_{11} = \frac{1}{j0.25} + \frac{1}{j0.2}$$

$$= -j4 -j5$$

$$= -j9$$

but a -j not given in output data

$$B_{11} = 9$$

The B-matrix is the Susceptance matrix. Susceptance being the inverse of Admittance when R = 0.

The program next prompts for:

"WANT B-INVERSE LISTED (Y/N) ?."

Select Y, press enter and B-INVERSE is displayed:

b)

B-INVERSE	
X(1,1)=	0.1579
X(1,2)=	0.1053
X(2,1)=	0.1053
X(2,2)=	0.2368

The B-inverse is needed to determine angles, namely:

$[\delta]$	=	$[\mathbf{b}]^{-1}$	$[P]$
------------	---	---------------------	-------

c) The program then also displays:

ANGLES (IN RADIAN) ARE:	
THETA(1)=	-0.0632
THETA(2)=	0.0579
THETA(3)=	0.0000

THE BUS ANGLES ARE THEREFORE:	
BUS 1 =	-0.0632 rads = -3.62°
BUS 2 =	0.0579 rads = 3.317°
BUS 3 =	0.00 rads = 0°
(Swing bus)	

d) Also displayed are:

LINE FLOWS (MW)	
P(1,2)=	-48.4211
P(1,3)=	-31.5790
P(2,3)=	11.5789
P(3) =	20.0000

From which the following can be derived:

P1 = -48.4211 - 31.5790 = -80MW (LOAD)  
P2 = 48.4211 + 11.5789 = 60MW (GENERATION)  
P3 = -31.579 + 11.5789 = 20MW (GENERATION)  
(Swing bus)

EXPERIMENT A 8  
4 BUS POWER SYSTEM  
 $R=0, Bc = 0 XL \neq 0$

INFORMATION AVAILABLE:

A one-line diagram of a 4 bus system with generator reactances omitted is shown in Figure 16.

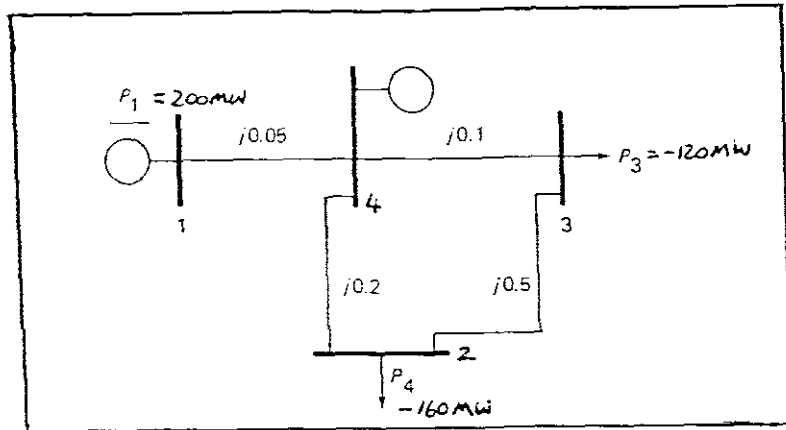


FIGURE 16.

The reactances are given on a 100 MVA base. Use Bus Data Powers in ascending order, namely 200 (bus 1), -100 (bus 2) and -120 (bus 3).

- EXPERIMENTAL RESULTS:  
Use program DCPFB to determine:
- a. The  $V/\delta^\circ$  for each bus in the system.
  - b. The line flows and the MW generation or loading at each bus. Sketch the power flow diagram.

SOLUTION

C:\GUNGOR\DCPFB

The same steps are prompted by the program as in EXPERIMENT A7. Follow the steps and obtain the Output Data results required, namely:

ANGLES (IN RADIAN) ARE:

THETA(1)= 0.1000  
THETA(2)= -0.2700  
THETA(3)= -0.1450  
THETA(4)= 0.0000

LINE FLOWS (MW)

P(1,4)= 199.9998  
P(2,3)= -25.0000  
P(2,4)= -135.0001  
P(3,4)= -145.0000  
  
P(4 )= 80.0000

a) Bus voltage and angles:

NB! With the linearised power flow procedure, it is assumed that all bus voltages are 1 pu.

Therefore:

BUS 1  
 $V_1 / \delta = 1 / 0.1 \text{ Rads} = 1 / 5.73 \text{ pu V}$   
  
BUS 2  
 $V_2 / \delta = 1 / -0.27 \text{ Rads} = 1 / -15.47^\circ \text{ pu V}$   
  
BUS 3  
 $V_3 / \delta = 1 / -0.145 \text{ Rads} = 1 / -8.3^\circ \text{ pu V}$   
  
BUS 4 (Swing bus)  
 $V_4 / \delta = 1 / 0^\circ \text{ Rads} = 1 / 0^\circ \text{ pu V}$



b)

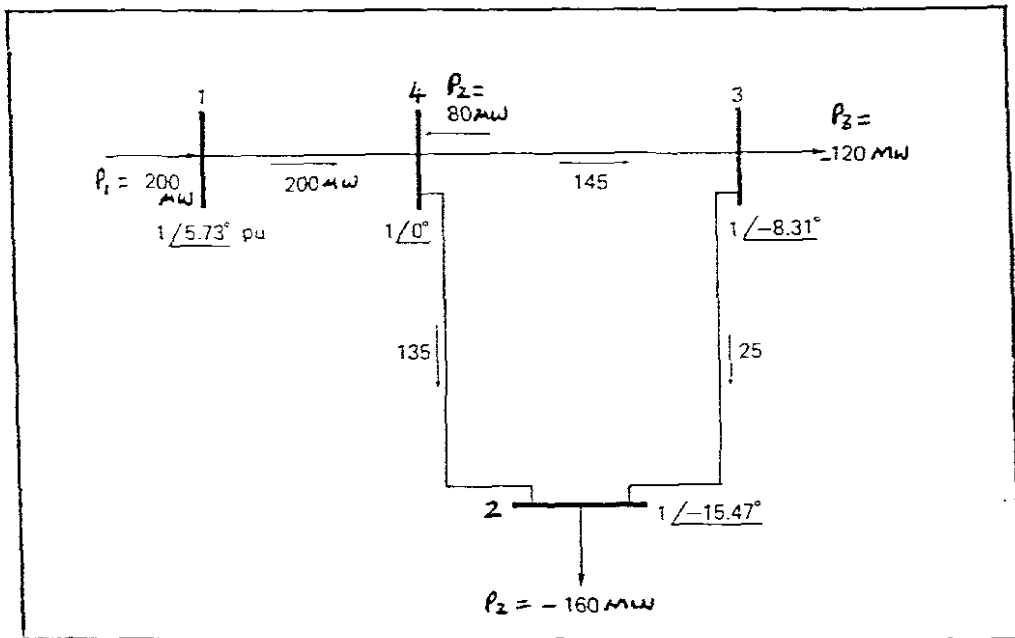


FIGURE 17.

P GENERATION	
P1	= 200 MW
P2	= -200 + 135 + 145 = 80 MW
P LOAD	
P3	= -145 + 25 = -120 MW
P4	= -135 - 25 = -160 MW

EXPERIMENT A9  
5 BUS 4 LINE POWER SYSTEM  
R = 0, Bc = 0, XL ≠ 0

INFORMATION AVAILABLE

The system has the following data:

NO. OF BUSES	=	5
NO. OF LINES	=	4
BASE MVA	=	100

LINE DATA		
NS	NR	XL pu
1	5	0.05
2	3	0.03
2	5	0.25
4	5	0.06

BUS DATA	
NO.	POWER (MW)
1	-200
2	-120
3	100
4	150

EXPERIMENTAL REQUIREMENTS:

Use DCPFB to derive the one-line power flow diagram also indicate thereon the bus voltages with their angles. Sum up the MW loading at the reference bus to obtain the P GENERATION for the swing bus.

SOLUTION

C:\GUNGOR\DCPFB.

Follow the same steps prompted by the program as was prompted in EXPERIMENT A7 to obtain the desired Output Data results.

a)

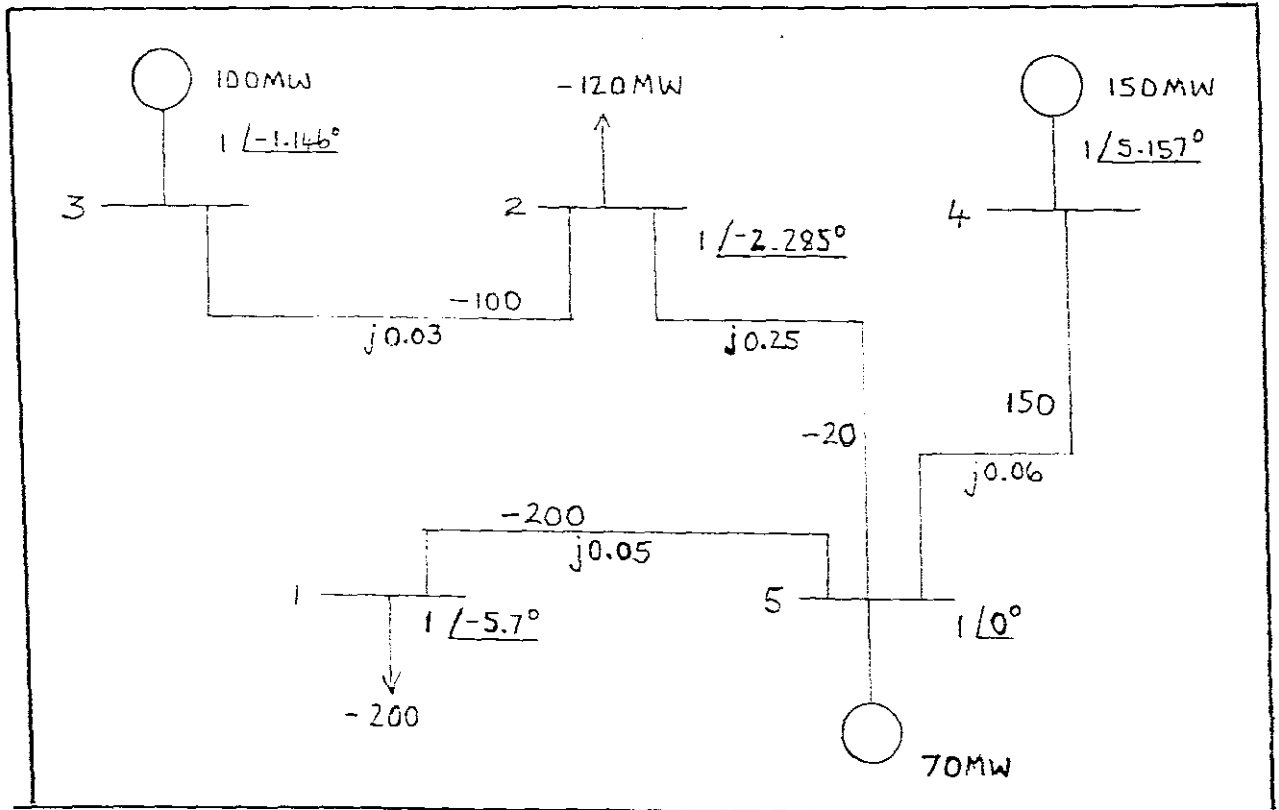


FIGURE 18.

RADIANS		DEGREES	
$\delta_1$	=	-0.1	-5.700
$\delta_2$	=	-0.05	-2.865
$\delta_3$	=	-0.02	-1.146
$\delta_4$	=	0.09	5.157
$\delta_5$	=	0.00	0.000

pu VOLTS	
V1	= 1/ $\underline{-5.7^\circ}$
V2	= 1/ $\underline{-2.285^\circ}$
V3	= 1/ $\underline{-1.146^\circ}$
V4	= 1/ $\underline{5.157^\circ}$
V5	= 1/ $\underline{0^\circ}$

LINE FLOWS (MW)	
P(1,5)	= -200
P(2,3)	= -100
P(2,5)	= -20
P(4,5)	= 150

$P_5 = +200 + 20 - 150 = 70\text{MW GENERATION}$

3. EXPERIMENTATION FOR SELF EVALUATION

1. EXPERIMENT A10

INFORMATION AVAILABLE:

No. of buses	=	7
No. of lines	=	9
No. of Gen	=	3
Base MVA	=	100
Tolerance	=	0.001
Max. Iter.	=	10

LINE DATA

NS	NR	R	XL	Bc
1	2	0.072	0.288	0.018
1	6	.056	.148	.009
1	7	.109	.225	.057
2	6	.0415	.108	.026
3	4	.001	.053	0
3	5	.014	.127	.134
4	7	.093	.244	.014
5	6	.001	.026	0
6	7	.09	.236	.014

BUS DATA

BUS				
1	1.03	0	75	20
2	1.02	75	50	10
3	1	200	0	0
4	1	0	60	15
5	1	0	0	0
6	1	0	100	10
7	1	0	50	10

EXPERIMENTAL REQUIREMENTS:

Use ACPF2B to determine:

- DE and DF at bus 2 for Iteration 1.
- DE and DF at bus 7 for Iteration 2.
- VR and VI at buses 1 and 7 for Iteration 3.
- The line flow for line 3 to 4.
- The total P GENERATION and Q GENERATION.
- The total P LOAD and Q LOAD.
- The total P LOSS and Q LOSS.

EXPERIMENTAL ANSWERS:

- 0.021, 0.0267.
- 0.0233, 0.0049.
- 1.03, 0.00, 1.007, 0.001.
- 101.573 + j12.565
- 338.375, 32.219.
- 335.000, 65.000
- 3.375, -32.781

2. EXPERIMENT A11

INFORMATION AVAILABLE

CASE ONE		
NO. OF BUSES	=	5
NO. OF LINES	=	7
BASE MVA	=	100
LINE DATA		
NS	NR	XL (pu)
1	2	.24
1	4	.12
2	3	.03
2	4	.18
3	4	.18
3	5	.24
4	5	.06
BUS DATA		
NO.	POWER (MW)	
1	-60	
2	-40	
3	-15	
4	20	

CASE TWO		
NO. OF BUSES	=	5
NO. OF LINES	=	7
BASE MVA	=	100
LINE DATA		
NS	NR	XL(pu)
2	5	.06
3	5	.24
2	3	.18
2	4	.18
1	2	.12
3	4	.03
1	4	.24
BUS DATA		
NO.	POWER(MW)	
1	-60	
2	20	
3	-15	
4	-40	

**EXPERIMENTAL REQUIREMENTS:**  
 Use DCPFB and run the program for CASE ONE and TWO and in each case derive a power flow diagram indicating thereon the bus voltages and their angles as well as the power flows in each line. What is the P GENERATION for the swing bus in each case. Compare your diagrams and make a conclusion.

EXPERIMENTAL ANSWERS

NB! The diagrams are not given as this detracts from the solution and the conclusion. To ensure that your answers are correct the following results are provided.

CASE ONE	
LINE FLOWS (MW)	
P(1,2)	= -9.7143
P(1,4)	= -50.2858
P(2,3)	= -29.1430
P(2,4)	= -20.5715
P(3,4)	= -15.7143
P(3,5)	= -28.4286
P(4,5)	= -66.5715

CASE TWO	
LINE-FLOWS (MW)	
P(1,2)	= -50.2857
P(1,4)	= -9.7143
P(2,3)	= 15.7143
P(2,4)	= 20.5714
P(2,5)	= -66.5715
P(3,4)	= 29.1428
P(3,5)	= -28.4286

SECTION B

TABLE OF COMPARISON OF THE MAIN POINTS OF THE PROGRAMS

ACPF1B

1. Follows Gauss-Seidel Iterative procedure with Ybus.
2. Program provides and AC power flow solution.
3. Program does not provide for entering generator impedance.
4. The program does not include graphics, therefore a one-line diagram cannot be obtained from the computer. One has to draw ones own representation.
5. The program does not give the mismatch value at a bus. This has to be hand calculated.
6. The program does not provide for tap changing transformers nor for maximum loadings.

ACPF2B

1. Follows Newton-Raphson Iterative procedure with Ybus.
2. Program provides and AC power flow solution.
3. Program does not provide for entering generator impedance.
4. The program does not include graphics, therefore a one-line diagram cannot be obtained from the computer. One has to draw ones own representation.
5. The program does not give the mismatch value at a bus. This has to be hand calculated.
6. The program does not provide for tap changing transformers nor for maximum loadings.
7. "R" cannot be entered as "0" as this results in the JACOBIAN becoming singular and hence no solution. To overcome this a very small value for "R" has to be entered for a solution.
8. Results are the same for the same network as used in ACPF1B proving the accuracy of both programs.

DCPFB

1. This program provides a D.C. linearized power flow solution. Uses Susceptance matrix [b] not a Ybus.
2. This program provides an approximate solution of the AC Load Flow.
3. Program does not provide for entering generator impedance.
4. The program does not include graphics, therefore a one-line diagram cannot be obtained from the computer. One has to draw ones own representation.
5. The program does not give the mismatch value at a bus. This has to be hand calculated.
6. The program does not provide for tap changing transformers nor for maximum loadings.
7. This program is useful for calculation of real power flows.
8. As equations used are linear the program does not use an iterative method.
9. The program does not request a pre-select tolerance.
10. Bus angles are given in radians requiring hand calculations to convert to degrees.

SECTION C

BIBLIOGRAPHY :

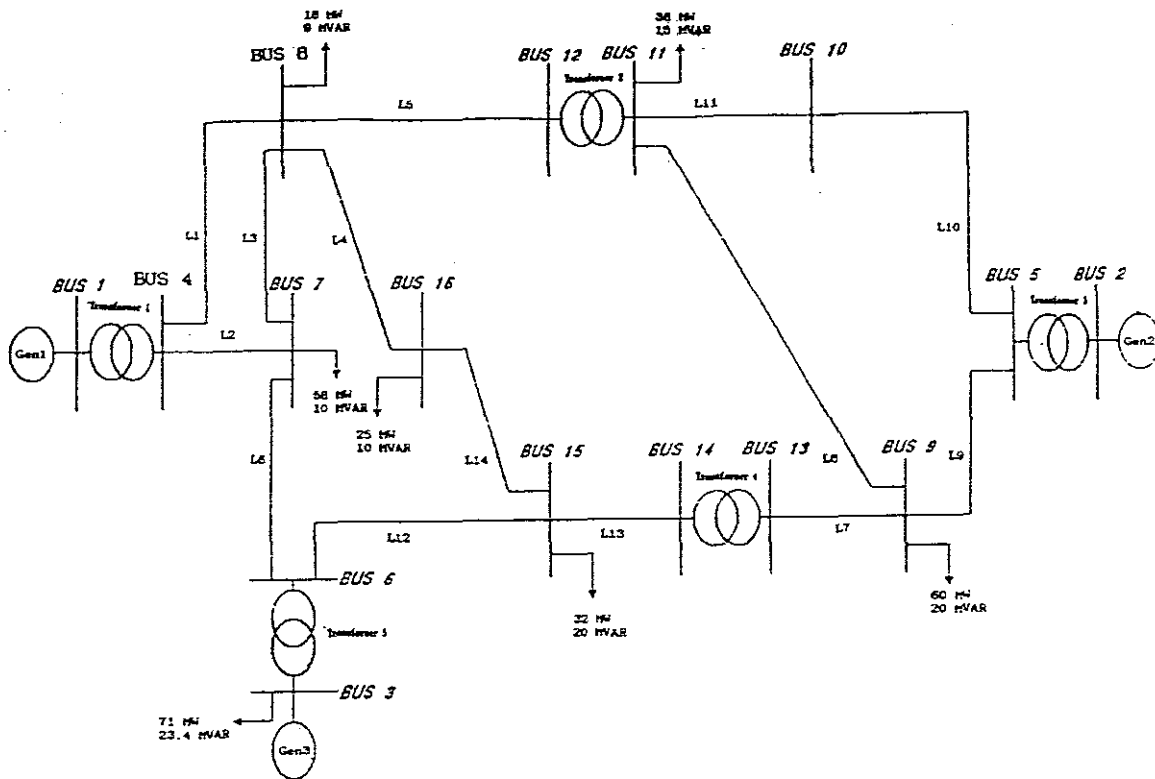
- a. GUNGOR'S PROGRAMS ACPF1B, ACPF1B, ACPF2B AND DCPFB.
- b. GUNGOR - POWER SYSTEMS.
- c. STEVENSON - ELEMENTS OF POWER SYSTEM ANALYSIS.

THE USE OF A COMPUTER TO ANALYSE A

16-BUS 3 GENERATOR POWER SYSTEM

WITH REGARDS TO LOAD FLOW, FAULT STUDIES, TRANSIENT

STABILITY AND ECONOMIC DESPATCH



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**THE USE OF A COMPUTER TO ANALYSE A 16 BUS 3 GENERATOR POWER SYSTEM WITH REGARDS TO LOAD FLOW, FAULT STUDIES, TRANSIENT STABILITY AND ECONOMIC DISPATCH.**

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**THE USE OF A COMPUTER TO ANALYSE A 16 BUS  
3 GENERATOR POWER SYSTEM WITH REGARDS TO  
LOAD FLOW, FAULT STUDIES, TRANSIENT STABILITY  
AND ECONOMIC DISPATCH**

**INTRODUCTION**

The electric power industry is witnessing the significant impact of personal computer (PCs) in the analysis and design of transmission and distribution systems (Bengiamin and Holcomb, 1992:1).

The work to follow will make use of different software to analyse a 16 bus, 3 generator power system with regard to load flow, symmetrical and assymetrical faults, transient stability and economic dispatch.

The following diagram and data for the 16 bus power system was received and forms the basis of the study.

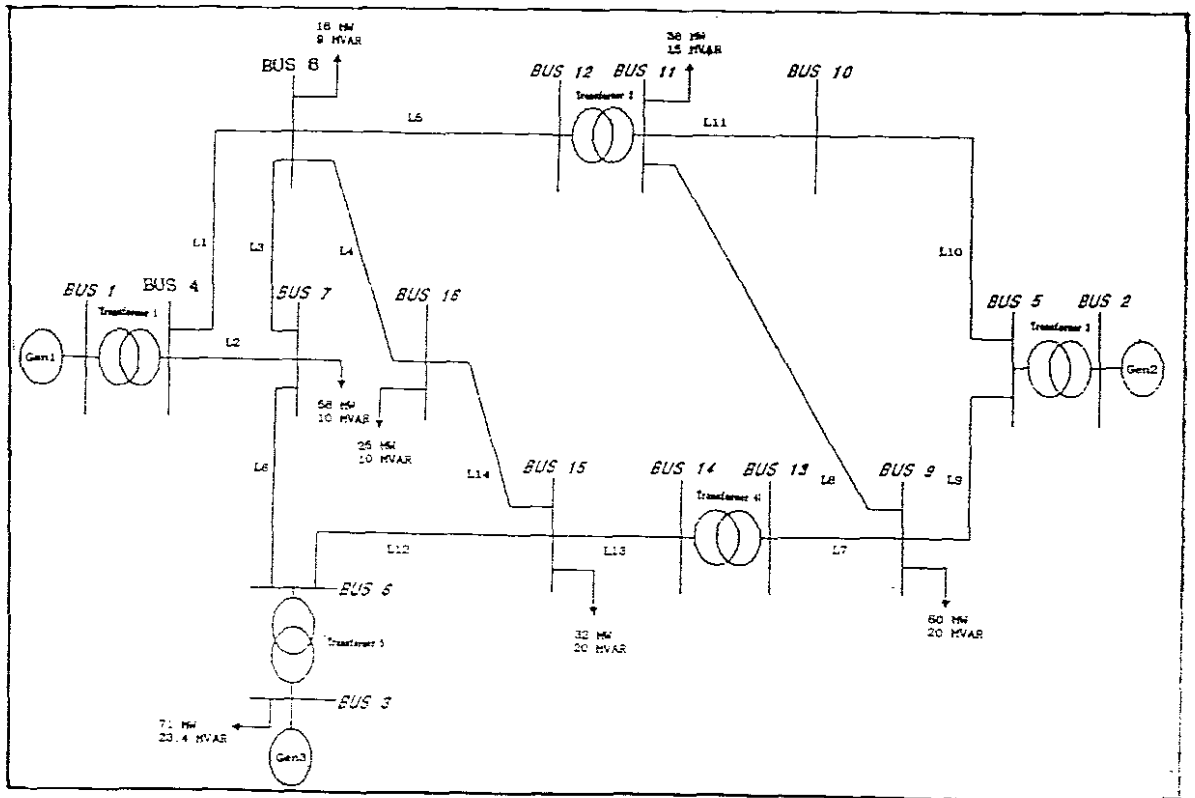


FIGURE. 1

SYSTEM POWER BASE = 100 MVA

**GENERATOR DATA**

No.	Type	Rating MVA	Conne ction	Power real min MW	Power real max MW	Power react min MVAR	Power react max MVAR	Volt Sched KV
G1	fossil	270	delta	50	200	-100	100	18
G2	nu - clear	245	star- grnd	35	300	-100	100	14.4
G3	hydro	260	delta	25	250	-100	100	15

TABLE.1

**GENERATOR IMPEDANCE DATA**

No.	R1 $\Omega$	X1 $\Omega$	R2 $\Omega$	X2 $\Omega$	Xo $\Omega$	Xd' $\Omega$	Xd'' $\Omega$
G1	0.0019	2.04	0	0.140	0.060	0.256	0.185
G2	0.0032	1.70	0.0211	0.160	0.110	0.320	0.21
G3	0.0021	2.39	0.0225	0.258	0.135	0.302	0.26

TABLE.2

**TRANSFORMER DATA**

No.	Type	Tran Rating MVA	Prim Conn	Sec Conn	Prim Volt KV	Sec Volt KV	R [%] Based on 100 MVA	X [%]	G&B [%]	Max- Tap
T1	fixed	270	delta	star- grnd	18	230	0.01	6.25	0	1
T2	tap sec	400	star- grnd	star- grnd	230	132	0.01	6.5	0	1.15
T3	fixed	250	delta	star- grnd	14.4	132	0.01	6.0	0	1
T4	tap sec	400	star- grnd	star- grnd	230	132	0.01	5.7	0	1.15
T5	fixed	260	delta	star- grnd	15	230	0.01	6.25	0	1

TABLE.3

**LOAD DATA**

BASE LOAD				HEAVY LOAD		
Busbar no.	Pload MW	Qload MVAR	Sload MVA	Pload MW	Qload MVAR	Sload MVA
B7	58	10	58.86	65	70	95.50
B8	18	9	20.12	48.7	25.1	54.79
B11	36	15	39	39.7	16.7	43.07
B9	60	20	63.25	56.9	18.9	59.96
B15	32	20	37.74	35.3	19	40.01
B3	71	23.5	74.76	56.9	18.7	59.89
B16	25	10	26.93	39.3	21.8	44.94

TABLE.4

**GENERATOR SCHEDULING**

Generator no.	Base Load Real power MW	Heavy Load Real power MW
G2	98	150
G3	100	100

TABLE.5a

**GENERATOR COSTS**

No.	Input/Output Curve	Order	Coefficient	Fuel Cost	H
1	Polynomial	2	a = 105 b = 1.5 c = 0.0015	1.0	3.3
2	Polynomial	2	a = 225 b = 1.6 c = 0.00142	1.0	6.3
3	Polynomial	2	a = 130 b = 1.35 c = 0.004	1.0	2.4

TABLE.5b

LINE DATA

Line no.	From node	To node	length Km	R1 $\Omega$ /Km	X1 $\Omega$ /Km	B1 $\mu$ MHO/Km	Ro $\Omega$ /Km	Xo $\Omega$ /Km	Bo $\mu$ MHO/Km	Rating MVA
L1	4	8	10	0.072	0.401	2.92	0.38	1.29	2	150
L2	4	7	20	0.072	0.401	2.92	0.38	1.29	2	150
L3	7	8	35	0.072	0.401	2.92	0.38	1.29	2	150
L4	8	16	30	0.072	0.401	2.92	0.38	1.29	2	150
L5	8	12	33	0.072	0.401	2.92	0.38	1.29	2	150
L6	6	7	30	0.188	0.418	2.760	0.47	1.473	1.980	150
L7	9	13	15	0.145	0.410	2.810	0.43	1.465	2.010	150
L8	9	11	17	0.291	0.450	2.650	0.576	1.50	1.930	150
L9	5	9	11	0.117	0.403	2.869	0.402	1.458	2.040	150
L10	5	10	40	0.145	0.410	2.810	0.430	1.465	2.01	150
L11	10	11	25	0.145	0.410	2.810	0.430	1.465	2.01	150
L12	6	15	22	0.072	0.401	2.92	0.38	1.29	2	150
L13	14	15	30	0.072	0.401	2.92	0.38	1.29	2	150
L14	15	16	10	0.072	0.401	2.92	0.38	1.29	2	150

TABLE.6

This received data is used to analyse the 16bus 3 generator power system with regards to Load Flow, Fault Studies, Transient Stability and Economic Despatch.

**CHAPTER ONE  
LOAD FLOW COMPUTER EXPERIMENTS  
ON THE 16 BUS 3 GENERATOR POWER SYSTEM**

Load flow is the calculation of the real and reactive powers flowing in each line and the magnitude and phase angle of the voltage at each bus of a given transmission system for specified generation and load conditions. The information obtained from the load flow studies can be used to test the system's capabilities to transfer energy from generation to load without overloading lines and to determine the adequacy of voltage regulation by capacitors, shunt reactors, tap changing transformers and the var-supplying capabilities of rotating machines (Gonan, 1987:460).

**1. EXPLANATION OF THE USAGE OF THE PROGRAMS**

**a. PROGRAM "POWER FLOW" BY GLOVER**

This program computes the voltage magnitude and phase angle at each bus in a power system under balanced three-phase steady-state operation. Bus voltages and phase angles are then used to compute generator, line and transformer loadings.

The maximum number of buses is 100. RAM up to 1 Meg is required for 100 buses. The maximum number of transmission lines or transformers is also 100.

Input data for the program consists of bus, line and transformer data. Examples of Tables of typical input data are as follows:

**(1) BUS DATA:**

BUS	TYPE	V	$\delta$	PG	QG	PL	QL	QG max	QG min
		per unit	degrees	per unit	per unit	per unit	per unit	per unit	per unit
1	Swing	1.0	0	-	-	0	0	-	-
2	Load	-	-	0	0	2.0	0.7	-	-
3	Constant voltage	1.05	-	1.3	-	0.2	0.1	1.0	-0.7
4	Load	-	-	0	0	0	0	-	-
5	Load	-	-	0	0	0	0	-	-

TABLE.7

where:

- Bus = Bus Number
- Type = Type of Bus, either Swing (Type 0), Load (Type 1) Voltage controlled bus (Type 2) and Voltage controlled bus with tap-changing transformer (Type 3).
- V = Bus Voltage
- $\delta$  = bus phase angle delta in degrees
- PG = Power Generation
- QG = Reactive Power generation
- PL = Load Power
- QL = Load Reactive Power
- QGMAX & QGMIN = Maximum and Minimum limits on reactive generation for voltage controlled (type 2) buses.

The swing bus is always bus 1 for this program and all data must be in per-unit on a common MVA base.

(11) LINE DATA

LINE	BUS-TO-BUS	R	X	G	B	MAX MVA
		per unit	per unit	per unit	per unit	per unit
1	2-4	0.036	0.4	0	0.43	3.0
2	2-5	0.018	0.2	0	0.22	3.0
3	4-5	0.009	0.1	0	0.11	3.0

TABLE.8

where:

- Line = Line Number
- Bus-to-bus = The two buses to which the line is connected
- R = Per-unit total line series resistance
- X = Per-unit total line series reactance
- G = Per-unit total line shunt conductance
- B = Per-unit total line shunt susceptance
- MAX MVA = Per-unit maximum line loading (apparent power)

NB! If the line data is received in per kilometer values as is the case for the 16 bus system being analysed, then these values have to be converted by hand to pu values as the "Power Flow" program only accepts data as per-unit and if all are referred to a common MVA base.

As lines usually include series impedance and shunt susceptance they both have to be converted to pu values.

The following steps are used to obtain pu values:

**SERIES IMPEDANCE**

STEP 1: Find series resistance and reactance for the line by multiplying the resistance and reactance/km by the length of the line.

STEP 2: Convert to Zactual for the line.

$$Z_{actual} = R_{actual} + j X_{actual}$$

STEP 3: Find Zbase for the particular zone in the power system from:

$$Z_{base} = \frac{kV^2}{MVA \text{ (rated)}}$$

STEP 4: Find Zpu (rated):

$$Z_{pu \text{ (rated)}} = \frac{Z_{actual}}{Z_{base}}$$

$$Z_{pu \text{ (rated)}} = \frac{Z_{actual} \text{ MVA (rated)}}{kV^2}$$

STEP 5: Find Zpu (new):

$$Z_{pu \text{ (new)}} = \frac{Z_{actual} \text{ MVA (rated)}}{kV^2} \times \frac{MVA \text{ (new)}}{MVA \text{ (rated)}}$$

$$Z_{pu \text{ (new)}} = \frac{Z_{actual} \text{ MVA (new)}}{kV^2}$$

or

$$Z_{pu \text{ (new)}} = \frac{Z_{actual}}{Z_{base \text{ (new)}}}$$



**SHUNT SUSCEPTANCE  
AND CHARGING CURRENT**

STEP 1. Find the actual susceptance for the line by multiplying the susceptance per kilometer by the length of the line.

STEP 2. Invert to obtain Xc actual.

STEP 3. Find Zbase for the particular zone in the power system from:

$$Z_{base} = \frac{kV^2}{MVA \text{ (rated)}}$$

STEP 4. Find Xcpu (rated):

$$X_{cpu} \text{ (rated)} = \frac{Xc \text{ actual}}{Z \text{ base}}$$

$$X_{cpu} \text{ (rated)} = \frac{Xc \text{ actual MVA (rated)}}{kV^2}$$

STEP 5. Find Xcpu (new) =  $\frac{Xc \text{ actual MVA (rated)}}{kV^2} \times \frac{MVA \text{ (new)}}{MVA \text{ (rated)}}$

$$X_{cpu} \text{ (new)} = \frac{Xc \text{ actual MVA (new)}}{kV^2}$$

but

$$Xc \text{ actual} = \frac{1}{Bc \text{ actual}}$$

STEP 6. Find Bc (new) pu:

$$\frac{1}{Bc \text{ (new) pu}} = \frac{MVA \text{ (new)}}{Bc \text{ actual } kV^2}$$

i.e. 
$$Bc \text{ (new) pu} = \frac{Bc \text{ actual } kV^2}{MVA \text{ (new)}} = \frac{Bc \text{ actual } Z_{base} \text{ (new)}}{MVA \text{ (new)}}$$

and if 1/2 Bc required, divide answer by 2.

STEP 7. Find I charging for half susceptances:

$$I \text{ charging} = \frac{V \text{ pu } B_c \text{ (new) pu}}{2}$$

where : Vpu = rated voltage pu to neutral  
 Bc = Total capacitive susceptance for a line.

NB! Only positive sequence line data is required for load flow.

(111) TRANSFORMER DATA

TRAN	Bus to Bus	R	X	G	B	MAX MVA	MAX TAP SET
		per unit	per unit	per unit	per unit	per unit	per unit
1	1-5	0.006	0.08	0	0	1.5	-
2	3-4	0.003	0.04	0	0	2.5	-

TABLE 9.

where:

- TRAN = Transformer Number
- Bus-to-Bus = The two buses to which the transformer is connected
- R = Per-unit winding resistance
- X = Per-unit leakage reactance
- G = Per-unit core loss conductance
- B = Per-unit magnetising susceptance
- MAX MVA = Per-unit maximum transformer loading (Apparent Power)
- MAX TAP = Per-unit maximum tap setting (1.0 to 1.25)

With the "Power Flow" program the transformers can be operated with fixed tapplings or as automatic tap changing transformers.

The program will prompt "DO ANY OF THE TRANSFORMERS HAVE TAP-CHANGERS WITH FIXED TAP SETTINGS (Y OR N)?"

If "Y" is answered, the specific transformer is then set to a fixed tap. Fixed tap-settings to be between 0.75 to 1.25.

The program assumes that the tap is on the same side of the transformer as the **second** bus number of that transformer.

If "N" is answered then this means an automatic tap changing transformer used with a **Type 3** bus. (See page 6 for the meaning of a Type 3 bus).

NB! When a user designates a Type 3 bus in his bus input data, then there must be a transformer in the transformer input data whose **second** bus number is the voltage controlled bus.

The program will warn the user when there is a Type 3 bus and no transformer whose second bus number is the Type 3 bus. Here the program also assumes that the tap is on the same side of the transformer as the second bus number of that transformer.

When the program runs and a Type 3 bus is specified with a tap-changing transformer, it varies the tap-setting connected to the Type 3 bus until:

- (I) The computed bus voltage is within  $\pm 0.4\%$  of the input bus voltage, or
- (II) The maximum or minimum tap setting is reached.

The user inputs a value from 1 to 1.25 for the maximum tap (MAX TAP) and the program sets the minimum tap (MIN TAP) equal to  $(2.0 - \text{MAX TAP})$ .

NB! With fixed tapplings the bus voltages may vary greater than the allowed  $\pm 5\%$  of lpu voltage. The fixed tapping may need to be altered until bus voltages are within  $\pm 5\%$  tolerance.

NB! As can be seen with Type 3 buses the bus voltages are adjusted within  $\pm 0.4\%$  automatically.

#### STORING AND UPDATING DATA

The above input data can be stored for up to three separate cases. The bus, line and transformer input data files for Case 1 are called PFB1.DAT, PFL1.DAT and PFT1.DAT. For cases 2 and 3 they have similar names except their numbers are 2 and 3.

The user has these following options for each input data file:

- (1) Initialise the file (which removes all data currently stored).
- (2) Enter (add) or change the data file for a selected bus, line or transformer.

NB! When a new system is studied, a file is initialised and the new number of buses, lines or transformers are added (entered) by selecting 2. For example these files may have a 5 bus 6 line, 2 transformer system stored therein. A new system having 16 buses, 14 lines, 5 transformers is to be analysed, therefore the files are initialised by selecting (1) and then selecting (2) and then entering information for a given bus, line or transformer, (2) being used each time as bus, line or transformer numbers are entered until 16 buses, 14 lines and 5 transformers are added (entered). Alternatively, the existing 5 bus system may be changed, that is updated with the first five buses detail, of the new 16 buses, and then the remaining 9 buses detail entered as above. Likewise for the lines and transformers.

- (3) Remove the bus, line or transformer. The user may wish to change a 16 bus system back to a 5 bus system. In such a case 9 buses are removed and then the remaining are changed by selecting (2) step by step.
- (4) Display the data for one bus, line or transformer.
- (5) Display the data for all buses, lines or transformers starting with a given one.

**PRINTING**

The program prompts "USE THE Ctrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS"

This usually takes place after Bus, Line and Transformer Data have been entered for a given case.

Once printing has ceased the program prompts "REMOVE Ctrl PRINT SCREEN".

The same steps are followed for Output Data files.

**RUNNING THE PROGRAM**

The program uses the Newton-Raphson iterative method for solving load flow. The user can select the maximum number of iterations (default value is 20) and the power mismatch for convergence (default value 0.0001 pu).

The user has the following options for starting values:

- (1) FLAT START

Here the initial voltage magnitudes of Type 1 buses are set equal to the swing bus voltage and all initial phase angles are set equal to the swing bus phase angle.

Also the initial tap settings of all variable tap-changing transformers are set equal to 1.0.

- (2) OUTPUT VALUES FROM PREVIOUS RUN

Here the initial bus voltage magnitudes and phase angles as well as initial transformer tap settings are set equal to the values from the bus output and transformers output data files.

When preparing a "base case" (e.g. a 16 bus system) for the first time with no output system, then select (1) for a flat start.

After running the program for a base case with a successful power flow solution stored in an output data file, select (2) when you make a change such as removing a line or transformer. The program will usually converge more rapidly when starting from a previous successful run. Therefore, for a series of runs with input data changes, the final values of each run are used as starting values for next run.

**OUTPUT DATA**

On completion of a run, the program displays the total number of iterations taken and the mismatch, e.g.

TOTAL NUMBER OF ITERATIONS = 5  
 MISMATCH = 1.08E -05

The output data includes bus output, line output and transformer output which are stored in three separate data files. For case 1, the files are called PFB01.DAT, PFL01.DAT and PFT01.DAT. Likewise, for cases 2 and 3. The program gives the user the option of displaying the data on the monitor and on the printer.

(1) BUS OUTPUT DATA includes for example.

POWER FLOW BUS OUTPUT DATA

BUS	VOLTAGE MAGNITUDE	PHASE ANGLE	GENERATION		LOAD		.95 >V>1.05
			PG	QG	PL	QL	
			per unit	per unit	per unit	per unit	
1	1.000	0.000	0.938	-0.844	0.000	0.000	
2	1.042	-11.333	0.000	0.000	2.000	0.200	
3	1.040	-1.116	1.300	-0.044	0.200	0.100	
4	1.043	-3.463	0.000	0.000	0.000	0.000	
5	1.022	-4.314	0.000	0.000	0.000	0.000	
		TOTAL	2.238	-0.888	2.200	0.300	

TABLE 10.

NB! If an \* appears in the last column the bus voltage exceeds ±5%, i.e., Those buses whose voltage magnitudes are greater than ±5% of the swing bus voltage are indentified by the program.

where:

- Bus = Bus Number
- Voltage Magnitude = Per-unit voltage
- Phase Angle = Voltage phase angle in degrees
- PG = Per-unit real generation
- QG = Per-unit reactive generation
- PL = Per-unit real power
- QL = Per-unit reactive load power

(11) LINE OUTPUT DATA includes for example:

POWER FLOW LINE OUTPUT DATA						RATING
LINE	BUS TO BUS		P	Q	S	EXCEEDED
1	2	4	-0.367	-0.179	0.408	
	4	2	0.372	-0.238	0.441	
2	2	4	-0.367	-0.179	0.408	
	4	2	0.372	-0.238	0.441	
3	2	5	-0.633	0.079	0.638	
	5	2	0.640	-0.232	0.681	
4	2	5	-0.633	0.079	0.638	
	5	2	0.640	-0.232	0.681	
5	4	5	0.177	0.143	0.227	
	5	4	-0.176	-0.254	0.309	
6	4	5	0.177	0.143	0.227	
	5	4	-0.176	-0.254	0.309	

TABLE 11.

where :

Line = Line Number  
 Bus-to-Bus = The two buses to which the line is connected.  
 P, Q and S = Pre-unit real, reactive and apparent power flows into each end of the line.

NB! Those lines whose loadings exceed their maximum loadings are also identified by the program by means of an \*.

(111) TRANSFORMER OUTPUT DATA includes for example:

POWER FLOW TRANSFORMER OUTPUT DATA							
TRAN	BUS TO BUS		P	Q	S	TAP SET	RATING EXCEEDED
1	1	5	0.977	-0.326	1.030	0.960	
	5	1	-0.971	0.408	1.053		
2	3	4	1.100	-0.144	1.109	1.000	
	4	3	-1.097	0.189	1.113		

TABLE 12.

where:

TRAN = Transformer Number  
 Bus-to-Bus = The two buses to which the transformer is connected.  
 P, Q and S = The per-unit real, reactive and apparent power flows into each winding  
 Tap Setting = Per-unit tap-setting.

NB! Those transformers whose maximums are exceeded are identified by the program by means of an \*.

**b. PROGRAM "LOADFLOW" BY WOODS/WOLLENBERG**

This program solves load flows up to a maximum of 25 buses, 40 lines, 20 generations and 10 transformers.

**INPUT DATA AND STORAGE**

On entering into the program, it prompts and asks for the name of the "Input Data File" that you will be using.

It is therefore necessary to create an "Input Data File" first before even using this program.

For example : 16bus.in

The program also after it has been run allows for the solution voltages to be stored in a file. This voltage solution file must also be created.

For example : 16bus.out

for more information on this latter file see paragraph below entitled:

**"WRITING VOLTAGE SOLUTION TO A FILE"**

The format of a typical "Input Data File" is for example the following:

```
SAMPLE 16 BUS LOADFLOW EXAMPLE - - - - TITLE LINE 1)
HEAVY LOAD PROJECT - - - - TITLE LINE 2)
16
3
19
1
1 B1 0.0 0.0 0.95 1.05 - - - - DATA FOR 1st BUS
2 B2 0.0 0.0 0.95 1.05
3 B3 0.569 0.187 0.95 1.05
4 B4 0.0 0.0 0.95 1.05
5 B5 0.0 0.0 0.95 1.05
6 B6 0.0 0.0 0.95 1.05
7 B7 0.65 0.7 0.95 1.05
8 B8 0.487 0.251 0.95 1.05
9 B9 0.569 0.189 0.95 1.05
10 B10 0.0 0.0 0.95 1.05
11 B11 0.397 0.167 0.95 1.05
12 B12 0.0 0.0 0.95 1.05
13 B13 0.0 0.0 0.95 1.05
14 B14 0.0 0.0 0.95 1.05
15 B15 0.353 0.19 0.95 1.05
16 B16 0.393 0.218 0.95 1.05
1 0.0 1.00 1.0 -1.0 - - - - DATA FOR 1st GENERATOR
2 1.50 1.00 1.0 -1.0
3 1.0 1.00 1.0 -1.0
4 8 0.001361 0.007580 0.007723 1.5 LINE ----DATA FOR 1st
4 7 0.002722 0.015160 0.015447 1.5 LINE LINE
7 8 0.004764 0.026531 0.027032 1.5 LINE
8 16 0.004083 0.022741 0.02317 1.5 LINE
8 12 0.004491 0.025015 0.02548 1.5 LINE
6 7 0.010662 0.023705 0.021900 1.5 LINE
9 13 0.012483 0.035296 0.00367 1.5 LINE
9 11 0.028392 0.043905 0.00392 1.5 LINE
5 9 0.007386 0.025442 0.00274 1.5 LINE
5 10 0.008322 0.023531 0.0024 1.5 LINE
10 11 0.020805 0.058827 0.00612 1.5 LINE
6 15 0.002994 0.016677 0.01699 1.5 LINE
14 15 0.001361 0.007580 0.0077235 1.5 LINE
15 16 0.001361 0.007580 0.0077235 1.5 LINE
1 4 0.0001 0.0625 0.0 2.7 TRAN 1 4 1.0 - - DATA FOR 1st
12 11 0.0001 0.0650 0.0 4.0 TRAN 12 11 1.0 TRANS
2 5 0.0001 0.0600 0.0 2.5 TRAN 2 5 1.0
14 13 0.0001 0.057 0.0 4.0 TRAN 14 13 1.0
3 6 0.0001 0.0625 0.0 2.6 TRAN 3 6 1.0
```

TABLE.13



- (1) The first and second lines are title lines (each line only up to 80 characters)
- (2) The next four lines, only integers are entered. These four lines are:

Number of buses (e.g. 16)  
Number of generators (e.g. 3)  
Number of branches (includes transformers and lines, for example, 14 lines and 5 transformers, 19 is entered for this third line).  
Bus number of the swing bus. (Usually 1)

- (3) The next lines are for each bus. (1 to 16). The details for each bus line are the bus number, the bus name (e.g. B1), MW loading on the bus, the MVAR loading on the bus, the voltage high limit and the voltage low limit. Per-unit values are stipulated.

NB! The bus name can be eight characters maximum.

- (4) The next lines are for each generator. The details for each generator line are, bus number (1 to 3), MW Generator, Scheduled Voltage, High MVAR Limit (Qmax) and Low MVAR Limit (Qmin). Per-unit Values are stipulated.
- (5) The next lines are for branches or transmission lines. The details for each line are, from bus number to bus number, Branch Rpu (new), Branch Xpu (new), half charging current pu, Branch MVA limit pu and Branch Type (LINE must be typed).
- (6) The next set of lines are for transformers. The details for each line are, from bus number to bus number, Branch Rpu (new), Branch Xpu (new). half charging current pu, Branch MVA limit pu, Branch type (TRAN must be typed), Tap bus, Non-Tap bus and Tap Ratio.

This data is saved and stored in the created "Input Data File" (e.g. 16bus.dat).

<b>DISPLAYING AND PRINTING INPUT DATA</b>
---

If the program is run, and once the name of this "Data File" has been entered it reads this "Data File" which can be displayed and/or printed and has the following format:

Bus Data (HEAVY LOAD PROJECT)						
Bus Number	Bus Name	Mw Load	Mvar Load	Voltage High Limit	Voltage Low Limit	Bus Type
1	B1	0.000	0.000	1.050	0.950	SWING
2	B2	0.000	0.000	1.050	0.950	GEN
3	B3	56.900	18.700	1.050	0.950	GEN
4	B4	0.000	0.000	1.050	0.950	LOAD
5	B5	0.000	0.000	1.050	0.950	LOAD
6	B6	0.000	0.000	1.050	0.950	LOAD
7	B7	65.000	70.000	1.050	0.950	LOAD
8	B8	48.700	25.100	1.050	0.950	LOAD
9	B9	56.900	18.900	1.050	0.950	LOAD
10	B10	0.000	0.000	1.050	0.950	LOAD
11	B11	39.700	16.700	1.050	0.950	LOAD
12	B12	0.000	0.000	1.050	0.950	LOAD
13	B13	0.000	0.000	1.050	0.950	LOAD
14	B14	0.000	0.000	1.050	0.950	LOAD
15	B15	35.300	19.000	1.050	0.950	LOAD
16	B16	39.300	21.800	1.050	0.950	LOAD

TABLE.14

Generator Data (HEAVY LOAD PROJECT)				
Bus Number	Mw Generation	Scheduled Voltage	High Mvar Limit	Low MVar Limit
1	0.00000	1.0000	1.0000	-1.0000
2	1.50000	1.0000	1.0000	-1.0000
3	1.00000	1.0000	1.0000	-1.0000

TABLE.15

Branch Data									
From Bus	To Bus	Branch R	Branch X	Line Charg	Branch Mva Lim	Branch Type	Tap Bus	Non-Tap Bus	Tap Ratio
1	4	0.0001	0.0625	0.000	2.7	TRAN	1	4	1.000
2	5	0.0001	0.0600	0.000	2.5	TRAN	2	5	1.000
3	6	0.0001	0.0625	0.000	2.6	TRAN	3	6	1.000
4	8	0.0014	0.0076	0.00772	1.5	LINE			
4	7	0.0027	0.0152	0.01544	1.5	LINE			
5	9	0.0074	0.0254	0.00274	1.5	LINE			
5	10	0.0083	0.0235	0.00240	1.5	LINE			
6	7	0.0107	0.0237	0.02190	1.5	LINE			
6	15	0.0030	0.0167	0.01699	1.5	LINE			
7	8	0.0048	0.0265	0.02703	1.5	LINE			
8	16	0.0041	0.0227	0.02317	1.5	LINE			
8	12	0.0045	0.0250	0.02548	1.5	LINE			
9	13	0.0125	0.0353	0.00367	1.5	LINE			
9	11	0.0284	0.0439	0.00392	1.5	LINE			
10	11	0.0208	0.0588	0.00612	1.5	LINE			
11	12	0.0001	0.0650	0.00000	4.0	TRAN	12	11	1.000
13	14	0.0001	0.0570	0.00000	4.0	TRAN	14	13	1.000
14	15	0.0014	0.0076	0.00772	1.5	LINE			
15	16	0.0014	0.0076	0.00772	1.5	LINE			

TABLE.16

**UPDATING INPUT DATA**

Data can be changed in the "Data "File" itself or by selecting the "Change Input Data" option provided by one of the menus provided by the program. This latter option provides for:

1. Change system load
2. Change generator scheduled voltage
3. Change scheduled MW
4. Return to main menu.

For example: User selects "1" to change system load. It displays the "Present total system MW load" and prompts for the new total load in MW.

For example: User selects "2" to change generator scheduled voltage.

It displays the following:

Present generator voltages are:

Generator bus 1 PU sched voltage = 1.000  
Generator bus 2 PU sched voltage = 1.050  
Generator bus 3 PU sched voltage = 1.000

etc, for more generators

Enter generator bus number, a space, new PU scheduled voltage (enter 0 0 to terminate):

Enter 2 1.000 (to change bus 2 from 1.050 to 1.000)  
(enter 0 0 to terminate):

For example: User selects "3" to change generator scheduled MW

Present generator MW schedules are:

Generator bus 1 scheduled MW = 0.00  
Generator bus 2 scheduled MW = 50.00  
Generator bus 3 scheduled MW = 60.00

Enter generator bus number, a space, new scheduled MW (enter 0 0 to terminate):

Enter 2 98 (To change bus 2 from 50 to 98)  
(enter 0 0 to terminate).

Repeat above to change bus 3 from 60 to 100MW

On completion of updating data select "4" to return to main menu.

NB! The above does not allow for adding or subtracting of buses, generators, lines, transformers etc, only for updating an already created "Input Data File". If such changes are required, user must change the given "Input Data File" itself or create a new file for a specific case.

**RUNNING THE PROGRAM**

To run this program, enter "LOADFLOW". The program will then ask for the name of the users "Input Data File" which once entered is followed by a displayed menu, namely:

Menu of options:

- 1 - print output data
- 2 - run Gauss-Seidal loadflow
- 3 - run Newton-Raphson loadflow
- 4 - print solution
- 5 - change input data
- 6 - write voltage solution to a file
- 7 - quit

Enter option >

The program allows the user to run either a Gauss-Seidal or a Newton-Raphson algorithm.

Either 2 or 3 is selected or 2 is selected firstly followed by 3.

The program can be "paused" so that each iteration can be displayed.

NB! For Gauss-Seidal maximum change in voltage at a bus is displayed for each iteration.

e.g.                                    ITERATION 1  
                                      MAXIMUM CHANGE IN THE VOLTAGE IS 0.00 AT BUS 2

NB! For Newton-Raphson the maximum P and Q mismatch is displayed.

e.g.                                    ITERATION 1  
                                      The maximum P mismatch is 0.3978  
                                      The maximum Q mismatch is 0.3608

At the end of a run, the user is returned back to the above menu.

**WRITING VOLTAGE SOLUTION TO A FILE**

The above menu includes a feature allowing the user to dump the solution voltages to a file so that they may be read by other programs.

To use this feature, option 6 is selected.  
The computer prompts for:

"Enter name of solution data file: ?"

Enter name of file, for example 16bus.out

The voltage solutions are written to this file.

To view and print this solution one must quit the program (option 7) and then call up this solutions file. It's typical format is:

SAMPLE 16 BUS LOADFLOW EXAMPLE PROJECT		
1	1.0000000000E+00	0.0000000000E+00
2	1.0000000000E+00	8.3558784630E-02
3	1.0000000000E+00	-3.7325262254E-02
4	9.6003658550E-01	-6.1135241580E-02
5	9.7511660260E-01	-8.8044976360E-03
6	9.6312153868E-01	-6.5231536724E-02
7	9.5428632635E-01	-6.6807694519E-02
8	9.5681640688E-01	-6.5157123219E-02
9	9.6106308616E-01	-3.5855990655E-02
10	9.6916278478E-01	-1.8720669355E-02
11	9.5421025015E-01	-4.3868705447E-02
12	9.5721197727E-01	-5.9173322245E-02
13	9.5715980658E-01	-4.7428983801E-02
14	9.5723318683E-01	-6.6145161607E-02
15	9.5678820350E-01	-6.8631121812E-02
16	9.5524261302E-01	-6.9993272771E-02

TABLE 17

where column 1 is the real component and column 2 is the imaginary component of the voltage. (It is a + jb format not polar format). User is hereafter returned to main menu.

**PRINTING OUTPUT DATA**

NB! This program can provide for Gauss-Seidel and Newton-Raphson solutions. To obtain the output data from either of these algorithms, "4" (print solution) on the main menu is selected after the program has been run for a given algorithm. It is thus possible to firstly run Gauss-Seidel and then obtain its solution, then secondly run Newton-Raphson and in turn obtain its solution.

In both cases, the loadflow solution is given in terms of the following headings:

From Bus	Volt. Mag.	Mw Load	Mvar Load	Mw Gen.	Mvar Gen.	To Bus	Mw Flow	Mvar Flow	Mva Flow
----------	------------	---------	-----------	---------	-----------	--------	---------	-----------	----------

TABLE 18

and is followed by the following summary of totals:- (for example)

Mw gen	=	217.8
Mvar gen	=	180.6
Mw load	=	210.0
Mvar load	=	210.0
Total 12R Mw losses	=	7.8
Total 12X Mvar losses	=	23.9
Total charging Mvar	=	53.2

TABLE 19 .

NB! None of the programs provide one-line diagrams whereon the solution is represented.

NB! Mismatches are also not indicated after program has been run.

**QUITTING THE PROGRAM**

"7" on main menu is selected to quit program.

**2. EXPERIMENTATION USING THE PROGRAM**

**a. PROGRAM "POWER FLOW" BY GLOVER**

**EXPERIMENT A 1  
16 BUS 3 GENERATOR POWER SYSTEM**

**INFORMATION AVAILABLE:**

The one-line diagram of the 16 bus, 3 generator, 14 line and 5 transformer system as shown in Figure 1 as well as Tables 1 to 6 form the basis of the information available.

**EXPERIMENTAL REQUIREMENTS:**

- a. Convert the per km line data values to per-unit values based on 100 MVA system base. Tabulate your new values.
- b. Convert the transformer data to per-unit values (100MVA base) and tabulate these new values.

**PART ONE**

- c. Use the "POWER FLOW" program and obtain:
  - (i) The bus, line and transformer input data for base load conditions.
  - (ii) The load flow solution under base load conditions (Table 4 and 5a) when all the transformers have fixed tapplings set to "1".
  - (iii) The bus input data and bus voltage and phase angles for base load conditions for all 16 buses with variable tap changers (T2 and T4) adjusting the Type 3 buses (11 and 13) automatically within  $\pm 0.4\%$  of the input bus voltage provided maximum or minimum tap settings are not reached. Tabulate your results in a comparative format to those voltages obtained in (ii). Comment on the results. What were the final tap settings to which the automatic tap changes settled on to provide the required Type 3 voltages? Were the ratings of any lines or transformers exceeded?
  - (iv) The power flows in and out of buses 7.8.10 and 15 under heavy load conditions (Table 4 and 5a) with fixed transformer tapplings set to "1". Represent your results on diagrams, one for each bus.

**PART TWO**

d. Use the "LOAD FLOW" program and obtain:

- (i) The bus input data based on the base loads of Table.4 and on the High and Low Voltage limits of 1.05 and 0.95pu.
- (ii) The generator input data using 1pu as the scheduled voltages for each generator, using Table 5a base load for the MW generator and MVAR high and low limits of 1 and -1.
- (iii) The input branch data based on the Tables derived in "a" and "b" above and must include the transformers in the system having tap ratios of "1".
- (iv) The load flow solution using base load conditions and using the Newton-Raphson algorithm. Compare the bus voltages and phase angle results with those of c(ii) above. Tabulate your results in a comparative format. Dump the NR bus voltage solutions to a solutions file but provide a table showing these results.

**PART THREE  
SELF EVALUATION**

- e. Compare the power flows found in c(ii) and d(iv) on a one-line diagram of the 16 bus system and comment thereon. (The solution is not given as user must provide it himself.)
- f. Determine the voltage in a + j b format for each bus using the "LOADFLOW" program (Newton-Raphson algorithm) under heavy load conditions for high and low voltage limits of 0.95 and 1.05pu and for tap ratios of "1". (SEE TABLES 13,14,15 and 16). Dump the NR bus voltage solutions to a solutions file. Tabulate your results.



SOLUTION

a. CONVERSION - LINE DATA

As only positive sequence data is required for load flow, only that of the line data given in Table.6 that is required is repeated here, namely:

POSITIVE SEQUENCE LINE DATA

LINE NO	FROM NODE	TO NODE	LENGTH	R1 $\Omega/\text{kM}$	X1 $\Omega/\text{km}$	B1 $\mu\text{MHO}/\text{km}$
L1	4	8	10	0.072	0.401	2.920
L2	4	7	20	0.072	0.401	2.920
L3	7	8	35	0.072	0.401	2.920
L4	8	16	30	0.072	0.401	2.920
L5	8	12	33	0.072	0.401	2.920
L6	6	7	30	0.188	0.408	2.760
L7	9	13	15	0.145	0.410	2.810
L8	9	11	17	0.291	0.450	2.650
L9	5	9	11	0.117	0.403	2.869
L10	5	10	40	0.145	0.410	2.810
L11	10	11	25	0.145	0.410	2.810
L12	6	15	22	0.072	0.401	2.920
L13	14	15	30	0.072	0.401	2.920
L14	15	16	10	0.072	0.401	2.920

TABLE.20

NB! Lines have negligible conductance

The system base power = 100 MVA.

The above positive sequence data is now converted to pu values based on the system base of 100 MVA by using the above shown methods and done by hand calculations: (A drawback of this program).

LINE DATA - DETERMINATION OF PER UNIT VALUES			
LINE NUMBER	L1	L2	L3
BUSES	4 to 8	4 to 7	7 to 8
LENGTH	10	20	35
R1 ohms/km	0.072	0.072	0.072
X1 ohms/km	0.401	0.401	0.401
R/Line ohms	0.720	1.440	2.52
X/Line ohms	4.010	8.020	14.035
Zactual/Line	4.07/_79°	8.15/_79°	14.26/_79°
Z base(new) = $\frac{kV^2 \text{ rated/zone}}{MVA (new)}$	$\frac{230^2/100}{529}$	$\frac{230^2/100}{529}$	$\frac{230^2/100}{529}$
Z pu (new) = $\frac{Z \text{ actual}}{Z \text{ base(new)}}$	4.07/529	8.15/529	14.26/529
Z pu (new) / Line	.00769/_79°	.0154/_79°	.0269/_79°
R pu (new) / Line	.00136	.002722	.004764
X pu (new) / Line	.00757	.01516	.026532
B1 $\mu$ MHO/km	2.92	2.92	2.92
B1 Actual/Line (MHO)	29.2E-6	58.4E-6	102.2E-6
Zbase (new) = $\frac{kV^2 \text{ rated/zone}}{MVA (new)}$	$\frac{230^2/100}{529}$	$\frac{230^2/100}{529}$	$\frac{230^2/100}{529}$
Bc (new pu = Bc actual Zbase(new))	29.2E-6*529	58.4E-6*529	102.2E-6*529
Bc (new) pu/Line	.01544	.03089	.054063
Bc/2 (new) pu	.007723	.015447	.027032
I - charging = $\frac{V_{pu} Bc (new) \text{ pu}}{2}$	.007723	.015447	.027032

TABLE.21

LINE DATA - DETERMINATION OF PER UNIT VALUES			
LINE NUMBER	L4	L5	L6
BUSES	8 to 16	8 to 12	6 to 7
LENGTH	30	33	30
R1 ohms/km	0.072	0.072	0.188
X1 ohms/km	0.401	0.401	0.418
R/Line ohms	2.16	2.376	5.64
X/Line ohms	12.03	13.233	12.54
Zactual/Line	12.2/_79°	13.4/_79°	13.75/_65°
Z base(new) = $\frac{\text{kV}^2 \text{ rated/zone}}{\text{MVA (new) Zactual}}$	$\frac{230^2/100}{= 529}$	$\frac{230^2/100}{= 529}$	$\frac{230^2/100}{= 529}$
Z pu (new) = $\frac{\text{Z pu (new) / Line}}{\text{Z base(new)}}$	12.22/529	13.44/529	13.75/529
Z pu (new) / Line	.0231/_79°	.0254/_79°	.0259/_65°
R pu (new) / Line	.004083	.004491	.010662
X pu (new) / Line	.02274	.02501	.023705
B1 $\mu$ MHO/km	2.92	2.92	2.760
B1 Actual/Line (MHO)	87.6E-6	96.36E-6	82.6E-6
Zbase (new) = $\frac{\text{kV}^2 \text{ rated/zone}}{\text{MVA (new)}}$	$\frac{230^2/100}{= 529}$	$\frac{230^2/100}{= 529}$	$\frac{230^2/100}{= 529}$
Bc (new pu = Bc actual Zbase(new))	87.6E-6*529	96.3E-6*529	82.6E-6*529
Bc (new) pu/Line	.04634	.050974	.043695
Bc/2 (new) pu	.02317	.02548	.02185
I - charging = $\frac{\text{Vpu Bc(new) pu}}{2}$	.02317	.02548	.02185

TABLE.22

LINE DATA - DETERMINATION OF PER UNIT VALUES			
LINE NUMBER	L7	L8	L9
BUSES	9 to 13	9 to 11	5 to 9
LENGTH	15	17	11
R1 ohms/km	0.145	0.291	0.117
X1 ohms/km	0.410	0.45	0.403
R/Line ohms	2.175	4.947	1.287
X/Line ohms	6.15	7.65	4.433
Zactual/Line	6.52/_70°	9.11/_57°	4.616/_73°
Z base(new) = $\frac{\text{kV}^2 \text{ rated/zone}}{\text{MVA (new)}}$	$\frac{132^2/100}{=174.24}$	$\frac{132^2/100}{=174.24}$	$\frac{132^2/100}{=174.24}$
Z pu (new) = $\frac{\text{Z actual}}{\text{Z base(new)}}$	6.52/174.24	9.11/174.24	4.61/174.24
Z pu (new) / Line	.0374/_70°	.0522/_57°	.0264/_73°
R pu (new) / Line	.012484	.028392	.007386
X pu (new) / Line	.035296	.043905	.025442
B1 $\mu$ MHO/km	2.810	2.650	2.869
B1 Actual/Line (MHO)	42.1E-6	45.05E-6	31.5E-6
Zbase (new) = $\frac{\text{kV}^2 \text{ rated/zone}}{\text{MVA (new)}}$	$\frac{132^2/100}{=174.24}$	$\frac{132^2/100}{=174.24}$	$\frac{132^2/100}{=174.24}$
Bc (new pu = Bc actual Zbase(new))	42.1E-6*174	45.0E-6*174	31.5E-6*174
Bc (new) pu/Line	.007344	.007849	.005498
Bc/2 (new) pu	.003672	.003924	.002749
I charging = $\frac{\text{Vpu Bc(new) pu}}{2}$	.003672	.003924	.002749

TABLE.23

LINE DATA - DETERMINATION OF PER UNIT VALUES			
LINE NUMBER . . .	L10	L11	L12
BUSES	5 to 10	10 to 11	6 to 15
LENGTH (Selected 40km)	40	25	22
R1 ohms/km	0.145	0.145	0.072
X1 ohms/km	0.410	0.410	0.401
R/Line ohms	5.8	3.625	1.584
X/Line ohms	16.4	10.25	8.822
Zactual/Line	17.39/_70°	10.87/_70°	8.963/_79°
Z base(new) = $\frac{kV^2 \text{ rated/zone}}{MVA (new)}$	$\frac{132^2/100}{= 174.24}$	$\frac{132^2/100}{=174.24}$	$\frac{230^2/100}{= 529}$
Z pu (new) = $\frac{Z \text{ actual}}{Z \text{ base(new)}}$	17.3/174.24	10.8/174.24	8.96/529
Z pu (new) / Line	.0998/_70°	.0623/_70°	.0169/_79°
R pu (new) / Line	.033293	.020808	.002994
X pu (new) / Line	.094121	.058826	.016677
B1 $\mu$ MHO/km	2.810	2.810	2.92
B1 Actual/Line (MHO)	112.4E-6	70.25E-6	64.22E-6
Zbase (new) = $\frac{kV^2 \text{ rated/zone}}{MVA (new)}$	$\frac{132^2/100}{=174.24}$	$\frac{132^2/100}{=174.24}$	$\frac{230^2/100}{= 529}$
Bc (new pu = Bc actual Zbase(new))	112E-6*174	70.2E-6*174	64.2E-6*529
Bc (new) pu/Line	.019584	.01224	.033972
Bc/2 (new) pu	.009792	.006120	.016986
I - charging = $\frac{V_{pu} Bc(new) \text{ pu}}{2}$	.009792	.00612	.016986

TABLE.24

LINE DATA - DETERMINATION OF PER UNIT VALUES		
LINE NUMBER	L13	L14
BUSES	14 to 15	15 to 16
LENGTH (Selected 30km)	30	10
R1 ohms/km	0.072	0.072
X1 ohms/km	0.401	0.401
R/Line ohms	2.16	0.720
X/Line ohms	12.03	4.010
Zactual/Line	12.222/_79°	4.07/_79°
Z base(new) = $\frac{\text{kV}^2 \text{ rated/zone}}{\text{MVA (new) Zactual}}$	230 <sup>2</sup> /100 = 529	230 <sup>2</sup> /100 =529
Z pu (new) = $\frac{\text{Z base(new)}}{\text{Z base(new)}}$	12.222/529	4.07/529
Z pu (new) / Line	.15089/_79°	.00769/_79°
R pu (new) / Line	.026668	.001368
X pu (new) / Line	.0148514	.00757
B1 μ MHO/km	2.92	2.92
B1 Actual/Line (MHO)	87.6E-6	29.2E-6
Zbase (new) = $\frac{\text{kV}^2 \text{ rated/zone}}{\text{MVA (new)}}$	230 <sup>2</sup> /100 = 529	230 <sup>2</sup> /100 = 529
Bc (new pu = Bc actual Zbase(new))	87.6E-6*529	29.2E-6*529
Bc (new) pu/Line	.04634	.01544
Bc/2 (new) pu	.02317	.007723
I - charging = $\frac{\text{Vpu Bc(new) pu}}{2}$	.02317	.007723

TABLE.25

The above per-unit data which is based on a 100MVA base can be summarized as follows:

PER-UNIT POSITIVE SEQUENCE LINE DATA, CHARGING CURRENT AND  
MAXIMUM MVA BASED ON 100MVA

Line no.	From node	To node	Rpu(new) per line	Xpu(new) per line	Bcpu per line	Bc/2 pu(new)	I/2charg pu(new)	Max MVA line
L1	4	8	.00136	.00757	.01544	.007723	.007723	1.5
L2	4	7	.00272	.01516	.03089	.015447	.015447	1.5
L3	7	8	.00476	.02653	.05406	.027032	.027032	1.5
L4	8	16	.00408	.02274	.04634	.02317	.02317	1.5
L5	8	12	.00449	.02501	.05097	.02548	.02548	1.5
L6	6	7	.01066	.02370	.04369	.02185	.02185	1.5
L7	9	13	.01248	.03529	.00734	.003672	.003672	1.5
L8	9	11	.02839	.04390	.00784	.003924	.003924	1.5
L9	5	9	.00738	.02544	.00549	.002749	.002749	1.5
L10	5	10	.03329	.09412	.01958	.009792	.009792	1.5
L11	10	11	.02080	.05882	.01224	.00612	.00612	1.5
L12	6	15	.00299	.01667	.03397	.016986	.016986	1.5
L13	14	15	.02666	.14851	.04634	.023170	.023170	1.5
L14	15	16	.00136	.00757	.01544	.007723	.007723	1.5

TABLE.26

b. CONVERSION-TRANSFORMER DATA

The available transformer data is given in Table.3.

NB! It can be seen from Table.3 that the series impedances of the transformers are given in percentage values and are based on 100MVA even though the transformer ratings are different.

The transformers also have no G and B values.

As per-unit values are required, herewith a revised table.

TRANSFORMER DATA

No	Bus No's	Type	Max pu MVA based on 100MVA	Prim/Sec Conn	Prim/Sec kV	Rpu Based on 100MVA	Xpu	G and B	Non Tap Bus	Tap Bus	Tap Ratio	Max Tap
T1	1 - 4	Fixed	2.7	Delta/Star grnd	18/ 230	.0001	.0625	0	-	-	1	1
T2	12-11	Tap sec	4.0	Star grnd/ Star grnd	230/ 132	.0001	.0625	0	12	11	1	1.15
T3	2 - 5	Fixed	2.5	Delta/Star grnd	14.4/ 132	.0001	.0600	0	-	-	1	1
T4	14-13	Tap sec	4.0	Star grnd/ Star grnd	230/ 132	.0001	.0570	0	14	13	1	1.15
T5	3 - 6	Fixed	2.6	Delta/Star grnd	15/ 230	.0001	.0625	0	-	-	1	1

TABLE.27



PART ONE

C. POWER FLOW PROGRAM

C(i). BUS, LINE AND TRANSFORMER INPUT DATA

C:\POWER>CHAP7

The program welcomes you to "Power Flow" and then asks for:

"WHAT IS YOUR CASE NUMBER (ENTER AN INTEGER FROM 1 TO 3)?"  
ENTER "1".

On selecting "1", case 1 input data will be saved and stored in files PFB1.DAT, PFL1.DAT and PFT1.DAT. The data in these files can be copied to case 2 and case 3 files and then updated with changes. This data is then also available for being read into another program (e.g. TRANSIENT STABILITY program) for use by that program.

It then prompts for the user to enter your "CASE NAME (ANY ALPHANUMERIC SEQUENCE)? e.g. GARY.001

The screen then displays:

```
MENU 1
WOULD YOU LIKE TO:
 1. UPDATA THE INPUT DATA FILES
 2. RUN THE PROGRAM
 3. DISPLAY THE OUTPUT DATA
 4. STOP
ENTER YOUR SELECTION (1,2,3 OR 4) 1
```

Select "1" to update Input Data Files and program prompts:

```
MENU 2
SELECTIONS:
 1. BUS DATA
 2. LINE DATA
 3. TRANSFORMER DATA
 4. DONE WITH DATA
ENTER YOUR SELECTION (1,2,3 OR 4): 1
```

Select "1" to update Bus Data and the program prompts:

```
MENU 3
SELECTION:
 1. INITIALIZE THE BUS DATA FILE
 2. ADD A NEW BUS OR CHANGE AN EXISTING BUS
 3. REMOVE A BUS
 4. DISPLAY ONE BUS
 5. DISPLAY ALL BUSES BELOW A GIVEN BUS
 6. DONE WITH BUS DATA
ENTER YOUR SELECTION :
```

If "1" is selected all existing data in the file will be removed. Select "5" and display existing buses below a given bus, e.g. bus 1. This displays the number of buses used for the previous cases. Press "ENTER" and return to menu 3.

As a 16 bus system is to be created, this input data file must be increased/decreased to 16 buses depending on the number of buses that were displayed. If more than 16 buses were displayed, select "3" and remove the excess buses. If less than 16 buses were displayed, select "2" to add to or change the existing buses.

The program prompts for bus number: Select bus number "1". It then asks if you wish to change data. Enter "Y". It then advises that bus 1 is the swing bus. It then prompts for:

```
BUS VOLTAGE MAGNITUDE (per unit) ? Enter "1".
BUS VOLTAGE ANGLE (degrees) ? Enter "0"
LOAD REAL POWER (per unit) ? Enter "0" as there are no loads
                                on bus 1
LOAD REACTIVE POWER (per unit) ? Enter "0"
```

It then returns the user to menu 3.

```
ENTER YOUR SELECTION : 2
BUS NUMBER ? 2
CHANGE (Y OR N)? Y
BUS TYPE ( ENTER 1 FOR LOAD BUS, 2 FOR VOLT. CONTROL BUS,
OR 3 FOR VOLT. CONTROL BUS WITH TAP-CHANGING TRSF.) "2"
```

Bus 2 is a voltage controlled bus. It then prompts:

```
BUS VOLTAGE MAGNITUDE (per unit) ? 1
GENERATOR REAL POWER (per unit) ? 0.98
LOAD REAL POWER (per unit) ? 0
LOAD REACTIVE POWER (per unit) ? 0
GENERATOR MAXIMUM var (per unit) ? 1
GENERATOR MINIMUM var (per unit) ? -1
```

It then returns to menu 3.

```
ENTER YOUR SELECTION : 2
BUS NUMBER ? 3
CHANGE (Y OR N)? Y
BUS TYPE ( ENTER 1 FOR LOAD BUS, 2 FOR VOLT. CONTROL BUS,
OR 3 FOR VOLT. CONTROL BUS WITH TAP-CHANGING TRSF.) "2"
BUS VOLTAGE MAGNITUDE (per unit) ? 1
GENERATOR REAL POWER (per unit) ? 1
LOAD REAL POWER (per unit) ? .71
LOAD REACTIVE POWER (per unit) ? .234
GENERATOR MAXIMUM var (per unit) ? 1
GENERATOR MINIMUM var (per unit) ? -1
```

NB! With this first part of the experiment the user is using fixed transformer settings therefore "3" which is for voltage controlled buses with tap-changing transformers is not chosen as a selection. In a subsequent part of this experiment a selection 3 will be made.

It then returns to menu 3.

The remaining buses are all load buses, therefore "1" will be selected and the remaining buses in this experiment will have PG and QG = 0 but will have PL and QL values except buses 4, 5, 6, 10, 12, 13, and 14 which have no loads thereon. Repeat the above procedure and add the required buses and enter the following PL and QL values for those buses which have loads:

BUS NO	PL	QL
7	0.58	0.1
8	0.18	0.09
9	0.6	0.2
11	0.36	0.15
15	0.32	0.2
16	0.25	0.1

The program then returns to menu 3. Enter "6" as "DONE WITH BUS DATA".

The program returns to menu 2.

Select "2" (LINE DATA).

If "1" is selected all existing data in the file will be removed.

Select "5" to display existing line data in file.

Return to menu 3.

In this experiment there are 14 lines. The line data file must be updated to these 14 lines.

Select "2" from menu 3 and working with Table 26, proceed as follows:

LINE NUMBER 1
CHANGE (Y OR N) ? Y
FIRST BUS NUMBER ? 4
SECOND BUS NUMBER ? 8
SERIES LINE RESISTANCE (per unit) ? .001
SERIES LINE REACTANCE (per unit) ? .00757
SHUNT LINE CONDUCTANCE (per unit) ? 0
SHUNT LINE SUSCEPTANCE (per unit) ? .01544
MAXIMUM MVA OF LINE (per unit) ? 1.5

Repeat the above procedure and add the remaining 13 lines, using the values of Table 26.

The program then returns to menu 3. Select "6" "DONE WITH LINE DATA".

Menu 2 appears.

Select "3" to update transformer data.

Select "5" to display existing data in file.

Return to menu 3 to update file.

Select "2" from menu 3 and working with Table 28, proceed as follows:

```

TRANSFORMER NUMBER ? 1
CHANGE (Y OR N) ? Y
FIRST BUS NUMBER ? 1
SECOND BUS NUMBER ? 4
SERIES TRANSFORMER RESISTANCE (per unit) ? .0001
SERIES TRANSFORMER REACTANCE (per unit) ? .0625
SHUNT TRANSFORMER CONDUCTANCE (per unit) ? 0
SHUNT TRANSFORMER SUCEPTANCE (per unit) ? 0
MAXIMUM MVA OF TRANSFORMER (per unit) ? 2.7
MAXIMUM TAP (ENTER NUMBER FROM 1 TO 1.25) ? 1

```

Repeat the above procedure and update the file to include the remaining 4 transformers using the values of Table 28. From menu 3 select "6" "DONE WITH TRANSFORMER DATA". Menu 2 re-appears. Select "4" "DONE WITH DATA". Menu 1 appears.

The first experimental requirements are that the bus, line and transformer Input Data must be obtained for base load and fixed transformer settings.

Select "1" from menu 1 to proceed to print this input data. Select "1" on menu 2. Select "5" on menu 3, then enter 1 to display all buses below bus 1.

USE Ctrl PRINT SCREEN OPTION TO PRINT RESULTS

BUS INPUT DATA FOR gary.001									
BUS	TYPE	V	DELTA	PG	QG	PL	QL	QGMAX	QGMIN
		per unit	degrees	per unit	per unit	per unit	per unit	per unit	per unit
1	0	1.0	0.0	-	-	.000	.000	-	-
2	2	1.0	-	0.98	-	.000	.000	1.0	-1.0
3	2	1.0	-	1.00	-	.710	.234	1.0	-1.0
4	1	-	-	0	0	.000	.000	-	-
5	1	-	-	0	0	.000	.000	-	-
6	1	-	-	0	0	.000	.000	-	-
7	1	-	-	0	0	.580	.100	-	-
8	1	-	-	0	0	.180	.090	-	-
9	1	-	-	0	0	.600	.200	-	-
10	1	-	-	0	0	.000	.000	-	-
11	1	-	-	0	0	.360	.150	-	-
12	1	-	-	0	0	.000	.000	-	-
13	1	-	-	0	0	.000	.000	-	-
14	1	-	-	0	0	.000	.000	-	-
15	1	-	-	0	0	.320	.200	-	-
16	1	-	-	0	0	.250	.100	-	-

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE

On menu 3 select "6".

On menu 2, select "2", then "5" from menu "3", then "1".

Use Ctrl Print screen and print line data:

LINE INPUT DATA FOR gary.001							
LINE	BUS	TO BUS	R per unit	X per unit	G per unit	B per unit	MAXMVA per unit
1	4	8	.001	.008	0	.015	1.5
2	4	7	.003	.015	0	.031	1.5
3	7	8	.005	.027	0	.054	1.5
4	8	16	.004	.023	0	.046	1.5
5	8	12	.004	.025	0	.051	1.5
6	6	7	.011	.024	0	.044	1.5
7	9	13	.012	.035	0	.007	1.5
8	9	11	.028	.044	0	.008	1.5
9	5	9	.007	.025	0	.005	1.5
10	5	10	.033	.094	0	.020	1.5
11	10	11	.021	.059	0	.012	1.5
12	6	15	.003	.017	0	.034	1.5
13	14	15	.027	.149	0	.046	1.5
14	15	16	.001	.008	0	.015	1.5

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE

Repeat the above procedure and in a similar manner obtain the transformer data:

TRANSFORMER INPUT DATA FOR gary.001								
TRAN	BUS	TO BUS	R per unit	X per unit	G per unit	B per unit	MAXMVA per unit	MAXTAP per unit
1	1	4	0	.063	0	0	2.700	1.00
2	12	11	0	.065	0	0	4.000	1.15
3	2	5	0	.060	0	0	2.500	1.00
4	14	13	0	.057	0	0	4.000	1.15
5	3	62	0	.063	0	0	2.600	1.00

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE

Select "6" on menu 3. Select "4" on menu 2.

C(ii) LOAD FLOW SOLUTION - BASE LOAD - FIXED TAPPINGS

Select "2" on menu 2 to "RUN THE PROGRAM"

It prompts:

DO ANY OF THE TRANSFORMERS HAVE TAP-CHANGERS WITH FIXED TAP SETTINGS ( Y OR N ) ? Y

HOW MANY FIXED-TAP TRANSFORMERS ? 5

FIXED-TAP TRANSFORMERS 1 :

ENTER THE TRANSFORMER NUMBER 1

WHAT IS THE FIXED TAP SETTING (ENTER A NUMBER FROM 0.75 TO 1.25) ? 1

FIXED-TAP TRANSFORMER 2 :

ENTER THE TRANSFORMER NUMBER 2

WHAT IS THE FIXED TAP SETTING (ENTER A NUMBER FROM 0.75 TO 1.25) ? 1

This is repeated for remaining 3 transformers as all are fixed tap transformers.

The screen then displays:

THE TOLERANCE LEVEL IS .0001

DO YOU WANT TO CHANGE THE TOLERANCE LEVEL (Y OR N) ? N

THE MAXIMUM NUMBER OF ITERATIONS IS 20

DO YOU WANT TO CHANGE THE NUMBER OF ITERATIONS (Y OR N) ? N

SELECTION OF INITIAL BUS VOLTAGE MAGNITUDE AND ANGLES :

1. FLAT START
2. OUTPUT VALUES FROM THE PREVIOUS RUN

ENTER YOUR SELECTION (1 OR 2) "1". For a flat start the program then runs until it displays :

```
ITERATION 7
MISMATCH = 8.79E-05
QG = .2170353
QG = .4300325
TOTAL NUMBER OF ITERATIONS = 7
MISMATCH = 8.79E-05
PRESS RETURN TO CONTINUE
```

NB! It advises that the results are now being sent to and stored in output data files. For case 1 the output files are PFBO1.DAT, PFLO1.DAT and PFTO1.DAT. The data in these files is then available for being read into another program (e.g. Transient stability program) for use by that program. It then returns to menu 1.

Select "3" to display output data:

DO YOU WANT TO DISPLAY THE BUS OUTPUT DATA (Y OR N) ? Y

DO YOU WANT TO DISPLAY THE LINE OUTPUT DATA (Y OR N) ? Y

DO YOU WANT TO DISPLAY THE TRANSFORMER OUTPUT DATA (Y OR N) ? Y

DO YOU WANT TO DISPLAY THE OUTPUT DAT IN EXPONENTIAL FORMAT (Y OR N) ? N

USE THE Ctrl PRINT SCREEN OPTION NOW IF YOU WANT TO PRINT THE RESULTS.

PRESS RETURN TO CONTINUE.

OUTPUT RESULTS UNDER BASE LOAD WITH FIXED TAPPINGS

POWER FLOW BUS OUTPUT DATA FOR gary.001						
BUS	VOLTAGE MAGNITUDE	PHASE ANGLE	GENERATION		LOAD	
			PG	QG	PL	QL .95>V>1.05
	per unit	degrees	per unit	per unit	per unit	per unit
1	1.000	0.000	1.030	0.222	0.000	0.000
2	1.000	0.862	0.980	0.217	0.000	0.000
3	1.000	-3.067	1.000	0.430	0.710	0.234
4	0.988	-3.734	0.000	0.000	0.000	0.000
5	0.989	-2.546	0.000	0.000	0.000	0.000
6	0.988	-4.118	0.000	0.000	0.000	0.000
7	0.987	-4.135	0.000	0.000	0.580	0.100
8	0.986	-3.981	0.000	0.000	0.180	0.090
9	0.979	-3.684	0.000	0.000	0.600	0.200
10	0.981	-3.515	0.000	0.000	0.000	0.000
11	0.975	-4.110	0.000	0.000	0.360	0.150
12	0.984	-3.997	0.000	0.000	0.000	0.000
13	0.980	-3.804	0.000	0.000	0.000	0.000
14	0.982	-3.945	0.000	0.000	0.000	0.000
15	0.984	-4.339	0.000	0.000	0.320	0.200
16	0.984	-4.329	0.000	0.000	0.250	0.100
		TOTAL	3.010	0.869	3.000	1.074

None of the voltages exceed the ±5% allowable volt-drop.

POWER FLOW LINE OUTPUT DATA FOR gary. 001						
LINE	BUS TO	BUS	P	Q	S	RATING EXCEEDED
1	4	8	0.575	0.145	0.593	
	8	4	-0.575	-0.157	0.596	
2	4	7	0.455	0.008	0.455	
	7	4	-0.454	-0.035	0.455	
3	7	8	-0.095	-0.003	0.095	
	8	7	0.095	-0.049	0.107	
4	8	16	0.270	0.038	0.273	
	16	8	-0.270	-0.081	0.282	
5	8	12	0.029	0.078	0.084	
	12	8	-0.029	-0.127	0.131	
6	6	7	0.031	0.020	0.037	
	7	6	-0.031	-0.062	0.069	
7	9	13	0.042	-0.047	0.063	
	13	9	-0.042	0.040	0.058	
8	9	11	0.152	-0.018	0.153	
	11	9	-0.152	0.011	0.152	
9	5	9	0.799	0.147	0.812	
	9	5	-0.794	-0.135	0.805	
10	5	10	0.181	0.009	0.181	
	10	5	-0.180	-0.025	0.182	
11	10	11	0.180	0.025	0.182	
	11	10	-0.179	-0.035	0.182	
12	6	15	0.259	0.169	0.309	
	15	6	-0.259	-0.200	0.327	
13	14	15	0.042	-0.040	0.058	
	15	14	-0.041	-0.004	0.042	
14	15	16	-0.020	0.004	0.021	
	16	15	0.020	-0.019	0.028	

No ratings exceeded.



POWER FLOW TRANSFORMER OUTOUT DATA FOR gary. 001							
TRAN	BUS	TO BUS	P	Q	S	TAP SETTING	RATING EXCEEDED
1	1	4	1.030	0.222	1.053	1.000	
	4	1	-1.030	-0.152	1.041		
2	12	11	0.029	0.127	0.131	1.000	
	11	12	-0.029	-0.126	0.130		
3	2	5	0.980	0.217	1.004	1.000	
	5	2	-0.980	-0.157	0.992		
4	14	13	-0.042	0.040	0.058	1.000	
	13	14	0.042	-0.040	0.058		
5	3	6	0.290	0.196	0.350	1.000	
	6	3	-0.290	-0.188	0.346		

No ratings exceeded.

REMOVE Ctrl PRINT SCREEN AND THEN RETURN TO CONTINUE.

**C(iii) BUS VOLTAGE/PHASE ANGLES-BASE LOAD-AUTOMATIC  
TAP CHANGERS**

Go to dos and copy case "1" files PFB1.DAT, PFL1.DAT and PFT1.DAT to case "2" files PFB2.DAT, PFL2.DAT and PFT2.DAT. The data in these case "2" files is then also available for being read into another program once updated and changes have been made.

Enter the "POWER FLOW" program and enter case number "2".

Before proceeding the following must be understood:

According to Table 3, Transformers T2 and T4 are transformers with automatic tap changers. These transformers are between buses 12 and 11 and buses 14 and 13. The second buses (11 and 13) of each are the secondaries at 132 kV. Buses 11 and 13 are thus Type 3 buses, namely voltage controlled buses with automatic tap changes.

The user has to input a value from 1 to 1.25 for the maximum tap (MAX TAP) and the program sets the minimum tap (MIN TAP) equal to (2.0 - MAX TAP).

When the program runs and a Type 3 bus is specified it varies the tap setting connected to the Type 3 bus until:

- (1) the computed bus voltage is within  $\pm 0.4\%$  of the input bus voltage or
- (11) the maximum or minimum tap setting is reached.

Go to menu 1 and select "1" update input data files with changes.

Select "1" to update bus data on menu 2.

Use menu 3 and update the bus input data. It is the same as for the fixed transformer condition except that bus 11 and 13 must be updated to Type 3 buses and initial bus voltage of 1 pu must be stated.

Print the input data which should be as follows:

BUS INPUT DATA FOR gary.002									
BUS	TYPE	V	DELTA	PG	QG	PL	QL	QGMAX	QGMIN
		per unit	degrees	per unit	per unit	per unit	per unit	per unit	per unit
1	0	1.0	0	-	-	0.00	.000	-	-
2	2	1.0	-	0.98	-	0.00	.000	1.0	-1.0
3	2	1.0	-	1.00	-	0.71	.234	1.0	-1.0
4	1	-	-	0.00	0	0.00	.000	-	-
5	1	-	-	0.00	0	0.00	.000	-	-
6	1	-	-	0.00	0	0.00	.000	-	-
7	1	-	-	0.00	0	0.58	.100	-	-
8	1	-	-	0.00	0	0.18	.090	-	-
9	1	-	-	0.00	0	0.60	.200	-	-
10	1	-	-	0.00	0	0.00	.000	-	-
11	3	1.0	-	0.00	0	0.36	.150	-	-
12	1	-	-	0.00	0	0.00	.000	-	-
13	3	1.0	-	0.00	0	0.00	.000	-	-
14	1	-	-	0.00	0	0.00	.000	-	-
15	1	-	-	0.00	0	0.32	.200	-	-
16	1	-	-	0.00	0	0.25	.100	-	-

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE

Select "6" on menu 3 as done with Bus data.

Select "4" on menu 2 as done with data.

Select "2" on menu 1 to "RUN THE PROGRAM".

The program prompts:

DO ANY OF THE TRANSFORMERS HAVE TAP-CHANGERS WITH FIXED SETTINGS (Y OR N) ? Y

HOW MANY FIXED-TAP TRANSFORMERS ? 3

FIXED-TAP TRANSFORMER 1 :

ENTER THE TRANSFORMER MUNBER 1

WHAT IS THE FIXED TAP SETTING (ENTRR A NUMBER FROM 0.75 TO 1.25) ? 1

FIXED-TAP TRANSFORMER 2 :

ENTER THE TRANSFORMER NUMBER 3

WHAT IS THE FIXED TAP SETTING (ENTER A NUMBER FROM 0.75 TO 1.25) ? 1

FIXED-TAP TRANSFORMER 3 :

ENTER THE TRANSFORMER NUMBER 5

WHAT IS THE TAP SETTING (ENTER A NUMBER FROM 0.75 TO 1.25 ) ? 1

THE TOLERANCE LEVEL IS .0001

DO YOU WANT TO CHANGE THE TOLERANCE LEVEL (Y OR N) ? N

THE MAXIMUM NUMBER OF ITERATIONS IS 20

DO YOU WANT TO CHANGE THE NUMBER OF ITERATIONS ( Y OR N ) ? N

Select flat start and let program run.

The output results for this case "2" are stored in output files PFB02.DAT, PFL02.DAT and PFT02.DAT. The data in these files is then available for being read into another program (e.g. Transient Stability program) for use by that program.

The resultant comparative table of voltages are:

BUS	VOLTAGE MAGNITUDE PER UNIT		PHASE ANGLE DEGREES	
CASES				
NO	C(11)	C(111)	C(11)	C(111)
1	1.000	1.000	0.000	0.000
2	1.000	1.000	0.862	0.991
3	1.000	1.000	-3.067	-3.127
4	0.988	0.979	-3.734	-3.772
5	0.989	1.004	-2.546	-2.368
6	0.988	0.980	-4.118	-4.185
7	0.987	0.977	-4.135	-4.180
8	0.986	0.976	-3.987	-4.017
9	0.979	0.999	-3.684	-3.534
10	0.981	1.003	-3.515	-3.464
11	0.975	1.001	-4.110	-4.132
12	0.984	0.968	-3.997	-3.985
13	0.980	1.001	-3.804	-3.691
14	0.982	0.967	-3.945	-3.861
15	0.984	0.975	-4.339	-4.391
16	0.984	0.974	-4.329	-4.379

Buses 11 and 13 which are Type 3 buses in case C(111) are held to 1.001 pu V respectively. All other voltages are within  $\pm 5\%$  of 1pu voltages.

FINAL TAP SETTING			
TRANSFORMER	T2	TAP SETTING	1.060
TRANSFORMER	T4	TAP SETTING	1.040

The ratings of the lines and transformers were not exceeded.

**C(1V) BUS POWER FLOWS-HEAVY LOAD CONDITIONS-FIXED TAPPINGS**

Go to dos and copy case "1" files PFB1.DAT, PFL1.DAT and PFT1.DAT to case "3" files PFB3.DAT, PFL3.DAT and PFT3.DAT.

The data in these files, once updated with changes is then also available for being read into another program (e.g. Transient Stability program) for use by that program.

Enter the "POWER FLOW" program and enter case number "3". Go to menu 1 to update input data file with changes. Use menu 3 and update the bus input data for heavy load conditions. It is the same as for case "1" except:

BUS 2 - PG = 1.5, BUS 3 - PL = 0.569, QL = 0.187, etc for buses 7,8,9,11,15 and 16, which is namely:

HEAVY LOAD - BUS INPUT DATA FOR gary.003									
BUS	TYPE	V	DELTA	PG	QG	PL	QL	QGMAX	QGMIN
		per unit	degrees	per unit	per unit	per unit	per unit	per unit	per unit
1	0	1.0	0	-	-	0.000	.000	-	-
2	2	1.0	-	1.50	-	0.000	.000	1.0	-1.0
3	2	1.0	-	1.00	-	0.569	.187	1.0	-1.0
4	1	-	-	0.00	0	0.000	.000	-	-
5	1	-	-	0.00	0	0.000	.000	-	-
6	1	-	-	0.00	0	0.000	.000	-	-
7	1	-	-	0.00	0	0.650	.700	-	-
8	1	-	-	0.00	0	0.487	.251	-	-
9	1	-	-	0.00	0	0.569	.189	-	-
10	1	-	-	0.00	0	0.000	.000	-	-
11	1	-	-	0.00	0	0.397	.167	-	-
12	1	-	-	0.00	0	0.000	.000	-	-
13	1	-	-	0.00	0	0.000	.000	-	-
14	1	-	-	0.00	0	0.000	.000	-	-
15	1	-	-	0.00	0	0.353	.190	-	-
16	1	-	-	0.00	0	0.393	.218	-	-

REMOVE Ctrl PRINT SCREEN AND THEN PERSS RETURN TO CONTINUE

The line and transformer data remain unchanged from case "1". Go to menu 2 to "Run the program". The output results for this case "3" are stored in output files PFB03.DAT, PFL03.DAT and PFT03.DAT. The data in these files is then available for being read into another program (e.g. Transient Stability program) for use by that program.

From the line flows the following diagrams can be drawn:

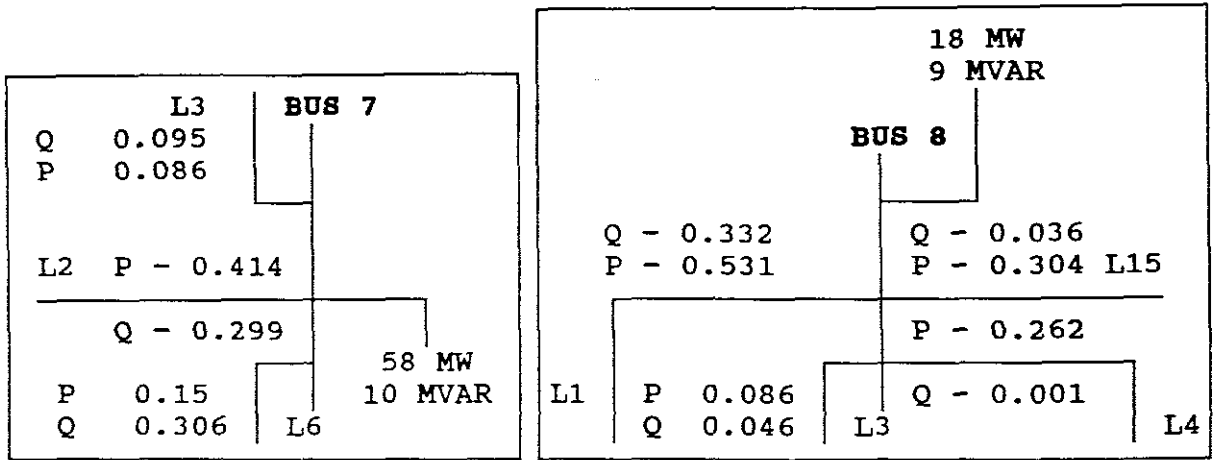


DIAGRAM. 1

DIAGRAM. 2

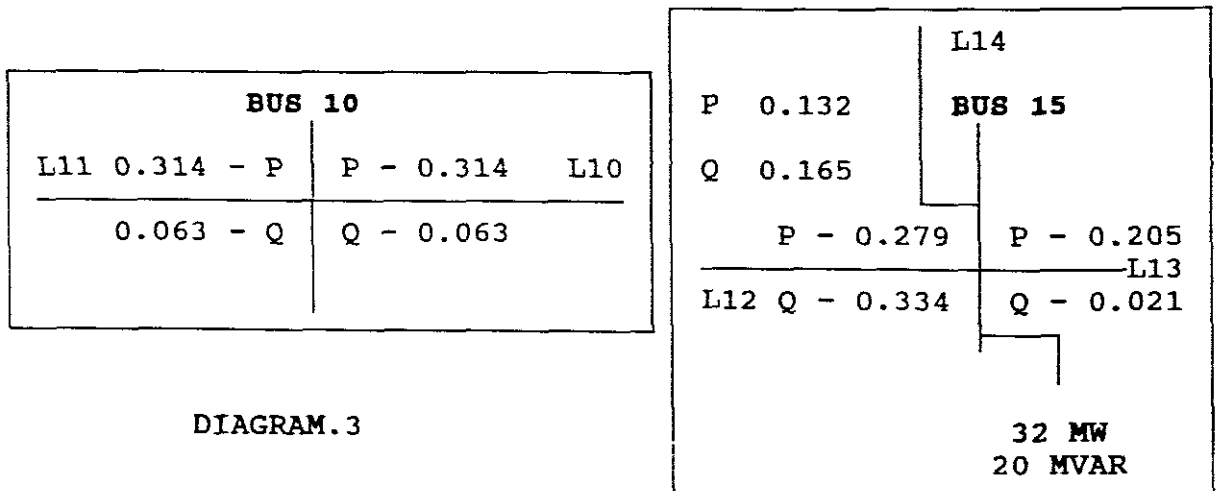


DIAGRAM. 3

DIAGRAM. 4

PART TWO

d. "LOADFLOW" PROGRAM

It is necessary to create an "Input Data File" and a "Voltage Solution File" before entering the program. Suggested file names are 16bus.in and 16bus.out. Use the data as provided in Tables 1 to 6 (Base Load only) to create an "Input Data File" (16bus.in) in accordance with the format of Table 13 and the instructions which follow directly thereafter. The Input Data File (16bus.in) is as follows: (NB! Different to Table 13 which was for heavy load conditions)

INPUT DATA FILE : 16bus.in

```
SAMPLE 16 BUS LOADFLOW EXAMPLE
BASE LOAD PROJECT
16
3
19
1
1 B1 0.0 0.0 0.95 1.05
2 B2 0.0 0.0 0.95 1.05
3 B3 0.710 0.234 0.95 1.05
4 B4 0.0 0.0 0.95 1.05
5 B5 0.0 0.0 0.95 1.05
6 B6 0.0 0.0 0.95 1.05
7 B7 0.58 0.1 0.95 1.05
8 B8 0.180 0.090 0.95 1.05
9 B9 0.600 0.200 0.95 1.05
10 B10 0.0 0.0 0.95 1.05
11 B11 0.360 0.150 0.95 1.05
12 B12 0.0 0.0 0.95 1.05
13 B13 0.0 0.0 0.95 1.05
14 B14 0.0 0.0 0.95 1.05
15 B15 0.320 0.20 0.95 1.05
16 B16 0.250 0.100 0.95 1.05
1 0.0 1.00 1.0 -1.0
2 0.98 1.00 1.0 -1.0
3 1.0 1.00 1.0 -1.0
4 8 0.001361 0.007580 0.007723 1.5 LINE
4 7 0.002722 0.015160 0.015447 1.5 LINE
7 8 0.004764 0.026531 0.027032 1.5 LINE
8 16 0.004083 0.022741 0.02317 1.5 LINE
8 12 0.004491 0.025015 0.02548 1.5 LINE
6 7 0.010662 0.023705 0.021900 1.5 LINE
9 13 0.012483 0.035296 0.00367 1.5 LINE
9 11 0 028392 0.043905 0.00392 1.5 LINE
5 9 0.007386 0.025442 0.00274 1.5 LINE
5 10 0.008322 0.023531 0.0024 1.5 LINE
10 11 0.020805 0.058827 0.00612 1.5 LINE
6 15 0.002994 0.016677 0.01699 1.5 LINE
14 15 0.001361 0.007580 0.0077235 1.5 LINE
15 16 0.001361 0.007580 0.0077235 1.5 LINE
1 4 0.0001 0.0625 0.0 2.7 TRAN 1 4 1.0
12 11 0.0001 0.0650 0.0 4.0 TRAN 12 11 1.0
2 5 0.0001 0.0600 0.0 2.5 TRAN 2 5 1.0
14 13 0.0001 0.057 0.0 4.0 TRAN 14 13 1.0
3 6 0.0001 0.0625 0.0 2.6 TRAN 3 6 1.0
```

**NB! This input data has been made as close as possible to the input data used with "POWER FLOW" in order to check the accuracy of results.**

This data is saved and stored in the created "INPUT DATA FILE" (16bus.in).



**d (1),(11)&(111) BUS INPUT DATA - BASE LOAD**

C:\> LOADFLOW

The program prompts:

Enter name of input data file : 16bus.in

Do you want output on printer ? (Y or N) Y

Menu of options:

- 1 - print input data
- 2 - run Gauss-Seidel loadflow
- 3 - run Newton-Raphson loadflow
- 4 - print solution
- 5 - change input data
- 6 - write voltage solution to a file
- 7 - quit

Enter option > 1 (to print input data)

The program prints

file 16bus.in

SAMPLE 16 BUS LOADFLOW EXAMPLE

BASE LOAD PROJECT

Number of Buses = 16

Number of lines = 19

Number of Generations = 3

Number of Transformers = 5

Swing Bus at bus number = 1

**d (1) BUS DATA**

**BUS DATA**

Bus Number	Bus Name	Mw Load	Mvar Load	Voltage High limit	Voltage Low Limit	Bus Type
1	B1	0.000	0.000	1.050	0.95	SWING
2	B2	0.000	0.000	1.050	0.95	GEN
3	B3	71.000	23.400	1.050	0.95	GEN
4	B4	0.000	0.000	1.050	0.95	LOAD
5	B5	0.000	0.000	1.050	0.95	LOAD
6	B6	0.000	0.000	1.050	0.95	LOAD
7	B7	58.000	10.000	1.050	0.95	LOAD
8	B8	18.000	9.000	1.050	0.95	LOAD
9	B9	60.000	20.000	1.050	0.95	LOAD
10	B10	0.000	0.000	1.050	0.95	LOAD
11	B11	36.000	15.000	1.050	0.95	LOAD
12	B12	0.000	0.000	1.050	0.95	LOAD
13	B13	0.000	0.000	1.050	0.95	LOAD
14	B14	0.000	0.000	1.050	0.95	LOAD
15	B15	32.000	20.000	1.050	0.95	LOAD
16	B16	25.000	10.000	1.050	0.95	LOAD

**d (11) GENERATOR DATA**

Generator Data				
Bus Number	Mw Generation	Scheduled Voltage	High Mvar Limit	Low MVar Limit
1	0.00000	1.0000	1.0000	-1.0000
2	0.98000	1.0000	1.0000	-1.0000
3	1.00000	1.0000	1.0000	-1.0000

**d (111) BRANCH DATA**

BRANCH DATA									
From Bus	To Bus	Branch		Line Charging	Mva Limit	Type	Tap Bus	Non	
		R	X					Tap Bus	Tap Ratio
1	4	.0001	.0625	.000000	2.7	TRAN	1	4	1.0
2	5	.0001	.0600	.000000	2.5	TRAN	2	5	1.0
3	6	.0001	.0625	.000000	2.6	TRAN	3	6	1.0
4	8	.0014	.0076	.007723	1.5	LINE			
4	7	.0027	.0152	.015447	1.5	LINE			
5	9	.0074	.0254	.002740	1.5	LINE			
5	10	.0083	.0235	.002400	1.5	LINE			
6	7	.0107	.0237	.021900	1.5	LINE			
6	15	.0030	.0167	.016990	1.5	LINE			
7	8	.0048	.0265	.027032	1.5	LINE			
8	16	.0041	.0227	.023170	1.5	LINE			
8	12	.0045	.0250	.025480	1.5	LINE			
9	13	.0125	.0353	.003670	1.5	LINE			
9	11	.0284	.0439	.003920	1.5	LINE			
10	11	.0208	.0588	.006120	1.5	LINE			
11	12	.0001	.0650	.000000	4.0	TRAN	12	11	1.0
13	14	.0001	.0570	.000000	4.0	TRAN	14	13	1.0
14	15	.0014	.0076	.007723	1.5	LINE			
15	16	.0014	.0076	.007723	1.5	LINE			

The program then returns to above menu.

d(1V)LOAD FLOW SOLUTION - NEWTON RAPHSON - BASE LOAD

Select "3" to run the NR algorithm.  
 Then select "4" to print solution:  
 The load flow solution is:

File: 16BUS.IN  
 SAMPLE 16 BUS LOADFLW EXAMPLE  
 BASE LOAD PROJECT

From Bus	Volt Mag.	Volt Angle	Mw Load	Mvar Load	Mw Gen	Mvar Gen	To Bus	Mw Flow	Mvar Flow	Mva Flow
1	1.000	0.00	00.0	00.0	102.84	22.86	4	102.84	22.86	105.35
2	1.000	0.46	00.0	00.0	98.00	23.87	5	98.00	23.87	100.86
3	1.000	-3.05	71.0	23.4	100.00	44.28	6	29.00	20.88	35.74
4	0.987	-3.73	00.0	00.0			8	57.54	14.11	59.25
							7	45.27	1.82	45.31
							1	-102.83	-15.92	104.05
5	0.987	-2.95	00.0	00.0			9	72.02	14.52	73.47
							10	25.95	3.25	26.16
							2	-97.99	-17.76	99.58
6	0.987	-4.10	00.0	00.0			7	3.38	1.01	3.53
							15	25.61	19.08	31.94
							3	-29.00	-20.08	35.27
7	0.986	-4.12	58.0	10.0			4	-45.22	-4.51	45.44
							8	-9.40	-0.22	9.40
							6	-3.38	-5.26	6.26
8	0.985	-3.97	18.0	9.0			4	-57.49	-15.34	59.50
							7	9.40	-5.01	10.65
							16	26.41	5.62	27.00
							12	3.69	5.73	6.81
9	0.978	-3.97	60.0	20.0			13	5.04	-5.75	7.65
							11	6.58	-0.61	6.61
							5	-71.61	-13.64	72.90
10	0.984	-3.29	00.0	00.0			5	-25.89	-3.55	26.14
							11	25.89	3.56	26.14
11	0.976	-4.14	36.0	15.0			9	-6.57	-0.12	6.57
							10	-25.74	-4.31	26.10
							12	-3.68	-10.56	11.19
12	0.983	-4.00	00.0	00.0			8	-3.68	-10.65	11.27
							11	3.68	10.65	11.27
13	0.979	-4.11	00.0	00.0			9	-5.04	5.07	7.15
							14	5.04	-5.07	7.15
14	0.982	-4.29	00.0	00.0			15	5.04	-5.10	7.17
							13	-5.04	5.10	7.17
15	0.982	-4.31	32.0	20.0			6	-25.58	-22.19	33.86
							14	-5.04	3.61	6.20
							16	-1.38	-1.42	1.98
16	0.982	-4.31	25.0	10.0			8	-26.38	-9.93	28.18
							15	1.38	-0.07	1.38

Mw gen	=	300.84
Mvar gen	=	91.01
Mw load	=	300.00
Mvar load	=	107.40
Total I2R Mw losses	=	0.84
Total I2X Mvar losses	=	17.00
Total charging Mvar	=	33.37

The resultant comparative table of voltages are:

BUS	VOLTAGE MAGNITUDE PER UNIT		PHASE ANGLE DEGREES	
	CASES			
NO	C(11)	d(111)	C(11)	d(111)
1	1.000	1.000	0.000	0.000
2	1.000	1.000	0.862	0.463
3	1.000	1.000	-3.067	-3.050
4	0.988	0.988	-3.734	-3.730
5	0.989	0.988	-2.546	-2.950
6	0.988	0.987	-4.118	-4.101
7	0.987	0.986	-4.135	-4.128
8	0.986	0.986	-3.981	-3.974
9	0.979	0.978	-3.684	-3.972
10	0.981	0.984	-3.515	-3.293
11	0.975	0.976	-4.110	-4.149
12	0.984	0.984	-3.997	-4.007
13	0.980	0.980	-3.804	-4.119
14	0.982	0.982	-3.945	-4.290
15	0.984	0.983	-4.339	-4.316
16	0.984	0.983	-4.329	-4.311

NB! The above results are very similar showing the accuracy of the two programs used.

NB! These results by the "LOADFLOW" program coincide with the results of the "POWER FLOW" program.

NB! The voltage solution for case d(111) is dumped into the solution file for subsequent use by another program (e.g. Economic Dispatch Program).

Select "6" on main menu and enter name of solutions file (16bus.out).

If this solution is now printed it has the following format.

SAMPLE 16 BUS LOADFLW EXAMPLE		
BASE LOAD PROJECT		
1	1.0000000000E+00	0.0000000000E+00
2	1.0000000000E+00	8.0787479086E-03
3	1.0000000000E+00	-5.3228634900E-02
4	9.8770160824E-01	-6.5095842332E-02
5	9.8733359585E-01	-5.1484579717E-02
6	9.8708609016E-01	-7.1570205518E-02
7	9.8596647732E-01	-7.2050578204E-02
8	9.8577699021E-01	-6.9367857931E-02
9	9.7829058998E-01	-6.9326097090E-02
10	9.8433259647E-01	-5.7469575512E-02
11	9.7648958275E-01	-7.2418951897E-02
12	9.8352738025E-01	-6.9938731162E-02
13	9.7959857626E-01	-7.1887532944E-02
14	9.8254716168E-01	-7.4876512074E-02
15	9.8281332848E-01	-7.5333327286E-02
16	9.8288461362E-01	-7.5234585744E-02

NB! The above results are in a + jb format and not in polar format as given by the loadflow solution.

Checking:

Bus 2:  $1 + j8.0787479086E-03$   
=  $1/_0.463^\circ$  pu Volts (which is the same as the polar form previously found by the program).

Likewise for remaining buses.

**PART THREE  
SELF EVALUATION**

e. The one-line diagram solution is not given as the user must provide it himself. (NB! The author of this computer laboratory set-up has such a one-line diagram solution and is available to an evaluator).

f. The answer to the voltage solution in a + jb is:

SAMPLE 16 BUS LOADFLOW EXAMPLE HEAVY LOAD PROJECT		
1	1.0000000000E+00	0.0000000000E+00
2	1.0000000000E+00	8.3558784630E-02
3	1.0000000000E+00	-3.7325262254E-02
4	9.6003658550E-01	-6.1135241580E-02
5	9.7511666026E-01	-8.8044976360E-03
6	9.6312153868E-01	-6.5231536724E-02
7	9.5428632635E-01	-6.6807694519E-02
8	9.5681640688E-01	-6.5157123219E-02
9	9.6106308616E-01	-3.5855990655E-02
10	9.6916278478E-01	-1.8720669355E-02
11	9.5421025015E-01	-4.3868705447E-02
12	9.5721197737E-01	-5.9173322245E-02
13	9.5715980658E-01	-4.7428983801E-02
14	9.5723318693E-01	-6.6145161607E-02
15	9.5678820350E-01	-6.8631121812E-02
16	9.5524261302E-01	-6.9993272771E-02

**NB! These results by the "LOADFLOW" program coincide with the results of the "POWER FLOW" program. See C(iv) results.**

COMPARATIVE SUMMARY OF PROGRAMS USED

"POWERFLOW"

- (1) Computes voltage magnitude (V) and phase angle ( $\delta$ ) at each bus under Steady-State conditions.
- (2) Computes generator, line and transformer loadings.
- (3) Maximum number of buses, transformers and transmission lines are 100.
- (4) Input data (Bus data) includes PG, QG, PL, QL, QGMAX and QGMIN.
- (5) Input data (line data) includes Rpu, Xpu, Gpu, Bpu and MAXMVA of a line. Per km values must be changed to pu values at system base by hand before use by the program.
- (6) Transformers can be operated with fixed tapings or as automatic tap-changing transformers.
- (7) Program handles 4 types of buses, namely swing, load, constant voltage bus and voltage controlled bus, the latter only being used with an automatic tap-changing transformer.
- (8) Transformer input data includes series impedance (Rpu, Xpu) and shunt circuits (Gpu, Bpu). Also MAXMVA and MAX TAP SETTING are provided.
- (9) Can store up to 3 cases under study.
- (10) Can FLAT START a run or use values from a PREVIOUS RUN.
- (11) The tolerance level and number of iterations can be chosen.
- (12) Advises if bus voltage is between  $0.95 > V > 1.05$  and if rating of a line or transformer is exceeded.
- (13) Advises the tap setting position of an automatic tap changer where it has controlled a bus voltage to within  $\pm 0.4\%$  OF 1puV.
- (14) Uses Newton-Raphson algorithm only.
- (15) No one-line diagrams or even sections thereof are drawn by the program. These must be hand drawn.
- (16) Mismatches at each bus are also not indicated at the end of a run.

**"LOADFLOW"**

- (1) Solves loadflow to a maximum of 25 buses, 40 lines, 20 generators and 10 transformers.
  - (2) Must create an input data file before using the program and a solutions file for dumping voltage solutions to.
  - (3) Input data requires per unit values for lines etc., therefore per km values must be changed by hand to per unit values on a common systems base.
  - (4) Bus input data requires MW and MVAR load, high and low voltage limits and bus type, either swing, generator or load.
  - (5) Generator input data requires MW generation, scheduled voltage and high and low MVAR limits.
  - (6) Branch input data requires Branch Rpu, Xpu, Line charging, Branch MVA limit, branch type, either line or transformer, tap bus number, non-tap bus number and tap ratio.
  - (7) Program can run on Gauss-Seidal or Newton-Raphson algorithms.
  - (8) Output data includes voltage magnitude and angle, MW load, MVAR load, MW generation, MVAR generation and Line and Transformer flows. Also gives totals for MW generation, MVAR generation, MW load, MVAR load,  $I^2R$  MW losses,  $I^2X$  MVAR Losses and Total Charging MVARs.
  - (9) No one-line diagrams or even sections thereof are drawn by the program. These must be hand drawn.
  - (10) Mismatches at each bus are also not indicated at the end of a
-



**CHAPTER TWO**  
**FAULT STUDIES COMPUTER EXPERIMENTS**  
**16 BUS 3 GENERATOR POWER SYSTEM**

The operation of a power system departs from normality after the occurrence of a fault.

A fault study includes the following: (Nasar, 1990: 74)

- a. Determination of the maximum and minimum three phase short circuit currents.
- b. Determination of unsymmetrical fault currents as in single line-to-ground, double line-to-ground, line-to-line and open circuit faults.
- c. Determination of the ratings of required circuit breakers.
- d. Investigation of schemes of protective relaying.
- e. Determination of voltage levels at strategic points during a fault.

The balanced three phase short circuit is relatively uncommon, however, it is the most severe fault and therefore determines the rating of the line protecting circuit breakers. It is for this reason that it is generally given primary consideration when doing fault studies.

Most faults that occur on power systems are unsymmetrical faults and it is for this reason that they are also considered when doing fault studies.

1. EXPLANATION OF THE USAGE OF THE PROGRAMS

a. PROGRAM "SYMMETRICAL SHORT CIRCUITS" BY GLOVER

In order to calculate the subtransient fault current for a 3 phase short circuit, the following assumptions are made: (Glover, 1991: 283)

1. Transformers are represented by their leakage reactances. Winding resistances, shunt admittances and D-Y phase shifts are neglected.
2. Transmission lines are represented by their positive sequence equivalent series reactances. Series resistance and shunt admittances are neglected.
3. Synchronous machines are represented by constant voltage sources behind subtransient reactances. Armature resistance, saliency and saturation are neglected.
4. All non-rotating impedance loads are neglected.
5. Induction motors are either neglected (especially for small motors rated less than 37.3kW or 50HP) or represented in the same manner as synchronous machines.

**NB!** In practice these assumptions should be not made for all cases. For example, in distribution systems, resistances may significantly reduce fault current magnitudes.

Also (Glover, 1991: 286):

When calculating the contributions to fault currents from each branch, pre-fault currents are usually small, and hence can be neglected. If it is necessary to take the pre-fault currents into account then these can be obtained from a power-flow program.

**NB!** The two power flow programs used in Chapter One provide as output data power flows only. They do not provide pre-fault currents. These would have to be hand calculated.

This program does not call for bus data as in Chapter One, therefore loads are ignored and therefore the load flow bus voltage results are not used.

**NB!** If pre-fault load current is neglected, then the internal positive sequence voltages of all machines are equal to the pre-fault voltage  $V_F$ . Therefore, the pre-fault voltage at each bus in the positive sequence network equals  $V_F$ . (Glover, 1991: 315).  $V_F$  can be other than 1pu, it can be for example 1.05pu.

This program computes the AC (symmetrical) fault current for a bolted three phase short circuit at any bus in an N-bus system. It also computes contributions to fault currents from synchronous machines, transmission lines and transformers connected to the faulted bus. Besides these, it also computes the bus voltages during the fault.(Glover, 1991: 288) as well as the positive sequence bus impedance matrix. The program uses the one step-at-a-time method (Glover,1991: 291) to compute the Zbus (pos-seq). The program can either compute Zbus from scratch or begin with an existing Zbus that has already been computed and stored.

After Zbus is computed, it is employed by the program to compute fault currents and voltages at each bus during the fault.

The maximum number of buses is 100. A 50 bus system can be run on a computer with 256K of RAM. More RAM (up to 500K for 100 buses) is required for more than 50 buses. The maximum number of lines or transformers is 100.

**INPUT DATA**

Input data for the program consists of synchronous machine data, transmission line data and transformer data. The tables of typical input data are as follows:

(1) SYNCHRONOUS MACHINE DATA:

Machine No.	Bus No.	X Per unit
1	1	0.18
2	3	0.09

Table.28

**NB!** When the machine reactance (X) input data consists of direct-axis subtransient reactance ( $X_d''$ ), the computed ac fault currents are subtransient fault currents. Alternatively, transient or steady-state ac fault currents are computed when direct-axis transient reactance ( $X_d'$ ) or synchronous reactance ( $X_1$ ) are used as input data. No machine resistance is considered.

(11) TRANSMISSION LINE DATA:

LINE No.	BUS - TO - BUS		X1 Per unit
1	2	4	0.4
2	2	4	0.4
3	2	5	0.2
4	2	5	0.2
5	4	5	0.1
6	4	5	0.1

Table.29

Here  $X_1$  is the transmission line reactance and is the equivalent positive sequence series reactance for long, medium or short lines. Resistances of lines are neglected.

(111) TRANSFORMER DATA:

LINE No.	BUS - TO - BUS		X1 Per unit
1	1	5	0.08
2	3	4	0.04

Table.30

Here  $X_1$  is the leakage reactance of a transformer. Resistance and shunt admittances are neglected.

**NB!** If input data received is not in per-unit then these values have to be converted by hand to pu values as all machine, line and transformer reactances must be in pu on a common MVA base.

**STORING AND UPDATING DATA**

The above input data can be stored for up to "five" separate cases. The bus, line and transformer input data files for Case 1 are called SSCM1.DAT, SSCL1.DAT and SSCT!.DAT. Similarly for cases 2 to 5.

When updating any of these input data files the user has the following options:

- MENU CHAPTER TWO No.1
- (1) INITIALIZE FILE
  - (2) ADD A NEW MACHINE (LINE OR TRANSFORMER) OR CHANGE AN EXISTING MACHINE (LINE OR TRANSFORMER)
  - (3) REMOVE A MACHINE (LINE OR TRANSFORMER)
  - (4) DISPLAY ONE MACHINE (LINE OR TRANSFORMER)
  - (5) DISPLAY ALL MACHINES (LINES OR TRANSFORMERS) AFTER A GIVEN MACHINE (LINE OR TRANSFORMER)
  - (6) DONE WITH MACHINE (LINE OR TRANSFORMER DATA).

**NB!** For more information on how to use this menu, see Storing and Updating data in Chapter One (program "a")

**PRINTING**

This usually takes place after the machine, line and transformer data have been entered for a given case. The "Ctrl PRINT SCREEN OPTION" is used. The same steps are followed for Output Data files.

RUNNING THE PROGRAM

When user runs the program, a value for the pre-fault voltage VF is prompted. As stated above if pre-fault load currents are neglected, then the pre-fault voltage is the only source voltage required to calculate the fault current. Therefore to run the program VF is the only bus voltage needed. It need not be only 1pu it can be values  $\pm 1pu$  up to a maximum of 5% variation.

The run can be a flat start or use a previously stored Zbus as stated above.

The program computes results firstly for a bus1, then at bus2, then bus3 and so on to bus "N".

OUTPUT DATA

For a fault at bus 1,2.....N, output data consists of:

- (1) The fault current.
- (2) Contribution to the fault current from each branch connected to the faulted bus.
- (3) The bus voltages during the fault.
- (4) Zbus (pos-seq) matrix if desired.

These can all be displayed or printed and the user has the option as to which he wishes to display or print. The outputs can also be in either exponential format (scientific notation) or fixed point format (numbers with decimal points).

**NB!** The results for (1), (2), and (3) are not stored in output files as was done in Chapter One as these results are not needed for use by other programs still to be covered in this study.

Typical examples of output results for a 5 bus system could be:

FAULT CURRENTS FOR gary.000				
FAULT BUS	THREE-PHASE FAULT CURRENT	GEN LINE OR TRSF	BUS-TO-BUS	CONTRIBUTIONS TO FAULT CURRENT
	per unit			per unit
1	9.510	G 1	GRND - 1	5.5556
		T 1	5 - 1	3.9548
2	6.344	L 1	4 - 2	1.1935
		L 2	4 - 2	1.1935
		L 3	5 - 2	1.9786
		L 4	6 - 2	1.9786
3	14.028	G 2	GRND - 3	11.1111
		T 2	4 - 3	2.9167
4	10.994	L 1	2 - 4	0.2358
		L 2	2 - 4	0.2358
		L 5	5 - 4	1.4151
		L 6	5 - 4	1.4151
		T 2	3 - 4	7.6923
5	9.631	L 3	2 - 5	0.4132
		L 4	2 - 5	0.4132
		L 5	4 - 5	2.4793
		L 6	4 - 5	2.4793
		T 1	1 - 5	3.8462

Table.31

VF = 1	PER-UNIT BUS VOLTAGE DURING FAULTS				
FAULT BUS	BUS1 (6..)	BUS2 (7..)	BUS3 (8..)	BUS4 (9..)	BUS5 (10..)
1	0.0000	0.3729	0.6441	0.4859	0.3264
2	0.5817	0.0000	0.6382	0.4774	0.3957
3	0.4750	0.2000	0.0000	0.1167	0.2417
4	0.4057	0.0943	0.3077	0.0000	0.1415
5	0.3077	0.0826	0.4793	0.2479	0.0000

Table.32

PER-UNIT ZBUS FOR gary.000					
ROW 1	0.10515	0.06594	0.03743	0.05406	0.07188
ROW 2	0.06594	0.15762	0.05703	0.08238	0.09525
ROW 3	0.03745	0.05703	0.07129	0.06297	0.05406
ROW 4	0.05406	0.08238	0.06297	0.09096	0.07809
ROW 5	0.07188	0.09525	0.05406	0.07809	0.10383

Table.33

**b. PROGRAM "SHORT CIRCUITS" BY GLOVER**

A three phase power system uses sequence networks, namely positive, negative and zero sequence networks for solving unsymmetrical faults. The following assumptions are made (Glover, 1991: 314):

1. The power system operates under balanced steady-state conditions before the fault occurs. Therefore the positive, negative and zero sequence networks are uncoupled before a fault occurs. During an unsymmetrical fault they are interconnected only at the fault location.
2. Pre-fault load current is neglected. Because of this the positive sequence internal voltages of all machines are equal to the pre-fault voltage  $V_F$ . Therefore, the pre-fault voltage at each bus in the positive sequence network equals  $V_F$ .
3. Transformer winding resistances and shunt admittances are neglected.
4. Transmission line series resistances and shunt admittances are neglected.
5. Synchronous machine armature resistance, saliency, and saturation are neglected.
6. Induction motors are either neglected (especially for motors 37.2 kw or 50Hp or less) or represented in the same manner as synchronous machines.

In practice these assumptions should not be made for all cases.

**NB!** Although fault currents as well as contributions to fault currents on the fault side of D-Y transformers are not affected by D-Y phase shifts, contributions to the fault from the other side of such transformers are affected by D-Y phase shifts for unsymmetrical faults. The program takes these phase shifts into account.

The program computes for an N-bus power system the fault for one of the following faults:

1. A balanced three phase fault.
2. A single line-to-ground fault through a fault impedance  $Z_F$ .
3. A line-to-line fault through  $Z_F$ .
4. A double line-to-ground fault through  $Z_F$ .

**NB!** For bolted faults,  $Z_F = 0$ , whereas for arcing faults  $Z_F$  is an arcing impedance. In the case of a transmission-line flashover  $Z_F$  includes the total fault impedance between the line and ground including the impedances of the arc and the transmission tower as well as the tower footing if there are no neutral wires. (Glover, 1991: 320).

The program also computes the contributions to the fault current from synchronous machines, transmission lines and transformers connected to the faulted bus. It also computes the bus voltages during the fault as well as the zero, positive and negative sequence bus impedance matrices.

The maximum number of buses is 100. A 30 bus system can run on 256k of RAM. More RAM (up to 1 Meg for 100 buses) is required for more than 30 buses. The maximum machines, lines or transformers is 100.

**INPUT DATA**

Input data includes synchronous data, transmission line data and transformer data. Tables of typical input data are as follows:

1. SYNCHRONOUS MACHINE DATA:

BUS	Xo	X1 = Xd"	X2	Neutral reactance of each machine Xn
	per unit	per unit	per unit	per unit
1	0.05	0.18	0.18	0
3	0.02	0.09	0.09	0.01

TABLE.34

where: Xo = zero-sequence reactance  
 X1 = positive-sequence reactance  
 X2 = negative-sequence reactance  
 Xn = neutral reactance of each machine.

**NB!** When the positive-sequence machine reactances are subtransient reactances (Xd"), subtransient fault current is computed by the program. Alternatively, when X1 = Xd1 or X1 = Xsyn, the program computes transient or steady-state fault currents.

2. TRANSMISSION LINE DATA:

BUS-TO-BUS	Xo per unit	X1 per unit
2 - 4	1.2	0.4
2 - 5	0.6	0.2
4 - 5	0.3	0.1

TABLE.35

Transmission line positive and zero sequence series reactances are those of the equivalent  $\pi$  circuit for medium or short lines. Also negative-sequence reactances equals the positive-sequence transmission-line reactances.



3. TRANSFORMER DATA:

LOW VOLTAGE (Connection) bus	HIGH VOLTAGE (Connection) bus	LEAKAGE REACTANCE per unit	NEUTRAL REACTANCE FOR EACH WYE Connection per unit
1 (delta)	5 (Y)	0.08	0
3 (delta)	4 (Y)	0.04	0

TABLE.36

**NB!** If input data received is not in per-unit then these values have to be converted by hand to pu values as all machine, line and transformer reactances must be in pu on a common MVA base.

**NB!** For a solidly grounded neutral, enter "0" (zero) for neutral reactance in machine or transformer input data. For an approximation to an open neutral, enter a large value such as 1000 for neutral reactance.

**STORING AND UPDATING DATA**

Same as for program "a" of this chapter and also for five separate cases except input data file names are SCM1.DAT, SCL1.DAT and SCT1.DAT. Similarly for cases 2 to 5. When updating the same applies for this program as for MENU CHAPTER TWO No. 1 as given above.

**PRINTING**

As given for program "a" of this chapter.

**RUNNING THE PROGRAM**

When the user runs the program, it computes Zbus-0, Zbus-1 and Zbus-2 which are used to compute the sequence fault currents and sequence voltages at each bus during a fault at bus 1 for the fault type selected by the program user, e.g. 3 phase fault, single line-to-ground fault through Zf, line-to-line fault through Zf or a double line-to-ground fault through Zf. The user also selects the per-unit resistive and reactive components of the fault impedance and the per-unit pre-fault voltage Vf. All these computations are then repeated for a fault at bus 2 then bus 3, and so on to bus N. The program also adjusts the phase angles of the positive and negative sequence voltages to account for delta-Y transformer phase shifts. The sequence currents and sequence voltages are then transformed to the phase domain.

OUTPUT DATA

Output data for the fault type and fault impedance selected by the user consists of:

1. Fault current in each phase in polar format.
2. Contributions to the fault current from each branch connected to the fault bus for each phase in polar format.
3. Line-to-ground voltages at each bus for a fault at bus 1, Bus 2 and so on to bus N.
4. Zbus-0, Zbus-1 and Zbus-2 matrices if desired.

These can all be displayed or printed and the user has the option as to which he wishes to display or print. The outputs can also be in either exponential format (scientific notation) or fixed point format (numbers with decimal points).

**NB!** The results for (1), (2), and (3) are not stored in output files as was done in Chapter One as these results are not needed for use by other programs still to be covered in this study.

Examples of typical headings for the output data are:

FAULT CURRENTS

1. Single Line-to-Ground Fault

FAULT CURRENTS for gary.000						
FAULT BUS	SINGLE LINE-TO-GROUND FAULT CURRENT (PHASE A) per unit/_deg	CONTRIBUTION TO FAULT CURRENT				
		GEN LINE OR trsf	BUS-TO-BUS	PHASE A, B, C per unit/_deg		
1	11.5/_ -90	G1	GRND - 1	8.6/_ -90	1.45/_ -90	1.45/_ -90
ETC						

TABLE.37

2. Double Line-to-Ground Fault

FAULT CURRENTS for gary.000						
FAULT BUS	DOUBLE LINE-TO-GROUND FAULT CURRENT (PHASE B) per unit/_deg	CONTRIBUTION TO FAULT CURRENT				
		GEN LINE OR trsf	BUS-TO-BUS	PHASE A, B, C per unit/_deg		
1	11.5/_ -90	G1	GRND - 1	8.6/_ -90	1.45/_ -90	1.45/_ -90
ETC						

TABLE.38

BUS VOLTAGES DURING FAULTS

VF=1.05/_0°		BUS VOLTAGES DURING FAULT FOR GARY.000		
FAULT BUS	BUS NO.	PHASE A	PHASE B per unit/_deg	PHASE C
1	1	0.0000/_00.00	0.9537/_252.45	0.9537/_107.55
	2	0.6843/_-50.10	1.0500/_-90.00	0.6843/_129.90
	3	0.7888/_00.00	0.9912/_246.55	0.9912/_113.45
	4	0.7842/_42.02	1.0500/_-90.00	0.7842/_137.98
	5	0.6406/_55.03	1.0500/_-90.00	0.6406/_124.97
2	ETC.			

TABLE.39

Zbus MATRICES

Zbus MATRICES FOR GARY .000  
 $Z_f = 0 + j0$  PER UNIT

$$Z_{bus -0} = j \begin{bmatrix} 0.05000 & \dots & 0.00000 \\ \vdots & & \vdots \\ 0.00000 & \dots & 0.06303 \end{bmatrix}$$

$$Z_{bus -1} = j \begin{bmatrix} 0.11189 & \dots & 0.08162 \\ \vdots & & \vdots \\ 0.08162 & \dots & 0.06303 \end{bmatrix}$$

$$Z_{bus -2} = j \begin{bmatrix} 0.11189 & \dots & 0.08162 \\ \vdots & & \vdots \\ 0.08162 & \dots & 0.06303 \end{bmatrix}$$

TABLE.40

**2. EXPERIMENTATION USING THE PROGRAMS**

**INFORMATION AVAILABLE**

The one-line diagram of the 16 bus, 3 generator, 14 lines and 5 transformer system as shown in Figure 1 as well as Tables 1 to 6 forms the basis of the information available for experimentation.

**EXPERIMENTAL REQUIREMENTS**

- a. Convert the machine, transformer and line data which is necessary for these programs to per unit values based on a 100 MVA systems base. Tabulate your new values.

**PART ONE**

- b. Use the "Symmetrical Short Circuits" program and obtain:
1. The machine, line and transformer input data necessary to run this program for this 16 bus system.
  2. Use  $V_f = 1\text{pu}$  and determine the pu three phase symmetrical subtransient fault current and the pu contributions to the fault current for a bolted short circuit at each bus in turn, namely firstly at bus 1, then bus 2 etc. Which bus produces the highest fault current when short circuited? Also determine the pu bus voltages during the fault. What is significant about the bus voltage at bus 3?

**PART TWO**

- c. Use the "Short Circuit" program and obtain the pu three phase transient, steady-state and subtransient fault currents for a bolted short circuit at each bus in turn. Using the results obtained here, draw up a table of fault currents comparing these three currents. What is your conclusion?

**PART THREE  
SELF EVALUATION**

- e. Re-run Case 3 from PART TWO for a single line-to-ground fault. If  $V_f = 1\text{puV}$  and  $Z_f = 0$  ohms, what is the line to ground fault at bus 2 and the contributions to this fault from phases A, B and C?
- f. Repeat "e" but for an arcing fault with an arc impedance of  $Z_f = 15 + j0$  ohms. (NB!  $Z_f$  must be changed to a pu value based on 100MVA systems base before use by this program).
- g. Re-run Case 2 from PART TWO for a steady-state double line-to-ground fault at bus 16 when  $V_f = 1\text{puV}$  and  $Z_f = 0$  ohms. What are the bus voltages at each of the other buses during this fault? What do you notice about Phase B and C voltages at bus 16?

SOLUTION

- a. The input data for these two programs require reactance values only. Resistance, susceptance, transformer G and B are ignored.

The necessary tables are:

GEN DATA:

GEN NO.	MVA RATING	CONNECTION	SCHED VOLTS	kv	POS SEQ	NEG SEQ	ZERO SEQ	TRAN	SUB
					X1	X2	Xo	Xd1	TRAN Xd1
G 1	270	delta	18		2.04	0.14	0.06		0.256 0.185
G 2	245	star-grnd	14.4		1.70	0.16	0.11		0.320 0.21
G 3	260	delta	15		2.39	0.258	0.135		0.302 0.26

TABLE.41

GENERATOR DATA BASED ON SYSTEM BASE 100 MVA								
	MVA RATING	SYSTEM BASE	SCHED VOLTS	100 MVA BASE				
				X1	X2	Xo	Xd1	Xd11
G 1	270	100	1 pu	0.755	0.052	0.022	0.095	0.068
G 2	245	100	1 pu	0.693	0.065	0.044	0.130	0.085
G 3	260	100	1 pu	0.919	0.099	0.051	0.116	0.100

TABLE.42

TRANSFORMER DATA BASED ON SYSTEM BASE 100 MVA					
No.	Prim Conn	Sec Conn	Prim Volts kv	Sec Volts kv	Xpu (pos seq)=Xpu (neg seq)
T1	Delta	Star-Grnd	18(1pu)	230(1pu)	0.0625
T2	Star-Grnd	Star-Grnd	230(1pu)	132(1pu)	0.0650
T3	Delta	Star-Grnd	14.4(1pu)	132(1pu)	0.0600
T4	Star-Grnd	Star-Grnd	230(1pu)	132(1pu)	0.0570
T5	Delta	Star-Grnd	15(1pu)	230(1pu)	0.0625

TABLE 43

LINE DATA (REACTANCE ONLY)							
Line No.	Bus- to Bus	Zero seq X <sub>0</sub> Ω/km based on 150 MVA	Line Length km	X <sub>0</sub> /line 150 MVA ohms	Zbase (new) from Tab 21-25	X <sub>0</sub> pu (new) 100 MVA	Pos & Neg seq based on 100MVA from Table 26 X <sub>1</sub> =X <sub>2</sub> pu (new)
L1	4-8	1.29	10	12.9	529	0.0243	0.00757
L2	4-7	1.29	20	25.8	529	0.0487	0.01516
L3	7-8	1.29	35	45.15	529	0.0853	0.026532
L4	8-16	1.29	30	38.7	529	0.0731	0.02274
L5	8-12	1.29	33	42.57	529	0.0804	0.02501
L6	6-7	1.473	30	44.19	529	0.0835	0.023705
L7	9-13	1.465	15	21.975	174.4	0.1260	0.035296
L8	9-11	1.500	17	25.5	174.4	0.1462	0.043905
L9	5-9	1.458	11	16.038	174.4	0.0919	0.025442
L10	5-10	1.465	40	58.6	174.4	0.3371	0.094121
L11	10-11	1.465	25	36.625	174.4	0.2100	0.058826
L12	6-15	1.29	22	28.38	529	0.0536	0.016677
L13	14-15	1.29	30	38.7	529	0.0731	0.148514
L14	15-16	1.29	10	12.9	529	0.0243	0.00757

TABLE. 44

**b. "SYMMETRICAL SHORT CIRCUITS PROGRAM"**

C:\POWER>CHAP 8

**1. INPUT DATA**

The program welcomes you and then asks for:

ENTER YOUR CASE NUMBER (1,2,3,4 OR 5)?  
ENTER "1"

On selecting "1" case 1 input data will be saved and stored in files namely SSCM1.DAT, SSCL1.DAT and SSCT1.DAT. The data in these files can be copied to case 2 etc and then updated with changes.

It then prompts for:

ENTER YOUR CASE NAME ? e.g. GARY.001

The screen then displays:

```

                MENU.1
SELECTIONS:

    1.  UPDATE THE INPUT DATA
    2.  RUN THE PROGRAM
    3.  STOP

ENTER YOUR SELECTION (1,2 OR 3)
```

Select "1" to update Input Data Files

```

                MENU.2
THESE ARE YOUR INPUT DATA SELECTIONS:

    1.  UPDATE THE SYNCHRONOUS MACHINE INPUT DATA
    2.  UPDATE THE TRANSMISSION LINE DATA
    3.  UPDATE THE TRANSFORMER INPUT DATA
    4.  DONE WITH INPUT DATA

ENTER YOUR SELECTION (1,2,3 OR 4)
```

Select "1" to update Machine Data.

```

                                MENU.3
CHOICES:

    1. INITIALIZE FILE
    2. ADD A NEW MACHINE OR CHANGE AN EXISTING MACHINE
    3. REMOVE THE MACHINE
    4. DISPLAY ONE MACHINE
    5. DISPLAY ALL MACHINES AFTER A GIVEN MACHINE
    6. DONE WITH MACHINE DATA

ENTER YOUR CHOICE (1,2,3,4,5 OR 6)
```

Select "5" then "1" to display content of file. This displays the data for a previous case. Press ENTER and return to menu 3. As we have a 16 bus system this file must be updated. Select "2" to add or change the existing data. The program prompts for:

```

WHAT IS YOUR MACHINE NUMBER?
ENTER "1"
CHANGE (Y OR N)? Y
WHAT BUS NUMBER IS THIS MACHINE CONNECTED TO?
ENTER "1"
ENTER THE POSITIVE SEQUENCE REACANCE (pu)? 0.068 (TABLE.42)
It then returns to menu 3. Select "2"
MACHINE NUMBER? "2"
CHANGE (Y OR N) Y
BUS NUMBER OF MACHINE? "2"
POSITIVE SEQUENCE REACTANCE (pu)? 0.085
REPEAT STEPS FOR GENERATOR 3
POSITIVE SEQUENCE REACTANCE (pu)? 0.100
Use Ctrl PRINT SCREEN for results.
```

```

SYNCHRONOUS MACHINE INPUT DATA FOR gary.001

MACHINE#    BUS        X1
                per unit
    1         1        0.0680
    2         2        0.0850
    3         3        0.1000

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE
```

ENTER "6" as done with data.

**NB! This program is for symmetrical short circuits, therefore only positive sequence reactances are required.**



It returns to menu 2. Select for updating transmission line data.  
Menu 3 appears.  
Select "2" to add to or change previous data.  
ENTER LINE NUMBER? 1  
CHANGE (Y OR N) Y  
BUS NUMBERS TO WHICH LINE CONNECTED TO?  
(NB! Use two integers separated by a comma)? 4,8  
POSITIVE SEQUENCE REACTANCE (pu) ? 0.00757 (TABLE 44)  
REPEAT STEPS FOR THE REMAINING 14 LINES.  
Select "5" and then "1"  
Use Ctrl PRINT SCREEN and obtain:

TRANSMISSION LINE INPUT DATA FOR gary.001			
LINE#	BUS - TO - BUS		X1 per unit
1	4	8	0.0076
2	4	7	0.0152
3	7	8	0.0265
4	8	16	0.0227
5	8	12	0.0250
6	6	7	0.0237
7	9	13	0.0353
8	9	11	0.0439
9	5	9	0.0254
10	5	10	0.0941
11	10	11	0.0588
12	6	15	0.0167
13	14	15	0.1485
14	15	16	0.0076

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE

Select "6" as done with line data.  
It returns to menu 3.  
Select "3" to update transformer data.  
Select "2" and update.  
TRANSFORMER NUMBER ? "1"  
CHANGE (Y OR N) Y  
BUS NUMBERS TO WHICH TRANSFORMER CONNECTED? 1,4  
LEAKAGE REACTANCE? 0.0625 (Table 43)  
Repeat steps for remaining transformers.  
Select "5" to print/display data, then "1"

TRANSFORMER INPUT DATA FOR gary.001			
TRANSF#	BUS - TO - BUS		XL per unit
1	1	4	0.0625
2	11	12	0.0650
3	2	5	0.0600
4	13	14	0.0570
5	2	5	0.0625

REMOVE Ctrl PRINT SCREEN AND THEN PRESS RETURN TO CONTINUE

Select "6" as done with transformer data.  
Menu 2 appears. Select "4" as done with input data.  
Program returns to menu 1.  
Select "2" to run the program.

It prompts:

WHAT IS THE PRE FAULT VOLTAGE (per unit)?.

Enter "1"

Do you wish to:

DISPLAY THE FAULT CURRENTS (Y OR N)? Y

DISPLAY THE BUS VOLTAGES DURING THE FAULT (Y OR N)? Y

DISPLAY THE BUS IMPEDANCE MATRIX (Y OR N)?N

DO YOU WANT OUTPUT IN EXPONENTIAL FORMAT (Y OR N)?N

DO YOU WANT TO CONTINUE (Y OR N) Y

Use Ctrl PRINT SCREEN and obtain:

**2. SUBTRANSIENT FAULT CURRENTS**

FAULT CURRENTS FOR gary.001

FAULT BUS	THREE-PHASE FAULT CURRENT	GEN LINE OR TRSF	BUS-TO-BUS	CONTRIBUTIONS TO FAULT CURRENTS
	per unit			per unit
1	18.232	G 1 T 1	GRND - 1 4 - 1	14.7059 3.5262
2	15.516	G 2 T 3 T 5	GRND - 2 5 - 2 5 - 2	11.7647 1.9138 1.8372
3	10.000	G 3	GRND - 3	10.0000
4	12.186	L 1 L 2 T 1	8 - 4 7 - 4 1 - 4	3.4269 1.0960 7.6628
5	12.887	L 9 L 10 T 3 T 5	9 - 5 10 - 5 2 - 5 2 - 5	3.1800 1.0576 4.4131 4.2365
6	10.217	L 6 L 12	7 - 6 15 - 6	5.5174 4.6995
7	11.240	L 2 L 3 L 6	4 - 7 8 - 7 6 - 7	6.1286 3.2672 1.8445

8	11.917	L 1	4 - 8	6.2626
		L 3	7 - 8	1.1943
		L 4	16 - 8	1.2552
		L 5	12 - 8	3.2051
9	11.565	L 7	13 - 9	1.5505
		L 8	11 - 9	3.1279
		L 9	5 - 9	6.8865
10	8.776	L 10	5 - 10	4.1099
		L 11	11 - 10	4.6658
11	10.673	L 8	9 - 11	4.6434
		L 11	10 - 11	1.9992
		T 2	12 - 11	4.0304
12	10.751	L 5	8 - 12	6.8039
		T 2	11 - 12	3.9473
13	9.199	L 7	9 - 13	7.0305
		T 4	14 - 13	2.1680
14	7.723	L 13	15 - 14	3.0876
		T 4	13 - 14	4.6350
15	10.445	L 12	6 - 15	3.4664
		L 13	14 - 15	1.8025
		L 14	16 - 15	5.1761
16	10.520	L 4	8 - 16	6.2622
		L 14	15 - 16	4.2583

NB! Bus 1 produces the highest fault current of 18.232 pu A

VF = 1

PER-UNIT BUS VOLTAGES DURING FAULTS

gary.001

FAULT BUS	BUS1(6..)	BUS2(7..)	BUS3(8..)	BUS4(9..)	BUS5(10..)
1	0.0000	0.7003	1.0000	0.2204	0.5923
	0.2471	0.2333	0.2406	0.5250	0.5095
	0.4577	0.3009	0.4857	0.4222	0.2568
	0.2527				
2	0.7449	0.0000	1.0000	0.5105	0.1148
	0.4821	0.4967	0.4890	0.1864	0.2029
	0.2580	0.4248	0.2283	0.2958	0.4718
	0.4761				
3	1.0000	1.0000	0.0000	1.0000	1.0000
	1.0000	1.0000	1.0000	1.0000	1.0000
	1.0000	1.0000	1.0000	1.0000	1.0000
	1.0000				
4	0.4789	0.6156	1.0000	0.0000	0.4771
	0.0343	0.0166	0.0259	0.3907	0.3709
	0.3044	0.1033	0.3403	0.2589	0.0467
	0.0415				
5	0.7118	0.2648	1.0000	0.4470	0.0000
	0.4149	0.4314	0.4227	0.0809	0.0995
	0.1618	0.3502	0.1282	0.2045	0.4033
	0.4081				
6	0.5781	0.6590	1.0000	0.1903	0.5361
	0.0000	0.1308	0.1730	0.4580	0.4476
	0.3923	0.2340	0.4023	0.3125	0.0784
	0.1020				
7	0.5273	0.6354	1.0000	0.0929	0.5041
	0.0437	0.0000	0.0867	0.4217	0.4049
	0.3430	0.1579	0.3709	0.2887	0.0745
	0.0775				
8	0.5036	0.6075	1.0000	0.0474	0.4661
	0.0354	0.0317	0.0000	0.3782	0.3568
	0.2885	0.0802	0.3284	0.2478	0.0380
	0.0285				
9	0.6987	0.3936	1.0000	0.4218	0.1752
	0.3865	0.4051	0.3966	0.0000	0.1519
	0.1373	0.3246	0.0547	0.1431	0.3734
	0.3792				
10	0.7639	0.5492	1.0000	0.5469	0.3868
	0.5255	0.5354	0.5264	0.3564	0.0000
	0.2745	0.4564	0.3802	0.4186	0.5186
	0.5205				
11	0.6826	0.4896	1.0000	0.3908	0.3058
	0.3652	0.3761	0.3628	0.2139	0.1176
	0.0000	0.2620	0.2264	0.2627	0.3575
	0.3588				
12	0.5878	0.6014	1.0000	0.2089	0.4579
	0.1939	0.1946	0.1702	0.3721	0.3340
	0.2566	0.0000	0.3459	0.3036	0.1935
	0.1876				

13	0.7405	0.5425	1.0000	0.5020	0.3777
	0.4619	0.4851	0.4816	0.2481	0.3503
	0.3333	0.4404	0.0000	0.1236	0.4456
	0.4546				
14	0.7553	0.6495	1.0000	0.5303	0.5233
	0.4803	0.5113	0.5126	0.4278	0.4884
	0.4665	0.4998	0.2642	0.0000	0.4586
	0.4720				
15	0.5742	0.6444	1.0000	0.1829	0.5163
	0.0578	0.1400	0.1569	0.4341	0.4270
	0.3712	0.2164	0.3704	0.2677	0.0000
	0.0392				
16	0.5688	0.6448	1.0000	0.1725	0.5168
	0.0753	0.1366	0.1424	0.4352	0.4252
	0.3680	0.2051	0.3762	0.2808	0.0322
	0.0000				

Program returns to menu 1.

SELECTIONS:

1. UPDATE THE INPUT DATA
2. RUN THE PROGRAM
3. STOP

Select "3" to stop and exit to dos.

**c. "SHORT CIRCUIT" PROGRAM**

1. ENTER CASE NUMBER? "1"  
 Input data will be saved and stored in files SCM1.DAT, SCL1.DAT and SCT1.DAT.  
 CASE NAME? e.g. Gary.001  
 The screen displays menu 1  
 Select "1" to update  
 Select "1" from menu 2  
 Select "2" from menu 3 to update machine data.  
 MACHINE NUMBER? "1"  
 CHANGE (Y OR N) Y  
 BUS NUMBER? "1"  
 X<sub>o</sub> = 0.022 (Table 42) **NB! Cannot enter a non-zero value.**  
 X<sub>1</sub> = X<sub>d</sub>' = 0.095 (transient reactance)  
 X<sub>2</sub> = 0.052  
 MACHINE NEUTRAL REACTANCE? 1000 (Delta No neutral)  
 Select "2" from menu 3  
 MACHINE NUMBER? "2"  
 CHANGE (Y OR N) Y  
 BUS NUMBER? "2"  
 X<sub>o</sub> = 0.044 (TABLE 42)  
 X<sub>1</sub> = X<sub>d</sub>' = 0.13 (Transient)  
 X<sub>2</sub> = 0.065  
 NEUTRAL REACTANCE? "0" (Star-ground)  
 Select "2" from menu 3  
 MACHINE NUMBER? "3"  
 BUS NUMBER? "3"  
 X<sub>o</sub> = 0.051  
 X<sub>1</sub> = X<sub>d</sub>' = 0.116  
 X<sub>2</sub> = 0.099  
 NEUTRAL REACTANCE? 1000 (Delta therefore No neutral)  
 Select "5" on menu 3 to display/print this input data.

SYNCHRONOUS MACHINE INPUT DATA FOR gary.001					
MACHINE	BUS	X <sub>o</sub> per unit	X <sub>1</sub> per unit	X <sub>2</sub> per unit	X <sub>N</sub> per unit
1	1	0.0220	0.0950	0.0520	%1000.0000
2	2	0.0440	0.1300	0.0650	0.0000
3	3	0.0510	0.1160	0.0990	%1000.0000

Select "6" as done with machine data  
 Select "2" to update Line data on menu 2  
 Select "2" on menu 3  
 LINE NUMBER ? "1"  
 CHANGE (Y OR N) Y  
 BUS NUMBER? (separate by a comma)  
 X<sub>o</sub> = 0.0243 (Table 44)  
 X<sub>1</sub> = X<sub>2</sub> = 0.00757

Repeat these steps for remaining lines.

TRANSMISSION LINE INPUT DATA FOR gary.001				
LINE#	BUS-TO-BUS		X0 per unit	X1 per unit
1	4	8	0.0243	0.0076
2	4	7	0.0487	0.0152
3	7	8	0.0853	0.0265
4	8	16	0.0731	0.0227
5	8	12	0.0804	0.0250
6	6	7	0.0835	0.0237
7	9	13	0.1260	0.0353
8	9	11	0.1462	0.0439
9	5	9	0.0919	0.0254
10	5	10	0.3371	0.0941
11	10	11	0.2100	0.0588
12	6	15	0.0536	0.0167
13	14	15	0.0731	0.1485
14	15	16	0.0243	0.0076

Select "6" as done with line data  
 Select "3" to update transformer data  
 Select "2" on menu 3  
 TRANSFORMER NUMBER?  
 CHANGE (Y OR N) Y  
 BUS NUMBER (L.V.)? "1"  
 Is L.V. Delta or Wye? "D"  
 BUS NUMBER (H.V.)? "4"  
 H.V. CONNECTION? Y  
 LEAKAGE REACTANCE? 0.0625 (Table 43)  
 ENTER THE H.V. NEUTRAL REACTANCE? "0" (Solidly grounded)  
 Select "2" on menu 3  
 TRANSFORMER NUMBER? "2"  
 CHANGE (Y OR N) Y  
 BUS NUMBER (L.V.)? "11"  
 L.V. CONNECTION? Y  
 BUS NUMBER (H.V.)? "11"  
 H.V. CONNECTION? Y  
 LEAKAGE REACTANCE? 0.065  
 L.V. NEUTRAL CONNECTION? "0" (Solidly grounded)  
 H.V. NEUTRAL CONNECTION? "0" (Solidly grounded)  
 Repeat for remaining transformers

TRANSFORMER INPUT DATA FOR gary.001						
TRANSF#	LOW(CNC)		HIGH(CNC)	XL per unit	NEUTRAL REACTANCES	
	VOLT. BUS		VOLT. BUS		LV per unit	HV per unit
1	1 (D)		4 (Y)	0.0625		0.0000
2	11 (Y)		12 (Y)	0.0650	0.0000	0.0000
3	2 (D)		5 (Y)	0.0600		0.0000
4	13 (Y)		14 (Y)	0.0570	0.0000	0.0000
5	3 (D)		6 (Y)	0.0625		0.0000

Select "6" done with transformer data.  
Select "4" menu 2 as done with data.  
Select "2" on menu 1 to run the program.  
A new menu appears.

```
Menu. 4

ONE OF THE FOLLOWING FAULT TYPES IS TO BE SELECTED:
(1) THREE-PHASE FAULT
(2) SINGLE LINE-TO-GROUND FAULT THROUGH ZF
(3) LINE-TO-LINE FAULT THROUGH ZF
(4) DOUBLE LINE-TO-GROUND FAULT THROUGH ZF

ENTER THE FAULT TYPE (1,2,3 OR 4)
```

Select "1" for three phase fault.  
What is the PREFault VOLTAGE? "1"  
DISPLAY FAULT CURRENTS (Y OR N) "Y"  
DISPLAY BUS VOLTAGES DURING FAULT? "N"  
DISPLAY IMPEDANCE MATRICES? "N"  
OUTPUTS IN EXPONENTIAL FORMAT? "N"  
DO YOU WANT TO CONTINUE? Y

```
NB! The fault current results obtained are for Xd'
```

Exit to dos.  
Copy SCM1.DAT, SCL1.DAT and SCT1.DAT to Case 2 files  
SCM2.DAT, SCL2.DAT and SCT1.DAT.

```
for example C:\>Copy SCM1.DAT SCM2.DAT etc.
```

Go back to:  
C:\POWER>CHAP 9  
CASE NUMBER? "2"  
CASE NAME? Gary.002  
Select "1" on menu 1 to update data  
Select "1" on menu 2 to update machine data in terms of  
steady-state reactance only. (NB! Line and transformer data need  
not be updated as will be the same as for case 1)  
Select "2" on menu 3  
MACHINE NUMBER? "1"  
BUS NUMBER? "1"  
Xo = 0.022  
X1 = 0.755 (Table 42 Steady-State Reactance)  
X2 = 0.052  
MACHINE NEUTRAL? 1000 (Delta)



Repeat for G2 and G3

SYNCHRONOUS MACHINE INPUT DATA FOR gary.002					
MACHINE#	BUS	X0	X1	X2	XN
		per unit	per unit	per unit	per unit
1	1	0.0220	0.7550	0.0520	\$1000.0000
2	2	0.0440	0.6930	0.0650	0.0000
3	3	0.1160	0.9190	0.0990	\$1000.0000

Select "6" on menu 3 as done with machine data.  
 Select "2" on menu 2 and check that data has been copied by selecting "5" to display line data.  
 Likewise check that transformer data was copied.  
 Select "2" on menu 1 and run program.  
 Menu 4 appears. Select "1" for three phase steady-state fault currents.  
 Vf = 1, obtain the results for the steady-state fault currents.

Repeat the above for subtransient conditions case 3.

Herewith the tabled results:

FAULT CURRENTS			
BUS NUMBER	Xd"	Xd	X1
1	20.509	15.919	3.215
2	16.013	11.744	3.085
3	16.077	14.132	3.107
4	16.770	14.483	3.368
5	12.598	10.617	3.149
6	15.952	14.010	3.329
7	15.903	13.884	3.336
8	16.493	14.300	3.368
9	11.997	10.379	3.149
10	9.089	8.150	2.910
11	11.618	10.238	3.144
12	13.475	11.933	3.251
13	9.788	8.756	2.987
14	8.540	7.822	2.869
15	15.070	13.283	3.305
16	14.869	13.112	3.296

NB! This shows that the fault current is the highest at sub-transient reactance and lowest at steady-state reactance.

ANSWERS TO SELF EVALUATION EXPERIMENTS

e. Single line-to-ground fault at bus 2 ( $Z_f = 0$ ):

FAULT CURRENTS FOR gary.003						
FAULT BUS	SINGLE LINE-TO-GROUND FAULT CURRENT (PHASE A)	GEN LINE OR TRSF	BUS-TO-BUS	CONTRIBUTIONS TO FAULT CURRENT		
				PHASE A	PHASE B	PHASE C
	per unit/_degrees			per unit/_ degrees		
2	19.093/_-90.00	G 2	GRND - 2	16.0021/ -90.00	1.5653/ -80.90	1.5653/ 260.90
		T 3	5 - 2	3.0913 -90.00	1.5653/ 99.10	1.5653/ 80.90

f. Single line-to-ground fault at bus 2 ( $Z_f = 15 + j0$ ):

FAULT CURRENTS FOR gary.003						
FAULT BUS	SINGLE LINE-TO-GROUND FAULT CURRENT (PHASE A)	GEN LINE OR TRSF	BUS-TO-BUS	CONTRIBUTIONS TO FAULT CURRENT		
				PHASE A	PHASE B	PHASE C
	per unit/_degrees			per unit/_ degrees		
2	0.138/_-0.42	G 2	GRND - 2	0.1159/ -0.42	0.0113/ 8.68	0.0113/ -9.51
		T 3	5 - 2	0.0224/ -0.41	0.0113/ 188.68	0.0113/ 170.49

g. Bus voltages at bus 16 during double line-to-ground fault.

VF = 1/0		BUS VOLTAGES DURING FAULTS FOR gary.002		
FAULT		PHASE A	PHASE B	PHASE C
BUS	BUS #	per unit/_degrees		
16	1	0.7082/-22.63	0.7082/202.63	0.5449/ 90.00
	2	0.7583/-25.15	0.7583/205.15	0.6446/ 90.00
	3	0.6955/-19.14	0.6955.199.14	0.4562/ 90.00
	4	0.7625/ 0.00	0.2687/217.42	0.2687/142.58
	5	0.7758/ 0.00	0.5024/230.31	0.5024/129.69
	6	0.7686/ 0.00	0.2343/213.46	0.2343/146.54
	7	0.7711/ 0.00	0.2455/216.48	0.2455/143.52
	8	0.7890/ 0.00	0.2180/218.09	0.2180/141.91
	9	0.8123/ 0.00	0.4170/232.45	0.4170/127.55
	10	0.7972/ 0.00	0.4196/230.66	0.4196/129.34
	11	0.8105/ 0.00	0.3680/230.95	0.3680/129.05
	12	0.7859/ 0.00	0.2648.221.81	0.2648/138.19
	13	0.8628/ 0.00	0.3412/237.88	0.3412/122.12
	14	0.8684/ 0.00	0.2621/237.75	0.2621/122.25
	15	0.8438/ 0.00	0.0847/213.30	0.0847/146.70
	16	0.8873/ 0.00	0.0000/ 0.00	0.0000/ 0.00

**CHAPTER THREE**  
**TRANSIENT STABILITY STUDIES COMPUTER EXPERIMENTS**  
**16 BUS 3 GENERATOR POWER SYSTEM**

Power system stability studies fall into three major categories, transient, steady-state and dynamic stability. Steady-state stability involves slow or gradual changes in operating points and are usually performed with a power flow study to ensure that phase angles across transmission lines are not too large, that bus voltages are close to nominal values and that generators and other equipment are not overloaded. (Glover 1991, 429).

Dynamic stability involves long time periods, typically several minutes. (Glover 1991, 429).

Transient stability, the main focus of this chapter, involves major disturbances such as a loss of generation, line switching operations, faults and sudden load changes. Transient state refers to the maximum flow of power possible through a point in the system without losing the stability with sudden and large changes in the network conditions such as those brought about by faults or by sudden large increments of load. (Wadhwa 1991, 550). It is the ability of a system to remain in operating equilibrium or synchronism while disturbances occur on the system. (Nasar 1990, 146).

Analysis of power system stability is complex and non-linear. As a consequence, final design decisions are generally based on detailed computer simulations, especially in to-day's large-scale power systems with many interconnected synchronous machines. (Glover 1991, 429). For a specific disturbance a program usually solves for pre-disturbance, disturbance and post-disturbance situations. (Glover 1991, 429). It computes the ability of synchronous machines to move from one steady-state operating point following a disturbance to another steady-state operating point without losing synchronism. Following a disturbance, synchronous machine frequency undergoes transient deviations from synchronous frequency (e.g. 50Hz) and the power angle changes.

The power angle  $\delta$  is the angle between the rotor axis and the stator magnetic field axis of a synchronous machine.  $\delta$  depends upon the loading of the machine. The larger the loading, the larger is the value of  $\delta$ . If some load is added or removed the rotor will decelerate or accelerate and relative motion begins. It is said that the rotor is swinging with regard to the stator field. The equation describing relative motion of rotor angle  $\delta$  with regard to stator field as a function of time is called the swing equation. (Wadhwa 1991, 554).

The swing equation by is:

$$\frac{Md^2\delta}{dt^2} = T_a = T_s - T_e$$

Which can be expressed as:

$$\frac{H}{180f} \frac{d^2\delta}{dt^2} = P_i - P_e = P_a \quad \text{per unit}$$

- Where:
- $P_a$  = accelerating power
  - $P_i$  = Mechanical input power
  - $P_e$  = Electro-magnetic Power
  - $\delta$  = Rotor angle and describes motion or swing of rotor
  - $t$  = time in seconds
  - $H$  = Inertia constant
  - $f$  = frequency of the system

NB!  
 The inertia constant  $H$  is based on the machines own MVA rating and must be converted to a system base, as is the case of p.u. reactance. The only difference is that the p.u. reactance corresponding to new base MVA is directly proportional to the MVA whereas the inertia constant is inversely proportional, namely:-

$$H_{\text{ syst }} = H_{\text{ mach }} \frac{S_{\text{ mach }}}{S_{\text{ syst }}}$$

The  $H$  constant has the advantage that it falls within a narrow range, namely between 1 and 10 pu-s.  $H$  does not vary widely with size and has a characteristic value or set of values for each class of machine. Whenever a value for  $H$  is not known a characteristic value may be used. (Wadhwa 1991, 556)

The solution of the swing equation gives the relation between rotor angle as a function of time and this can be plotted in terms of curves. If the curve shows that the angle between two machines is increasing without reaching a limit, the system is unstable, if angle initially increases then reduces the system is stable. (Wadhwa 1991, 557).

Instead of solving the swing equation, there is a direct method for determining stability but which only applies to a single machine connected to an infinite bus or to two machines and this method is called the equal-area criterion. (Glover 1991, 439). It is a graphical solution and solves the swing equation by graphical integration (Gungor 1989, 374). The power- $\delta$  angle curve is used. The equal-area criterion requires that for stability, the accelerating area must equal the decelerating area. (Nasar 1990, 148).

If a disturbance (or fault) occurs in a system, and if  $\delta$  becomes very large the system will become unstable. There is a critical angle within which the fault must be cleared if the system is to remain stable and the equal-area criterion is to be satisfied. This angle is called the critical clearing angle  $\delta_{cr}$ .

The equal-area criterion method is useful in determining  $\delta_{cr}$ . If a fault is cleared before the time taken ( $t_{cr}$ ) which corresponds to  $\delta_{cr}$  stability will be maintained.

The power system engineer is not interested in knowing the critical clearing angle  $\delta_{cr}$ . He wants to know the critical clearing time corresponding to the critical clearing angle so that he can design the operating times for the relay and circuit breakers so that the total time taken by them should be less than the critical clearing time for stable operation of the system. (Wadhwa 1991, 574).

In many cases transient stability is determined during the first swing of machine power angles following a disturbance, which typically lasts 1 second. During this time it is usually assumed that the mechanical output power and the internal voltage of a generating unit are constant. (Glover 1991, 429) Therefore, the usual time period under study is the first second following a fault. If machines of a system are found to remain in synchronism within first second, the system is stable.

The equal-area criterion cannot be used directly in systems where 3 or more machines are represented. Although 2 machine problems basically reflect the multi-machine case, nonetheless, the complexity of numerical computations increases with increase in machine numbers. Inter machine oscillations occur between machines through the interconnected system.

For a multi-machine system a solution of several swing equations is required. For multi-machine stability, numerical integration techniques are employed to solve swing equations for each method. For e.g. with **Eulers modified method** the procedure begins at  $t = 0$  with initial values  $\delta_0$  and " $\omega_0$ " and continues iteratively until  $t = T$ , a specified final time. For such calculations a small integration step, denoted " $dt$ " is usually used for accuracy (e.g.  $dt = 0.01$  secs). (Glover 1991, 448). Other techniques can use a larger step size for comparable accuracy but computations are more complex. Calculations are best performed by using a digital computer.

**A. EXPLANATION OF THE USAGE OF THE GLOVER PROGRAM  
"TRANSIENT STABILITY"**

The explanation of the usage of this program is best described by a worked **computer** example.

However before proceeding with an example the following should be stated:

The program computes machine power angles and frequencies in a three phase power system subjected to disturbances, machine electrical power outputs and bus voltages magnitudes.

Before running this program, it is first necessary to run a load flow case from Chapter One for your specific power system under consideration. This program opens and reads data from your chosen load flow cases input and output files (e.g. PFB1.DAT, PFL1.DAT, PFT1.DAT, PFB01.DAT, PFL01.DAT, and PFT01.DAT).

The input data taken from the "POWER FLOW" program of Chapter One includes the bus admittance matrix, initial bus voltages, initial machine currents and initial machine electrical power outputs.

Also in order to simplify transient stability studies, the following assumptions are made:

1. Only balanced three-phase systems and balanced disturbances are considered. Therefore only positive-sequence networks are employed.
2. Deviations of machine frequencies from synchronous frequency [e.g. 50Hz (RSA), 60Hz (USA)] are small, and dc offset currents and harmonics are neglected. Therefore the network of transmission lines, transformers and impedance loads is essentially in steady-state and voltages, currents and powers can be computed from algebraic power flow equations.

The input data for this program also includes synchronous machine data, which are stored in a data file. The user can store up to three separate cases. The synchronous machine data file for case 1 is called TSM1.DAT. Likewise for cases 2 and 3. The maximum number of machines is 25. The synchronous machine data includes the machine bus number, the per-unit transient reactance and the per-unit H constant for each machine.

The user has the following options: (1) update the synchronous machine input data, (2) set the disturbances and run the program, (3) stop the program.

The program executes the transient stability computation procedure given in Section 12.5 (Glover 1989, 449)

The program user selects the type of each disturbance and the time at which each disturbance begins. Disturbance types include, switching operations (opening and closing of circuit breakers selected by the user, three phase short circuits, changes in load and changes in input data).

The user also sets the integration interval  $dt(s)$  and the final time  $tF(s)$ .  $dt$  should be small in order that an accurate solution is obtained, e.g.  $dt = 0.01s$  or  $dt = 0.01667s$  (one cycle in a 60Hz system).

Next the user selects the number of disturbances (1,2,3 or 4) and the disturbance times (s). The user has the following options for the first disturbance: (1) put a three-phase short circuit at a bus; and (2) open one or more machine breakers, transmission line breakers, or transformer breakers.

The user has the following disturbance options after the first disturbance: (1) put a three-phase short circuit at a bus; (2) extinguish an existing short circuit; (3) open one or more machine breakers, transmission line breakers, or transformer breakers; and (4) close one or more machine breakers, transmission line breakers, or transformer breakers.

The program alternately solves, step-by-step, algebraic power flow equations representing the network and differential equations representing the machines. The Gauss-Seidel iterative method is used to solve the power flow equations, and a modified Euler's method is used to solve the differential equations.

The user can select from the following outputs: (1) machine power angle; (2) machine frequency; (3) machine real power output; and (4) bus voltage. Up to five outputs can be displayed during any run. The user also selects the printout integer  $K$ . Then the outputs are displayed at intervals of  $Kdt$ . The outputs can be displayed in exponential format (scientific notation) or in fixed-point format (numbers with decimal points).



**A THREE PART EXAMPLE  
5 BUS 2 GENERATOR  
POWER SYSTEM**

**PART ONE : LOAD FLOW ANALYSIS**

Figure 2 shows a single-line diagram of a five-bus power system.

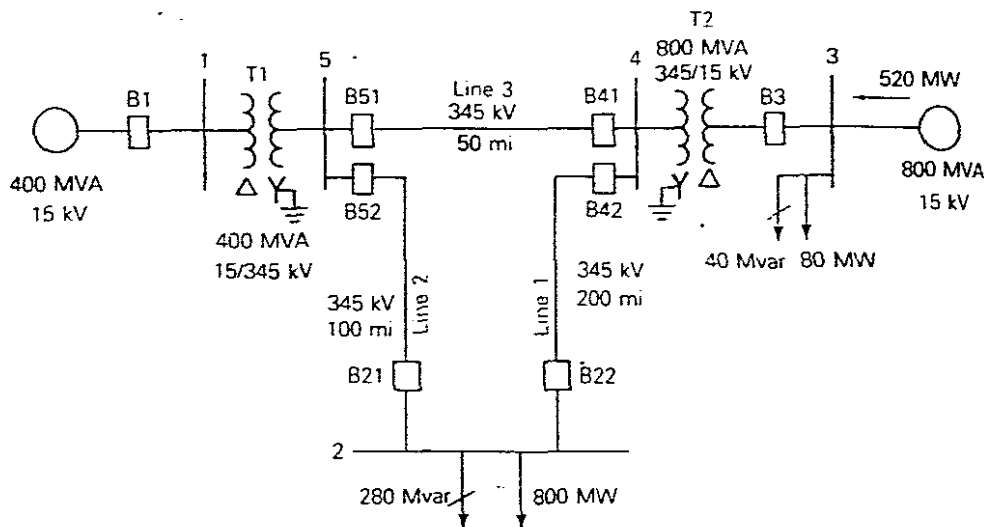


FIGURE.2.

The "POWER FLOW" program of chapter one can store a maximum of 3 separate cases and all 3 cases have been used in chapter one for the 16 bus 3 generator system under study.

NB! Do not update any of those 3 cases with data from this example. It is recommended that the total "POWER" package be saved on to a stiffy and that this example be worked from the stiffy. This will enable the user to update the input data files of the "POWER FLOW" program with data from this example without altering those stored on the hard-drive.

Using the stiffy use the "POWER FLOW" program of the "POWER" package and update case 1 with data from this example:

Now using the stiffy the input data after updating with data from this example will be:

BUS INPUT DATA FOR					sample run				
BUS	TYPE	V	DELTA	PG	QG	PL	QL	QG MAX	QG MIN
		per unit	deg	per unit	per unit	per unit	per unit	per unit	per unit
1	0	1.000	0.000	---	---	0.000	0.000	---	---
2	1	---	---	0.000	0.000	2.000	0.700	---	---
3	2	1.050	---	1.300	---	0.200	0.100	1.000	-0.700
4	1	---	---	0.000	0.000	0.000	0.000	---	---
5	1	---	---	0.000	0.000	0.000	0.000	---	---

LINE INPUT DATA FOR				sample run			
LINE	BUS-TO-BUS	R	X	G	B	MAXMVA	
		per unit	per unit	per unit	per unit	per unit	
1	2 4	0.036	0.400	0.000	0.430	3.000	
2	2 5	0.018	0.200	0.000	0.220	3.000	
3	4 5	0.009	0.100	0.000	0.110	3.000	

TRANSFORMER INPUT DATA FOR				sample run			
TRAN#	BUS-TO-BUS	R	X	G	B	MAXMVA	MAXTAP
		per unit	per unit	per unit	per unit	per unit	per unit
1	1 5	0.006	0.080	0.000	0.000	1.500	1.000
2	3 4	0.003	0.040	0.000	0.000	2.500	1.000

Run the program.

The "POWER FLOW" output results are:

POWER FLOW OUTPUT DATA FOR							sample run
			GENERATION		LOAD		
VOLTAGE MAGNITUDE	PHASE ANGLE	PG	QG	PL	QL	.95>V>1.05	
BUS#	per unit	deg	per unit	per unit	per unit	per unit	
1	1.000	0.000	0.987	0.286	0.000	0.000	
2	0.834	-22.407	0.000	0.000	2.000	0.700	***
3	1.050	-0.598	1.300	0.844	0.200	0.100	(too low)
4	1.019	-2.834	0.000	0.000	0.000	0.000	
5	0.974	-4.548	0.000	0.000	0.000	0.000	
TOTAL			2.287	1.129	2.200	0.800	

NB! Note that the bus 2 voltage magnitude is low (0.834)

POWER FLOW LINE OUTPUT DATA FOR						sample run
LINE#	BUS-TO-BUS		P	Q	S	RATING EXCEEDED
1	2	4	-0.730	-0.348	0.808	
	4	2	0.759	0.304	0.818	
2	2	5	-1.270	-0.352	1.318	
	5	2	1.314	0.658	1.469	
3	4	5	0.336	0.376	0.504	
	5	4	-0.333	-0.456	0.565	

POWER FLOW TRANSFORMER OUTPUT DATA FOR						sample run	
TRAN#	BUS-TO-BUS		P	Q	S	TAP SETTING	RATING EXCEEDED
1	1	5	0.987	0.286	1.028	1.000	
	5	1	-0.981	-0.201	1.001		
2	3	4	1.100	0.744	1.328	1.000	
	4	3	-1.095	-0.680	1.289		

**PART TWO : REACTIVE COMPENSATION TECHNIQUE**

As the bus voltage is too low at 0.834 puV add a 200 Mvar shunt capacitor bank at bus 2 to increase the bus voltage closer to its rated 1pu value.

NB! The addition of a 200 Mvar (0.5pu) shunt capacitor bank corresponds to adding -0.5pu of reactive load. Therefore QL at bus 2 is changed from 0.7 to  $(0.7 - 0.5) = 0.2$  per unit.

The Case 1 (as stored on the stiffy) "POWER FLOW" input data files PFB1.DAT, PFL1.DAT and PFT1.DAT must be copied to PFB2.DAT, PFL2.DAT and PFT2.DAT files to create Case 2. The PFB2.DAT file is now updated to include the 200 MVar shunt capacitor bank, namely:-

BUS INPUT DATA FOR					sample run				
BUS#	TYPE	V	DELTA	PG	QG	PL	QL	QG MAX	QG MIN
		per unit	deg	per unit	per unit	per unit	per unit	per unit	per unit
1	0	1.000	0.000	---	---	0.000	0.000	---	---
2	1	---	---	0.000	0.000	2.000	0.200	---	---
3	2	1.050	---	1.300	---	0.200	0.100	1.000	-0.700
4	1	---	---	0.000	0.000	0.000	0.000	---	---
5	1	---	---	0.000	0.000	0.000	0.000	---	---

NB! Case 2 line and transformer data files remain the same as for Case 1.

The "POWER FLOW" program is now re-run and the data is :

POWER FLOW OUTPUT DATA FOR							sample run
			GENERATION		LOAD		
VOLTAGE MAGNITUDE	PHASE ANGLE	PG	QG	PL	QL	.95>V>1.05	
BUS#	per unit	deg	per unit	per unit	per unit	per unit	
1	1.000	0.000	0.963	-0.118	0.000	0.000	
2	0.968	-19.629	0.000	0.000	2.000	0.200	
3	1.050	-0.408	1.300	0.370	0.200	0.100	
4	1.037	-2.680	0.000	0.000	0.000	0.000	
5	1.007	-4.427	0.000	0.000	0.000	0.000	
TOTAL			2.263	0.252	2.200	0.300	

NB! Bus 2 voltage has now been increased to 0.968puV

POWER FLOW LINE OUTPUT DATA FOR						sample run
LINE#	BUS-TO-BUS		P	Q	S	RATING EXCEEDED
1	2	4	-0.731	-0.195	0.757	
	4	2	0.752	-0.010	0.752	
2	2	5	-1.269	-0.005	1.269	
	5	2	1.300	0.137	1.307	
3	4	5	0.345	0.234	0.416	
	5	4	-0.343	-0.329	0.476	

POWER FLOW TRANSFORMER OUTPUT DATA FOR						sample run	
TRAN#	BUS-TO-BUS		P	Q	S	TAP SETTING	RATING EXCEEDED
1	1	5	0.963	-0.118	0.970	1.000	
	5	1	-0.957	0.193	0.976		
2	3	4	1.100	0.270	1.133	1.000	
	4	3	-1.097	-0.224	1.119		

**PART THREE : DETERMINATION OF TRANSIENT STABILITY**

Use the program TRANSIENT STABILITY, as stored on the stiffy (B:\POWER>CHAP12) to study a temporary three-phase short circuit at bus 5 of the power system (first disturbance). For pre-fault conditions, use the power-flow output given in Case 2 above, where a 200-Mvar shunt capacitor bank is installed at bus 2. Machine transient reactances are  $X'd1 = 0.20$  and  $X'd2 = 0.10$  per unit and machine inertia constants are  $H1 = 5.0$  and  $H2 = 50$ pu-s (where machine 2 represents a large system). The short circuit (first disturbance) is cleared by opening machine breakers B1, B51, and B52 at  $t = 0.05$ s (3cycles), (second disturbance) followed by reclosing these circuit breakers (third disturbance). Assume that the temporary fault has already self-extinguished when reclosure occurs.

Run the following two cases.

- Case 1 Reclosure at  $t = 0.27$ s (13 cycles after fault clearing)
- Case 2 Reclosure at  $t = 0.30$ s (15 cycles after fault clearing)

For computation purposes, select an integration step size  $dt = 0.01$  and final time  $T = 0.75$ s

NB! The "POWER FLOW" output of Case 2 above (part two of this example) is selected as input to the transient stability program.

The first disturbance selected is a short circuit at bus 5 ( $V5 = 0$ ) at a time  $t = 0$ . The second disturbance selected is the opening of circuit breakers B1, B51 and B52 to clear the fault at  $t = 0.05$ s. The third disturbance selected is the reclosure of these breakers at  $t = 0.27$ s and then repeated for  $t = 0.3$ s. The condition  $V5 = 0$  is also removed.

**SOLUTION**

C:\POWER>CHAP12 and enter the program  
WHAT IS THE CASE NUMBER FOR YOUR POWER FLOW PROGRAM  
(ENTER AN ITEGER FROM 1 TO 3) 2

ENTER YOUR CASE NAME sample run

MENU 1 CHAP 3  
WOULD YOU LIKE TO:  
1. UPDATE THE SYNCHRONOUS MACHINE INPUT DATA  
2. SET DISTURBANCES AND RUN THE PROGRAM  
3. STOP  
ENTER YOUR SELECTION (1,2 OR 3) 1

MENU 2 CHAP 3

SELECTIONS:

1. INITIALIZE FILE
2. ADD A NEW SYNCHRONOUS MACHINE OR CHANGE AN EXISTING ONE
3. REMOVE A MACHINE
4. DISPLAY ONE MACHINE
5. DISPLAY ALL MACHINES BELOW A GIVEN ONE
6. DONE WITH MACHINE; DATA

ENTER YOUR SELECTION (1 TO 6) 5

ENTER THE NUMBER OF THE FIRST MACHINE TO BE DISPLAYED 1

The contents of the file is displayed. Update if data exists or is empty. Proceed by using menu 2 chap 3.

ENTER YOUR SELECTION (1 TO 6) 2

MACHINE NUMBER (1 TO 25) ? 1

MACHINE BUS NUMBER ? 1

MACHINE TRANSIENT REACTANCE (per unit) ?.2

Return to menu 2 chap 3

ENTER YOUR SELECTION (1 TO 6) 4

MACHINE NUMBER (1 TO 25) ? 1

MACHINE#	BUS	X	H
1	1	.2	5

PRESS RETURN TO CONTINUE

Return to menu 2 chap 3 and update for machine 2, return again to this menu.

ENTER YOUR SELECTION (1 TO 6) 4

MACHINE NUMBER (1 TO 25) ? 2

MACHINE#	BUS	X	H
2	3	.1	50

PRESS RETURN TO CONTINUE

Return to menu 2 chap 3, select 6 as done with machine data.

Return to menu 1 chap 3

WOULD YOU LIKE TO:

1. UPDATE THE SYNCHRONOUS MACHINE INPUT DATA
2. SET DISTURBANCES AND RUN THE PROGRAM
3. STOP

ENTER YOUR SELECTION (1,2 OR 3) 2

ENTER THE INTEGRATION TIME INTERVAL (SECONDS) .01

ENTER THE FINAL TIME (SECONDS) .75

ENTER THE NUMBER OF DISTURBANCE TIMES (1,2,3 OR 4) 3

FIRST DISTURBANCE

ENTER THE FIRST DISTURBANCE TIME (SECONDS) 0  
IS THERE A SHORT CIRCUIT AT THE FIRST DISTURBANCE TIME (Y OR N)?Y  
ENTER THE SHORT CIRCUIT BUS NUMBER 5  
DO GENERATOR BREAKERS OPEN AT THE FIRST DISTURBANCE ( Y OR N ) ? N  
DO LINE BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N) ? N  
DO TRANSFORMER BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N)? N

SECOND DISTURBANCE

ENTER THE SECOND DISTURBANCE TIME (SECONDS) .05  
IS THERE A SHORT CIRCUIT AT THE SECOND DISTURBANCE TIME (Y OR N) ? N  
IS THE SHORT CIRCUIT AT THE FIRST DISTURBANCE EXTINGUISHED (Y OR N) ? Y  
DO GENERATOR BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N) ? Y  
HOW MANY GENERATOR CIRCUIT BREAKERS OPEN ? 1  
GENERATOR OPENING CIRCUIT BREAKER 1  
ENTER THE GENERATOR NUMBER ? 1  
DO LINE BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N) ? Y  
HOW MANY LINE BREAKERS OPEN ? 2  
TRANSMISSION LINE OPENING CIRCUIT BREAKER 1  
ENTER THE LINE NUMBER 3  
ENTER THE BUS NUMBER 5  
TRANSMISSION LINE OPENING CIRCUIT BREAKER 2  
ENTER THE LINE NUMBER 2  
ENTER THE BUS NUMBER 5  
DO TRANSFORMER BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N)?N

RECLOSURE TIME  $t = 0.27$  s (13 Cycles after fault clearing)

THIRD DISTURBANCE

ENTER THE THIRD DISTURBANCE TIME (SECONDS) .27  
IS THERE A SHORT CIRCUIT AT THE THIRD DISTURBANCE TIME (Y OR N) ?N  
DO GENERATOR BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N  
DO GENERATOR BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ?Y  
HOW MANY GENERATOR CIRCUIT BREAKERS CLOSE ? 1  
GENERATOR CLOSING CIRCUIT BREAKER 1  
ENTER THE GENERATOR NUMBER ? 1  
DO LINE BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N  
DO LINE BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ? Y  
HOW MANY LINE BREAKERS CLOSE ? 2  
TRANSMISSION LINE CLOSING CIRCUIT BREAKER 1  
ENTER THE LINE NUMBER 3  
ENTER THE BUS NUMBER 5  
TRANSMISSION LINE CLOSING CIRCUIT BREAKER 2  
ENTER THE LINE NUMBER 2  
ENTER THE BUS NUMBER 5  
DO TRANSFORMER BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ?N  
DO TRANSFORMER BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ? N



FOR OUTPUT LABELLING

ENTER THE FIRST DISTURBANCE NAME fault at bus 5  
ENTER THE SECOND DISTURBANCE NAME fault cleared  
ENTER THE THIRD DISTURBANCE NAME reclosure

YOUR MAY PRINT FROM 1 TO 5 OUTPUTS

ENTER THE NUMBER OF OUTPUTS (1 TO 5) 5

OUTPUT 1

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 1

OUTPUT 2

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 2

ENTER THE MACHINE NUMBER 1

OUTPUT 3

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 2

OUTPUT 4

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 2

ENTER THE MACHINE NUMBER 2

OUTPUT 5

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 4  
ENTER THE BUS NUMBER 5  
THE OUTPUTS ARE PRINTED EVERY KTH TIME INTERVAL  
ENTER THE PRINTOUT INTEGER K (K>=1) 3  
DO YOU WANT THE OUTPUTS IN EXPONENTIAL FORMAT (Y OR N) N  
CONTINUE (Y) OR RESET THE DISTURBANCES (N) ? Y

TRANSIENT STABILITY OUTPUT FOR sample run t = 0.27s

TIME	DELTA 1	OMEGA 1	DELTA 2	OMEGA 2	V 5
seconds	degrees	rad/s	degrees	rad/s	per unit
fault at bus 5					
0.000	11.15	376.99	6.10	376.99	0.000
0.030	12.01	377.99	6.19	377.10	0.000
fault cleared					
0.060	14.59	378.99	6.47	377.20	0.000
0.090	18.96	380.07	6.82	377.19	0.000
0.120	25.19	381.15	7.16	377.18	0.000
0.150	33.26	382.23	7.48	377.17	0.000
0.180	43.18	383.30	7.78	377.16	0.000
0.210	54.94	384.37	8.06	377.15	0.000
0.240	68.54	385.43	8.32	377.14	0.000
reclosure					
0.270	83.97	386.50	8.56	377.13	0.792
0.300	98.94	384.91	9.00	377.37	0.709
0.330	111.26	383.43	9.88	377.63	0.636
0.360	121.14	382.09	11.21	377.89	0.578
0.390	128.85	380.90	12.98	378.15	0.536
0.420	134.62	379.82	15.18	378.40	0.510
0.450	138.61	378.81	17.82	378.65	0.500
0.480	140.87	377.80	20.88	378.90	0.506
0.510	141.37	376.75	24.37	379.15	0.527
0.540	139.97	375.58	28.29	379.40	0.565
0.570	136.44	374.26	32.65	379.66	0.619
0.600	130.51	372.78	37.46	379.92	0.689
0.630	121.89	371.16	42.71	380.17	0.771
0.660	110.46	369.53	48.37	380.39	0.858
0.690	96.35	368.11	54.38	380.57	0.936
0.720	80.19	367.20	60.64	380.67	0.991
0.750	63.13	367.11	67.00	380.69	1.009

REMOVE Ctrl PRINT SCREEN AND THEN RETURN TO CONTINUE

The program then returns to menu 1 chap 3

WOULD YOU LIKE TO:  
1. UPDATE THE SYNCHRONOUS MACHINE INPUT DATA  
2. SET DISTURBANCES AND RUN THE PROGRAM  
3. STOP  
  
ENTER YOUR SELECTION (1,2 OR 3) 2

"2" is selected as we wish to reset reclosure time to  $t = 0.3s$  in order to make a comparison to the above results.

ENTER THE INTEGRATION TIME INTERVAL (SECONDS) .01  
ENTER THE FINAL TIME (SECONDS) .75  
ENTER THE NUMBER OF DISTURBANCE TIMES (1,2,3 OR 4) 3

FIRST DISTURBANCE

ENTER THE FIRST DISTURBANCE TIME (SECONDS) 0  
IS THERE A SHORT CIRCUIT AT THE FIRST DISTURBANCE TIME(Y OR N)?Y  
ENTER THE SHORT CIRCUIT BUS NUMBER 5  
DO GENERATOR BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N)? N  
DO LINE BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N) ?N  
DO TRANSFORMER BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N)?N

SECOND DISTURBANCE

ENTER THE SECOND DISTURBANCE TIME (SECONDS) .05  
IS THERE A SHORT CIRCUIT AT THE SECOND DISTURBANCE TIME (Y OR N) ? N  
IS THE SHORT CIRCUIT AT THE FIRST DISTURBANCE EXTINGUISHED (Y OR N) ? Y  
DO GENERATOR BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N) ? Y  
HOW MANY GENERATOR CIRCUIT BREAKERS OPEN ? 1  
GENERATOR OPENING CIRCUIT BREAKER 1  
ENTER THE GENERATOR NUMBER ? 1  
DO LINE BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N) ? Y  
HOW MANY LINE BREAKERS OPEN ? 2  
TRANSMISSION LINE OPENING CIRCUIT BREAKER 1  
ENTER THE LINE NUMBER 3  
ENTER THE BUS NUMBER 5  
TRANSMISSION LINE OPENING CIRCUIT BREAKER 2  
ENTER THE LINE NUMBER 2  
ENTER THE BUS NUMBER 5  
DO TRANSFORMER BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N)?N

THIRD DISTURBANCE

ENTER THE THIRD DISTURBANCE TIME (SECONDS) .3  
IS THERE A SHORT CIRCUIT AT THE THIRD DISTURBANCE TIME (Y OR N)?N  
DO GENERATOR BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N  
DO GENERATOR BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N)?Y  
HOW MANY GENERATOR BREAKERS CLOSE ? 1  
GENERATOR CLOSING CIRCUIT BREAKER 1  
ENTER THE GENERATOR NUMBER ? 1  
DO LINE BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N  
DO LINE BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ? Y  
HOW MANY LINE BREAKERS CLOSE ? 2  
TRANSMISSION LINE CLOSING CIRCUIT BREAKER 1  
ENTER THE LINE NUMBER 3  
ENTER THE BUS NUMBER 5  
TRANSMISSION LINE CLOSING CIRCUIT BREAKER 2  
ENTER THE LINE NUMBER 2  
ENTER THE BUS NUMBER 5  
DO TRANSFORMER BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ?N  
DO TRANSFORMER BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ? N

FOR OUTPUT LABELLING

ENTER THE FIRST DISTURBANCE NAME fault at bus 5

ENTER THE SECOND DISTURBANCE NAME fault cleared

ENTER THE THIRD DISTURBANCE NAME reclosure

YOUR MAY PRINT FROM 1 TO 5 OUTPUTS

ENTER THE NUMBER OF OUTPUTS (1 TO 5) 5

OUTPUT 1

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 1

OUTPUT 2

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 2

ENTER THE MACHINE NUMBER 1

OUTPUT 3

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 2

OUTPUT 4

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 2

ENTER THE MACHINE NUMBER 2

OUTPUT 5

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 4

ENTER THE BUS NUMBER 5

THE OUTPUTS ARE PRINTED EVERY KTH TIME INTERVAL

ENTER THE PRINTOUT INTEGER K (K>=1) 3

DO YOU WANT THE OUTPUTS IN EXPONENTIAL FORMAT (Y OR N) N  
CONTINUE (Y) OR RESET THE DISTURBANCES (N) ? Y

TRANSIENT STABILITY OUTPUT FOR sample run t = 0.30s

TIME	DELTA 1	OMEGA 1	DELTA 2	OMEGA 2	V 5
seconds	degrees	rad/s	degrees	rad/s	per unit
fault at bus 5					
0.000	11.15	376.99	6.10	376.99	0.000
0.030	12.01	377.99	6.19	377.10	0.000
fault cleared					
0.060	14.59	378.99	6.47	377.20	0.000
0.090	18.96	380.07	6.82	377.19	0.000
0.120	25.19	381.15	7.16	377.18	0.000
0.150	33.26	382.23	7.48	377.17	0.000
0.180	43.18	383.30	7.78	377.16	0.000
0.210	54.94	384.37	8.06	377.15	0.000
0.240	68.54	385.43	8.32	377.14	0.000
0.270	83.97	386.50	8.56	377.13	0.000
0.300	101.22	387.56	8.78	377.11	0.000
reclosure					
0.330	119.35	387.01	9.09	377.28	0.576
0.360	135.62	385.97	9.81	377.54	0.464
0.390	150.43	385.34	10.95	377.76	0.363
0.420	164.56	385.17	12.45	378.40	0.271
0.450	178.80	385.48	14.27	378.12	0.193
0.480	193.98	386.28	16.32	378.24	0.152
0.510	211.00	387.61	18.52	378.30	0.196
0.540	230.79	389.51	20.77	378.29	0.312
0.570	254.33	391.95	22.95	378.21	0.471
0.600	282.41	394.76	24.93	378.06	0.653
0.630	315.38	397.52	26.61	377.87	0.833
0.660	352.64	399.60	27.96	377.69	0.966
0.690	392.45	400.40	29.07	377.61	1.007
0.720	432.38	399.81	30.17	377.68	0.936
0.750	470.47	398.40	31.51	377.88	0.773

REMOVE Ctrl PRINT SCREEN AND THEN RETURN TO CONTINUE

WOULD YOU LIKE TO:

1. UPDATE THE SYNCHRONOUS MACHINE INPUT DATA
2. SET DISTURBANCES AND RUN THE PROGRAM
3. STOP

ENTER YOUR SELECTION (1,2 OR 3) 3

**CONCLUSION**

Machine power angle outputs versus time for reclosure times  $t = 0.27s$  and  $t = 0.3s$  are given above. The printout interval is  $0.03s$ .

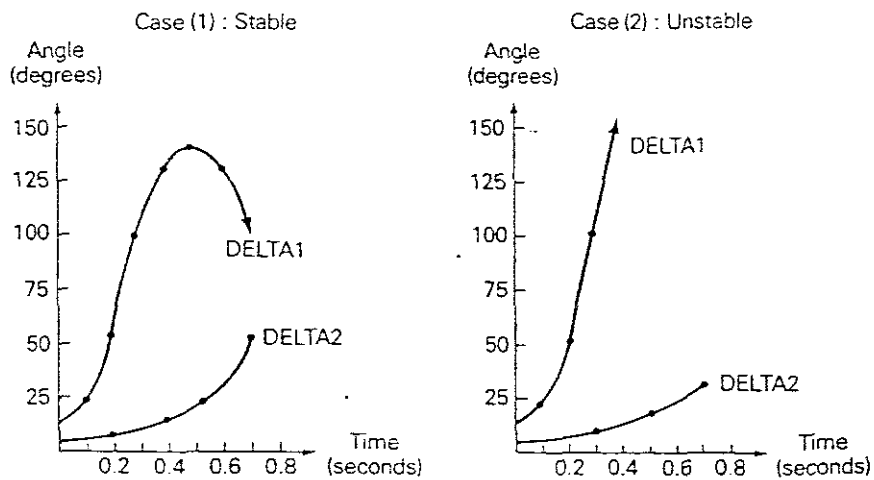
**For  $t = 0.27s$**

The power angle  $\delta$ , reaches a maximum value then swings back. With damping included,  $\delta_1$  and  $\delta_2$  would settle down to new steady-state values. The system is therefore **STABLE**.

**For  $t = 0.30s$**

The power angle  $\delta_1$  of machine 1 exceeds  $180^\circ$  degrees and diverges away from  $\delta_2$ . That is machine 1 pulls out of synchronism with machine 2 on the first swing. The system is therefore **UNSTABLE**.

Their curves are approximately as follows:



**B. EXPERIMENTATION USING THE PROGRAM  
"TRANSIENT STABILITY" ON A 16 BUS 3 GENERATOR  
USING DATA FROM CHAPTER ONE A(1) AND B**

The one-line diagram of the 16 bus, 3 generator, 14 lines and 5 transformer system as shown in Figure 1 as well as Tables 1 to 6 forms the basis of the information available.

Experimentation to determine transient stability will be carried out using input and output data of the "POWER FLOW" program as used in Chapter One and stored on the hard drive. The 3 separate "POWER FLOW" cases 1,2 and 3 from Chapter One can be summarized as follows:

**CHAPTER ONE "POWER FLOW" PROGRAM CASES**

**CASE 1**

Base Load - Fixed tapplings.

**CASE 2**

Base Load - Automatic tap changers.

**CASE 3**

Heavy Load - Fixed tapplings.

**EXPERIMENTAL REQUIREMENTS**

**PART ONE**

Use the "Transient Stability" program to analyze a temporary three-phase short circuit at bus 4 of the power system given in Figure 1. For pre-fault conditions, use the "POWER FLOW" Case 1 from Chapter One. Machine transient reactances on a 100 MVA systems base are from Table 42 Chapter Two:

	Xd1pu
MACHINE 1	0.095
MACHINE 2	0.130
MACHINE 3	0.116

Machine Inertia constants from Table 5b are:

	H pu-s	RATING MVA
MACHINE 1	3.3	270
MACHINE 2	6.3	245
MACHINE 3	2.4	260

The short circuit is cleared by opening the generator breaker of machine 1 and the two line breakers on lines 1 and 2 at 0.05s (3 cycles), followed by reclosing these circuit breakers. Assume that the fault has already self-extinguished when reclosure occurs.

Run the following two cases:

- Case 1 Reclosure at  $t = 0.27s$  (13 cycles after fault clearing)
- Case 2 Reclosure at  $t = 0.30s$  (15 cycles after fault clearing)

Use an integration step  $dt = 0.01s$  and final time  $T = 0.75s$ . Obtain the following output results, namely:

Delta 1, Delta 2, Delta 3, Omega 1, and Omega 2 and determine whether the system is stable or unstable?.

<p style="text-align: center;"><b>PART TWO SELF EVALUATION EXPERIMENTATION</b></p>
--

- a. Use the "Transient Stability" program and repeat the above experimental requirements, except for pre-fault conditions, use "POWER FLOW" Case 3 from Chapter One. Is the system stable or unstable under these heavy load fixed tapings condition?
- b. Repeat "a" with the circuit breakers opening at  $t = 0.075s$  (4.5 cycles) instead of at  $t = 0.05$  secs. Assume that reclosure occurs 13 cycles (0.2166 secs) after fault clearing ( $0.2166 + 0.075 = 0.2916s$ ), that is the third disturbance time is 0.2916 secs.
- c. Repeat "b" with circuit breakers opening at  $t = 0.025s$  (1.5 cycles) instead of  $t = 0.05s$ . The third disturbance remains at 13 cycles after fault clearing, namely 0.2416 secs.



**SOLUTION**

Before proceeding the H constants must be adjusted to systems base.

H1 syst	=	(3.3)(270)	÷	100	=	8.91	pu-s
H2 syst	=	(6.3)(245)	÷	100	=	15.435	pu-s
H3 syst	=	(2.4)(260)	÷	100	=	6.24	pu-s

C:\POWER>CHAP12

"TRANSIENT STABILITY" PROGRAM

THIS PROGRAM EVALUATES A BALANCED THREE-PHASE POWER SYSTEM SUBJECTED TO A DISTURBANCE. THE FOLLOWING QUANTITIES ARE COMPUTED FOR EACH DISCRETE TIME:

- (1) POWER ANGLE OF EACH SYNCHRONOUS MACHINE
- (2) FREQUENCY OF EACH SYNCHRONOUS MACHINE
- (3) REAL POWER OUTPUT OF EACH SYNCHRONOUS MACHINE
- (4) VOLTAGE MAGNITUDE AT EACH BUS

**NB! BEFORE YOU CAN RUN THIS PROGRAM  
YOU MUST FIRST RUN THE POWER FLOW PROGRAM  
THAT IS ON THIS DISK FOR YOUR POWER SYSTEM**

PRESS RETURN TO CONTINUE

EXIT THIS PROGRAM AND RETURN TO DOS AND GO TO:

C:\POWER>CHAP7

"POWER FLOW" PROGRAM

ENTER CASE 1 AND CASE NAME e.g. GARY.001

RUN THE PROGRAM FOR CASE 1

EXIT THE PROGRAM, GO TO "TRANSIENT STABILITY" PROGRAM

C:\POWER>CHAP12

WHAT IS THE CASE NUMBER FOR YOUR POWER FLOW PROGRAM?

(ENTER AN INTEGER FROM 1 TO 3) 1

ENTER YOUR CASE NAME gary. 001

Select 1 from menu 1 CHAP 3 to update synchronous machine data.

Select 5 from menu 2 CHAP 3 to display all machines below a given one, enter 1 to display contents of existing file.

Return to menu 2 CHAP 3, select 3 and remove existing details from a previous run.

Return to menu 2 CHAP 3, select 2 and update for all three machines of this 16 bus system

ENTER YOUR SELECTION (1 TO 6) 2

MACHINE NUMBER (1 TO 25) ? 1

MACHINE BUS NUMBER ? 1

MACHINE TRANSIENT REACTANCE (per unit) ? .095

MACHINE H CONSTANT (per unit seconds) ? 8.91

ENTER YOUR SELECTION (1 TO 6) 2  
MACHINE NUMBER (1 TO 25) ? 2  
MACHINE BUS NUMBER ? 2  
MACHINE TRANSIENT REACTANCE (per unit) ? .13  
MACHINE H CONSTANT (per unit seconds) ? 15.435

ENTER YOUR SELECTION (1 TO 6) 2  
MACHINE NUMBER (1 TO 25) ? 3  
MACHINE BUS NUMBER ? 3  
MACHINE TRANSIENT REACTANCE (per unit) ? .116  
MACHINE H CONSTANT (per unit seconds) ? 6.245

SYNCHRONOUS MACHINE DATA FOR gary. 001			
MACHINE#	BUS	X per unit	H per unit seconds
1	1	.095	8.91
2	2	.13	15.435
3	3	.116	6.24

Select 2 from menu 2 Chap 3 to set disturbances and run the program.

ENTER THE INTEGRATION TIME INTERVAL (SECONDS) .01  
ENTER THE FINAL TIME (SECONDS) .75  
ENTER THE NUMBER OF DISTURBANCE TIMES (1,2,3 OR 4) 3

FIRST DISTURBANCE

ENTER THE FIRST DISTURBANCE TIME (SECONDS) 0  
IS THERE A SHORT CIRCUIT AT THE FIRST DISTURBANCE TIME(Y OR N)?Y  
ENTER THE SHORT CIRCUIT BUS NUMBER 4  
DO GENERATOR BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N)? N  
DO LINE BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N)N  
DO TRANSFORMER BREAKERS OPEN AT THE FIRST DISTURBANCE (Y OR N)?N

SECOND DISTURBANCE

ENTER THE SECOND DISTURBANCE TIME (SECONDS) .05  
IS THERE A SHORT CIRCUIT AT THE SECOND DISTURBANCE TIME (Y OR N) ? N  
IS THE SHORT CIRCUIT AT THE FIRST DISTURBANCE EXTINGUISHED (Y OR N) ? Y  
DO GENERATOR BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N) ? Y  
HOW MANY GENERATOR CIRCUIT BREAKERS OPEN ? 1  
GENERATOR OPENING CIRCUIT BREAKER 1  
ENTER THE GENERATOR NUMBER ? 1  
DO LINE BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N) ? Y  
HOW MANY LINE BREAKERS OPEN ? 2  
TRANSMISSION LINE OPENING CIRCUIT BREAKER 1  
ENTER THE LINE NUMBER 1  
ENTER THE BUS NUMBER 4  
TRANSMISSION LINE OPENING CIRCUIT BREAKER 2  
ENTER THE LINE NUMBER 2  
ENTER THE BUS NUMBER 4  
DO TRANSFORMER BREAKERS OPEN AT THE SECOND DISTURBANCE (Y OR N)?N

RECLOSURE t = 0.27 secs

THIRD DISTURBANCE

ENTER THE THIRD DISTURBANCE TIME (SECONDS) .27  
IS THERE A SHORT CIRCUIT AT THE THIRD DISTURBANCE TIME (Y OR N)?N  
DO GENERATOR BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N  
DO GENERATOR BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N)?Y  
HOW MANY GENERATOR CIRCUIT BREAKERS CLOSE ? 1  
GENERATOR CLOSING CIRCUIT BREAKER 1  
ENTER THE GENERATOR NUMBER ? 1  
DO LINE BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N  
DO LINE BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ? Y  
HOW MANY LINE BREAKERS CLOSE ? 2  
TRANSMISSION LINE CLOSING CIRCUIT BREAKER 1  
ENTER THE LINE NUMBER 1  
ENTER THE BUS NUMBER 4  
TRANSMISSION LINE CLOSING CIRCUIT BREAKER 2  
ENTER THE LINE NUMBER 2  
ENTER THE BUS NUMBER 4  
DO TRANSFORMER BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ?N  
DO TRANSFORMER BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N)  
? N

FOR OUTPUT LABELLING

ENTER THE FIRST DISTURBANCE NAME fault at bus 4  
ENTER THE SECOND DISTURBANCE NAME fault cleared  
ENTER THE THIRD DISTURBANCE NAME reclosure

YOUR MAY PRINT FROM 1 TO 5 OUTPUTS

ENTER THE NUMBER OF OUTPUTS (1 TO 5) 5

OUTPUT 1

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 1

OUTPUT 2

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 2

OUTPUT 3

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 1

ENTER THE MACHINE NUMBER 3

OUTPUT 4

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 2

ENTER THE MACHINE NUMBER 1

OUTPUT 5

SELECTIONS:

1. MACHINE POWER ANGLE
2. MACHINE FREQUENCY
3. MACHINE REAL POWER OUTPUT
4. BUS VOLTAGE

ENTER YOUR SELECTION (1,2,3 OR 4) 2

ENTER THE MACHINE NUMBER 2

THE OUTPUTS ARE PRINTED EVERY KTH TIME INTERVAL

ENTER THE PRINTOUT INTEGER K ( $K \geq 1$ ) 3

DO YOU WANT THE OUTPUTS IN EXPONENTIAL FORMAT (Y OR N) N

CONTINUE (Y) OR RESET THE DISTURBANCES (N) ? Y

TRANSIENT STABILITY OUTPUT FOR	gary.001
--------------------------------	----------

TIME	DELTA 1	DELTA 2	DELTA 3	OMEGA 1	OMEGA 2
seconds	degrees	degrees	degrees	rad/s	rad/s
fault at bus 4					
0.000	5.47	7.93	3.24	376.99	376.99
0.030	6.03	8.12	3.76	377.64	377.22
fault cleared					
0.060	7.71	8.70	5.32	378.29	377.44
0.090	10.50	9.40	6.98	378.94	377.35
0.120	14.41	9.92	7.66	379.59	377.24
0.150	19.44	10.25	7.29	380.24	377.13
0.180	25.58	10.39	5.96	380.89	377.01
0.210	32.84	10.33	3.83	381.53	376.90
0.240	41.20	10.08	1.17	382.18	376.78
reclosure					
0.270	50.67	9.60	-1.87	382.82	376.64
0.300	59.28	9.26	-3.53	381.13	376.97
0.330	64.84	9.54	-1.89	379.31	377.35
0.360	67.24	10.50	3.11	377.47	377.76
0.390	66.51	12.20	11.20	375.69	378.21
0.420	62.85	14.70	21.80	374.07	378.69
0.450	56.65	18.04	34.04	372.78	379.18
0.480	48.63	22.22	46.65	371.99	379.65
0.510	39.78	27.17	58.23	371.84	380.07
0.540	31.26	32.77	67.46	372.37	380.41
0.570	24.18	38.85	73.41	373.48	380.64
0.600	19.40	45.24	75.59	375.00	380.75
0.630	17.43	51.73	73.91	376.72	380.75
0.660	18.49	58.11	68.62	378.48	380.63
0.690	22.47	64.18	60.28	380.09	380.39
0.720	29.00	69.74	49.85	381.40	380.04
0.750	37.39	74.61	38.63	382.24	379.59

Delta 1 reaches a maximum of 67.24 degrees and 382.82 rad/sec (i.e.  $f = 60.92\text{Hz}$ ). It seems to be turning back.

Delta 2 reaches 74.61 degrees and 380.75 rad/sec (i.e.  $f = 60.59\text{Hz}$ ) and has as yet not turned back.

Delta 3 reaches a maximum of 75.59 degrees and seems to be turning back.

The system is stable.

Return to menu 1 Chap 3 and select 2 to set disturbances once again and to run the program for  $t = 0.3$  secs reclosure time.

Repeat the above steps for the first and second disturbances as they are the same as the previous run.

RECLOSURE  $t = 0.3$  secs

THIRD DISTURBANCE

ENTER THE THIRD DISTURBANCE TIME (SECONDS) .3

IS THERE A SHORT CIRCUIT AT THE THIRD DISTURBANCE TIME (Y OR N)?N

DO GENERATOR BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N

DO GENERATOR BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N)?Y

HOW MANY GENERATOR CIRCUIT BREAKERS CLOSE ? 1

GENERATOR CLOSING CIRCUIT BREAKER 1

ENTER THE GENERATOR NUMBER ? 1

DO LINE BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ? N

DO LINE BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N) ? Y

HOW MANY LINE BREAKERS CLOSE ? 2

TRANSMISSION LINE CLOSING CIRCUIT BREAKER 1

ENTER THE LINE NUMBER 1

ENTER THE BUS NUMBER 4

TRANSMISSION LINE CLOSING CIRCUIT BREAKER 2

ENTER THE LINE NUMBER 2

ENTER THE BUS NUMBER 4

DO TRANSFORMER BREAKERS OPEN AT THE THIRD DISTURBANCE (Y OR N) ?N

DO TRANSFORMER BREAKERS RECLOSE AT THE THIRD DISTURBANCE (Y OR N)

? N

FOR OUTPUT LABELLING

ENTER THE FIRST DISTURBANCE NAME fault at bus 4

ENTER THE SECOND DISTURBANCE NAME fault cleared

ENTER THE THIRD DISTURBANCE NAME reclosure

Select the same output labelling as for previous run.

TRANSIENT STABILITY OUTPUT FOR	gary.001
--------------------------------	----------

TIME	DELTA 1	DELTA 2	DELTA 3	OMEGA 1	OMEGA 2
seconds	degrees	degrees	degrees	rad/s	rad/s
fault at bus 4					
0.000	5.47	7.93	3.24	376.99	376.99
0.030	6.03	8.12	3.76	377.64	377.22
fault cleared					
0.060	7.71	8.70	5.32	378.29	377.44
0.090	10.50	9.40	6.98	378.94	377.35
0.120	14.41	9.92	7.66	379.59	377.24
0.150	19.44	10.25	7.29	380.24	377.13
0.180	25.58	10.39	5.96	380.89	377.01
0.210	32.84	10.33	3.83	381.53	376.90
0.240	41.20	10.08	1.17	382.18	376.78
0.270	50.67	9.60	-1.87	382.82	376.64
0.300	61.25	8.85	-5.13	383.47	376.46
reclosure					
0.330	71.97	7.99	-7.65	382.42	376.67
0.360	79.64	7.81	-6.47	380.48	377.12
0.390	83.96	8.44	-1.33	378.53	377.60
0.420	84.94	9.94	7.52	376.60	378.13
0.450	82.63	12.39	19.63	374.71	378.72
0.480	77.16	15.90	34.28	372.96	379.36
0.510	68.97	20.53	50.29	371.59	380.02
0.540	58.93	26.30	66.09	370.86	380.66
0.570	48.30	33.12	79.98	370.92	381.23
0.600	38.47	40.81	90.55	371.77	381.68
0.630	30.66	49.15	96.98	373.24	381.99
0.660	25.75	57.90	98.95	375.09	382.15
0.690	24.22	66.80	96.51	377.13	382.16
0.720	26.24	75.58	89.97	379.19	382.02
0.750	31.72	84.01	79.94	381.11	381.74

Delta 1 reaches a maximum of 84.94 degrees and 383.47 rad/sec ( $f = 61.03$  Hz) and turns back.

Delta 2 reaches 84.01 degrees and 382.02 rad/sec ( $f = 60.8$  Hz), the frequency starts to return after its maximum.

Delta 3 reaches a maximum of 98.95 degrees and 383.47 rad/sec ( $f = 61.03$  Hz) and turns back.

The system is stable.

Exit from the program.

**ANSWERS TO SELF EVALUATION EXPERIMENTS**

a. After updating synchronous machine data for Case 3 of "POWER FLOW" the following outputs results were obtained:

RECLOSURE  $t = 0.27s$

TRANSIENT STABILITY OUTPUT FOR                    gary.003

TIME	DELTA 1	DELTA 2	DELTA 3	OMEGA 1	OMEGA 2
seconds	degrees	degrees	degrees	rad/s	rad/s
fault at bus 4					
0.000	5.41	8.28	3.09	376.99	376.99
0.030	5.97	8.48	3.61	377.64	377.22
fault cleared					
0.060	7.64	9.08	5.16	378.29	377.45
0.090	10.44	9.81	6.81	378.94	377.37
0.120	14.36	10.38	7.55	379.59	377.27
0.150	19.39	10.78	7.30	380.24	377.17
0.180	25.54	10.99	6.12	380.89	377.07
0.210	32.80	11.03	4.17	381.54	376.96
0.240	41.17	10.89	1.71	382.18	376.85
reclosure					
0.270	50.65	10.55	-1.10	382.83	376.72
0.300	59.28	10.36	-2.53	381.15	377.05
0.330	64.89	10.77	-0.71	379.34	377.42
0.360	67.35	11.85	4.43	377.51	377.83
0.390	66.70	13.67	12.62	375.75	378.28
0.420	63.15	16.29	23.28	374.15	378.75
0.450	57.10	19.72	35.50	372.88	379.23
0.480	49.28	23.98	48.05	372.12	379.70
0.510	40.68	28.99	59.51	372.00	380.11
0.540	32.46	34.64	68.60	372.55	380.43
0.570	25.70	40.77	74.41	373.67	380.66
0.600	21.23	47.20	76.46	375.17	380.77
0.630	19.55	53.72	74.68	376.87	380.77
0.660	20.84	60.13	69.32	378.60	380.65
0.690	24.98	66.23	60.97	380.17	380.41
0.720	31.59	71.83	50.61	381.42	380.06
0.750	39.96	76.74	39.55	382.20	379.62

The system is stable.



RECLOSURE  $t = 0.3s$

TRANSIENT STABILITY OUTPUT FOR gary.003

TIME	DELTA 1	DELTA 2	DELTA 3	OMEGA 1	OMEGA 2
seconds	degrees	degrees	degrees	rad/s	rad/s
fault at bus 4					
0.000	5.41	8.28	3.09	376.99	376.99
0.030	5.97	8.48	3.61	377.64	377.22
fault cleared					
0.060	7.64	9.08	5.16	378.29	377.45
0.090	10.44	9.81	6.81	378.94	377.37
0.120	14.36	10.38	7.55	379.59	377.27
0.150	19.39	10.78	7.30	380.24	377.17
0.180	25.54	10.99	6.12	380.89	377.07
0.210	32.80	11.03	4.17	381.54	376.96
0.240	41.17	10.89	1.71	382.18	376.85
0.270	50.65	10.55	-1.10	382.83	376.72
0.300	61.24	9.96	-4.11	383.47	376.57
reclosure					
0.330	71.98	9.29	-6.37	382.43	376.77
0.360	79.67	9.29	-4.96	380.49	377.22
0.390	84.01	10.09	0.38	378.54	377.70
0.420	85.00	11.76	9.40	376.61	378.23
0.450	82.71	14.37	21.65	374.72	378.81
0.480	77.28	18.03	36.37	373.00	379.44
0.510	69.20	22.80	52.36	371.68	380.09
0.540	59.35	28.68	68.03	371.00	380.72
0.570	49.02	35.57	81.69	371.12	381.27
0.600	39.58	43.31	92.00	372.02	381.70
0.630	32.23	51.69	98.14	373.51	382.00
0.660	27.79	60.44	99.83	375.36	382.14
0.690	26.71	69.33	97.14	377.38	382.15
0.720	29.14	78.10	90.39	379.41	382.01
0.750	34.95	86.51	80.23	381.28	381.73

The system is stable.

b.

CIRCUIT BREAKERS OPEN  $t = 0.075s$   
 RECLOSURE  $t = 0.2916s$

TRANSIENT STABILITY OUTPUT FOR gary.003

TIME	DELTA 1	DELTA 2	DELTA 3	OMEGA 1	OMEGA 2
seconds	degrees	degrees	degrees	rad/s	rad/s
fault at bus 4					
0.000	5.41	8.28	3.09	376.99	376.99
0.030	5.97	8.48	3.61	377.64	377.22
0.060	7.64	9.08	5.16	378.29	377.45
fault cleared					
0.090	10.44	10.05	7.62	378.94	377.58
0.120	14.36	11.00	9.60	379.59	377.50
0.150	19.38	11.80	10.51	380.24	377.42
0.180	25.52	12.45	10.31	380.89	377.32
0.210	32.78	12.94	9.09	381.54	377.23
0.240	41.15	13.26	7.02	382.18	377.12
0.270	50.63	13.40	4.36	382.83	377.02
reclosure					
0.300	61.22	13.33	1.35	383.47	376.89
0.330	70.83	13.47	-0.11	381.66	377.26
0.360	77.23	14.29	2.02	379.75	377.68
0.390	80.32	15.86	7.79	377.84	378.14
0.420	80.15	18.25	16.93	375.96	378.63
0.450	76.85	21.52	28.89	374.21	379.16
0.480	70.75	25.70	42.79	372.75	379.70
0.510	62.54	30.82	57.32	371.80	380.23
0.540	53.26	36.82	70.94	371.54	380.71
0.570	44.19	43.57	82.16	372.03	381.10
0.600	36.56	50.89	89.93	373.18	381.38
0.630	31.33	58.58	93.68	374.79	381.53
0.660	29.11	66.42	93.27	376.64	381.54
0.690	30.16	74.17	88.90	378.56	381.44
0.720	34.45	81.63	81.05	380.37	381.20
0.750	41.64	88.59	70.59	381.90	380.84

The system remains stable.

c.

CIRCUIT BREAKERS OPEN  $t = 0.025s$   
 RECLOSURE  $t = 0.2416s$

TRANSIENT STABILITY OUTPUT FOR gary.003

TIME	DELTA 1	DELTA 2	DELTA 3	OMEGA 1	OMEGA 2
seconds	degrees	degrees	degrees	rad/s	rad/s
fault at bus 4					
0.000	5.41	8.28	3.09	376.99	376.99
fault cleared					
0.030	5.97	8.48	3.61	377.64	377.22
0.060	7.65	8.81	4.29	378.29	377.13
0.090	10.45	8.97	4.20	378.95	377.04
0.120	14.37	8.97	3.36	379.60	376.94
0.150	19.40	8.79	1.86	380.25	376.84
0.180	25.56	8.45	-0.12	380.89	376.74
0.210	32.82	7.93	-2.46	381.54	376.62
0.240	41.20	7.18	-5.07	382.19	376.48
reclosure					
0.270	49.84	6.34	-7.20	381.33	376.62
0.300	55.83	5.98	-6.39	379.59	376.96
0.330	58.77	6.24	-2.35	377.80	377.34
0.360	58.65	7.20	4.73	376.06	377.76
0.390	55.63	8.90	14.32	374.46	378.22
0.420	50.08	11.42	25.60	373.14	378.69
0.450	42.64	14.75	37.42	372.29	379.16
0.480	34.21	18.86	48.42	372.02	379.59
0.510	25.89	23.65	57.33	372.40	379.95
0.540	18.74	28.99	63.19	373.36	380.22
0.570	13.60	34.70	65.43	374.72	380.39
0.600	11.06	40.60	63.91	376.33	380.44
0.630	11.34	46.49	58.82	377.98	380.37
0.660	14.40	52.16	50.72	379.52	380.19
0.690	19.89	57.43	40.51	380.78	379.90
0.720	27.22	62.11	29.46	381.62	379.50
0.750	35.54	66.03	19.04	381.94	379.03

The system continues to remain stable.

**CHAPTER FOUR**  
**ECONOMIC DISPATCH STUDIES**  
**COMPUTER EXPERIMENTS**  
**16 BUS 3 GENERATOR POWER SYSTEM**

For a power system to return a profit on the capital invested, proper operation is very important. The conservation of fuel places pressure on companies to achieve maximum efficiency of operation. How engineers meet and solve this challenging problem is introduced in this chapter. (Stevenson 1982, 227).

The real power output of each controlled generating unit in an area is selected to meet a given load and to minimize the total operating costs in the area. This is the economic dispatch problem. (Glover 1987, 359). This problem involves the solution of two different problems. The first of these is the Unit Commitment or predispatch problem wherein it is required to select optimally out of the available generating sources to operate, to meet the expected load and provide a specified margin of operating reserve over a specified period of time. The second aspect of economic dispatch is the on-line economic dispatch wherein it is required to distribute the load among the generating units actually paralleled with the system in such a manner as to minimize the total cost of supplying the minute-to-minute requirements of the system. It is this second aspect of the economic dispatch problem which will be introduced in this chapter. (Wadhwa 1991, 646).

In chapter one we made a load flow study for the power system, in that for a particular load demand the generation at all generator buses are fixed except at the swing bus where we allow the generation to take value within certain limits. In economic dispatch the generations are not fixed but are allowed to take values again within certain limits so as to meet a particular load demand with minimum full consumption. It is clear from this, that since total cost of generation is a function of the individual generation of the sources which can take values within certain constraints, the cost of generation will depend upon the system constraint for a particular load demand. This means the cost of generation is not fixed for a particular load demand. In fact the modern power system has to operate under various operational and network constraints. It is therefore best to state the various constraints before actually taking up the economic load dispatching problem. (Wadhwa 1991, 646).

System constraints are of two types: (1) Equality constraints and (11) Inequality constraints. (Wahhwa 1991, 647).

**Equality Constraints** are the basic flow equations as the economic load dispatching problem is really the solution of a large number of load flow problems and choosing the one which is optimal in the sense that it needs minimum cost of generation.

### Inequality Constraints

#### a. Generator Constraints

The kVA loading on a generator should not exceed a prespecified value because of the temperature rise conditions. The maximum active power generation of a source is limited by thermal consideration and also minimum power generation is limited by the flame instability of a boiler. If the power output of a generator for optimum operation is less than the prespecified value  $P_{min}$ , the unit is not put on the bus because it is not possible to generate that low value of power from that unit. Hence the generator powers  $P_p$  cannot be outside the range stated by the inequality, i.e.:

$$P_{pmin} \leq P_p \leq P_{pmax} \quad - - - (1)$$

Similarly the maximum and minimum reactive power generation of a source are limited. The maximum is limited because of rotor overheating and the minimum because of the stability limit of the machine.

$$Q_{pmin} \leq Q_p \leq Q_{pmax} \quad - - - (2)$$

#### b. Voltage Constraints

It is essential that the voltage magnitudes and phase angles at various nodes should vary within certain limits.

$$\begin{aligned} V_{pmin} &\leq V_p \leq V_{pmax} \\ \delta_{pmin} &\leq \delta_p \leq \delta_{pmax} \end{aligned} \quad - - - (3)$$

The normal operating angle of a transmission line lies between 30 to 45 degrees for transient stability reasons.

#### c. Transmission Line Constraints

The flow of active and reactive power through the transmission line circuit is limited by the thermal capability of the circuit.

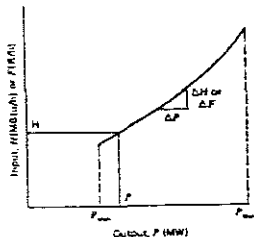
The above are the main constraints which have to be taken into account, although there are others of less importance.

Since we are considering a system which is already in existence, the fixed costs like salaries and capital costs are neglected from the cost criterion. We will thus be only concerned with the cost of fuel input. This 16 bus power system has 3 generators. Generator One is a fossil-fuel unit, Generator Two is a nuclear unit and Generator Three is a hydro-electric unit.

We introduce this topic by considering an area with only fossil-fuel units, with no constraints on maximum and minimum generator outputs and with no transmission losses. The economic dispatch problem is first approached from this idealised case. Then we include inequality constraints on generator outputs, then we include transmission losses. Next we mention co-ordination of economic dispatch. (Glover 1987, 360) and then mention other types of units e.g. nuclear and hydro units.

**1. FOSSIL-FUEL UNITS - NO INEQUALITIES CONSTRAINTS  
- NO TRANSMISSION LOSSES**

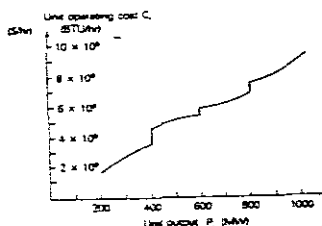
Fundamental to the economic operating problem is the set of input-output characteristics for each generator. Figure 3 shows the input-output characteristics of a steam unit in idealised form. (Wollenberg 1984, 6).



INPUT-OUTPUT CURVE OF A STEAM TURBINE GENERATOR

FIGURE.3

This data may be obtained from design calculations or from heat rate tests. When heat rate test data is used, it will usually be found that the data points do not fall on a smooth curve, for instance as in Figure 4. (Glover 1987, 360).



UNIT OPERATING COST VERSUS REAL POWER OUTPUT  
FOSSIL-FUEL GENERATING UNIT

FIGURE.4

Figure 4 shows the operating cost  $C_i$  of a fossil-fuel generating unit versus real power output  $P_i$ .

In practice,  $C_i$  is constructed of piecewise continuous functions valid for ranges of output  $P_i$  based on empirical data. The discontinuities are due to the firing of equipment such as boilers or condensers as power outputs is increased.

$C_i$  is often expressed in terms of BTU/h (heat input to unit) and sometimes as \$/h.

$C_i$  is converted to \$/h by multiplying the fuel input in BTU/h by the cost of fuel in \$/BTU, therefore fuel cost is :

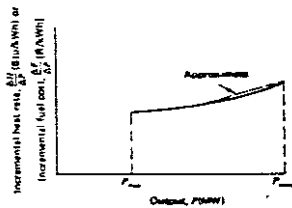
$$\text{Fuel Cost} = \$/h = \text{Fuel Input(BTU/h)} \text{ times Cost of Fuel}(\$/\text{BTU}) \quad - - (4)$$

For the idealised form of Figure 3, the cost in \$/h is:

$$F = \text{Cost} = \$/h = H(\text{MBTU/h}) \text{ times Cost of Fuel} (\$/\text{MBTU}) \quad - - - - (5)$$

NB! Generating units consume fuel at a specified rate (e.g. MBTU/h) and can be converted to \$/h which represents the cost rate.

The incremental heat rate characteristic for a unit of this type is shown in Figure 5. (Wollenberg 1984, 7)



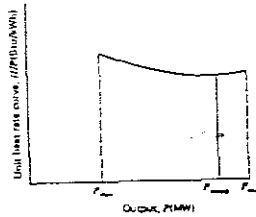
INCREMENTAL HEAT (COST) RATE CHARACTERISTIC

FIGURE. 5

This incremental heat rate characteristic is the slope (derivative) of the input-output characteristic of Figure 3 ( $H/P$  or  $F/P$ ). The data shown is in terms of BTU/kWh or dollars/kWh versus the net power output of the unit in megawatts. This characteristic is widely used in economic dispatching.

It is converted to an incremental fuel cost characteristic by multiplying the incremental heat rate in BTU/kWh by the equivalent fuel cost in terms of dollars/BTU.

The last important characteristic of a steam unit is the unit (net) heat rate characteristic as shown in Figure 6:



NET RATE CHARACTERISTIC OF A STEAM TURBINE GENERATOR UNIT

FIGURE. 6

This characteristic is H/P versus P. The unit heat rate characteristic shows the heat input per kWh of output versus the megawatt output of the unit.

NB! The heat rate is H/P or from Figure.4 it is C/P, namely input over output. which is the reciprocal of the usual efficiency for machines, which is output over input.

The unit heat rate characteristic figure 6 shows the heat input per kWh of output versus the megawatt output of the unit. Conventional steam turbine units are between 30 and 35% efficient so that their heat rate ranges between approximately 11400 to 9800 BTU/kWh.

NB! A kWh has a thermal equivalent of approximately 3413 BTU.

FOR EXAPMLE : (USING FIG.4)

At  $P_i = 600\text{MW}$   $C_i = 5.4\text{E}9$ , therefore

$$C/P = 5.4\text{E}9 / 600\text{E}3 = 9000 \text{ BTU/kWh} \quad - - - - (6)$$

or

$$\begin{aligned} \text{RECIPROCAL} &= P/C = 1/9000 \text{ kWh/BTU} \\ &= 1.1111\text{E-}4\text{kWh/BTU} \end{aligned}$$

but  $1 \text{ kWh} = 3413 \text{ BTU's}$

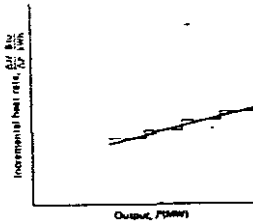


$$\begin{aligned}\text{Therefore Percentage Efficiency} &= \text{Output/Input} \times 100\% \\ &= 1.1111\text{E}^{-4} (3413) \times 100\% \\ &= 37.92\%\end{aligned}$$

NB! Maximum efficiency occurs at that point where the slope of the line from the origin to a point on a curve (e.g. as in Figure. 3) is a minimum, that is, at the point where the line is tangent to the curve.

Many different formats are used to represent the input-output characteristics shown in Figure.3. The data obtained from heat rate tests or from the plant design engineers may be fitted by a polynomial curve. In some cases quadratic characteristics have been fitted to these data. A series of straight line segments may also represent the input-output characteristics.

The different representations will of course, result in different incremental heat rate characteristics. Figure.7 shows two variations.



#### APPROXIMATE REPRESENTATIONS OF THE INCREMENTAL HEAT RATE CURVE

FIGURE. 7

The solid line shows the incremental heat rate characteristic that results when the input-output is a quadratic curve. The dashed lines shows a stepped incremental characteristic that results when a series of straight line segments are used to represent the input-output characteristics of a unit. The use of these different representations may require that different scheduling methods be used for establishing the optimum economic operation of a power system. Both formats are useful and both may be represented by tables of data. Only the first, the solid line may be represented by a continuous analytic function. (Wollenberg 1984, 8).

Figure. 8 shows a typical curve for a units incremental operating cost versus real power output for a fossil-fuel generating unit. (Glover 1987, 361).

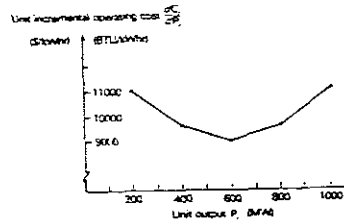


FIGURE.8

It shows the unit incremental operating cost  $dC_i/dP_i$  versus unit output  $P_i$ . This curve being derived from Figure.4. This  $dC_i/dP_i$  curve is also represented by piecewise continuous functions valid for ranges of output  $P_i$ . The  $dC_i/dP_i$  incremental operating cost is expressed in BTU/kWh. It is converted to \$/kWh by multiplying the incremental heat rate in BTU/kWh by the cost of fuel in \$/BTU. Therefore

$$\boxed{\text{UNIT INCREMENTAL OPERATING COST} = dC_i/dP_i \text{ \$/kWh}} \text{ --- (7)}$$

NB! It could be expressed in \$/MWh and if operating cost is only fuel cost then it could be called unit incremental fuel cost in \$/MWh, that is  $dF_i/dP_i$  where "F" is fuel cost.

For an area of an interconnected power system consisting of N units operating on economic dispatch the essential constraint is that the sum of the output powers must equal the load demand  $P_T$ , that is, neglecting losses:

$$\boxed{P_1 + P_2 \text{ --- } + P_N = P_T} \text{ --- (8)}$$

If  $C_T$  is the total cost of operating these units then the economic dispatch problem can be stated as follows:

$$\boxed{\begin{array}{l} \text{Find the values of unit outputs } P_1 \ P_2 \ \text{---}, \ P_N \ \text{that} \\ \text{minimize } C_T \ \text{subject to the equality constraint} \\ P_1 + P_2 + \text{---} + P_N = P_T \end{array}}$$

A criterion for the solution to this problem is that all units on economic dispatch should operate at equal incremental operating cost, that is:

$$\boxed{\frac{dC_1}{dP_1} = \frac{dC_2}{dP_2} = \dots = \frac{dC_N}{dP_N}} \quad \text{--- (9)}$$

This can be intuitively explained as follows:

Suppose that the total output of a plant is supplied by two units and that the division of load between these units is such that the incremental fuel cost of one is higher than that of the other. Now suppose that some of the load is transferred from the unit with the higher incremental cost to the unit with the lower incremental cost. Reducing the load on the unit with the higher incremental cost will result in a greater reduction of cost than the increase in cost for adding that same amount of load to the unit with the lower incremental cost. The transfer of load can be continued with a reduction in total fuel cost until the incremental fuel costs of the two units are equal. The same reasoning can be extended to a plant with more than two units. Thus the criterion for economical division of load between units within a plant is that all units must operate at the same incremental fuel cost. If plant output is to be increased, the incremental cost at which each unit operates will rise but remain the same for all. (Stevenson 1982, 230).

The criterion which has been developed intuitively can be found mathematically using the LaGrange multiplier (Lambda) such that the above equation becomes: (Glover 1987, 362)

$$\boxed{\frac{dC_1}{dP_1} = \frac{dC_2}{dP_2} = \dots = \frac{dC_N}{dP_N} = \lambda} \quad \text{--- (10)}$$

Therefore all units have the same incremental operating cost, denoted here by  $\lambda$ , in order to minimize the total operating cost CT.

In order to explain the economic dispatch solution the following example is included by way of explanation.

EXAMPLE 1

An area of an interconnected power system has two fossil-fuel units operating on economic dispatch. The variable operating costs of these units are given by:

$$\begin{aligned} C_1 &= 10P_1 + 8E-3P_2 \quad \$/hr \\ C_2 &= 8P_2 + 8E-3P_2 \quad \$/hr \end{aligned}$$

where  $P_1$  and  $P_2$  are in megawatts. Determine the power output of each unit, the incremental operating cost, and the total operating cost  $CT$  that minimizes  $CT$  as the total load demand  $PT$  varies from 500 to 1500 MW. Generating unit inequality constraints and transmission losses are neglected. (Glover 1987, 363)

Solution

The incremental operating costs of the units are:

$$\frac{dC_1}{dP_1} = 10 + 16 \text{ EXP-3 } P_1 \quad \$/MWhr$$

$$\frac{dC_2}{dP_2} = 8 + 18 \text{ EXP-3 } P_2 \quad \$/MWhr$$

Using (EQ.9), the minimum total operating cost occurs when:

$$\frac{dC_1}{dP_1} = 10 + 16 \text{ Exp-3 } P_1 = \frac{dC_2}{dP_2} = 8 + 18 \text{ Exp-3 } P_2$$

Using  $P_2 = PT - P_1$ , the preceding equation becomes:  
 $10 + 16 \text{ Exp-3 } P_1 = 8 + 18 \text{ Exp-3 } (PT - P_1)$

Solving for  $P_1$

$$P_1 = \frac{18 \text{ Exp-3 } PT - 2}{34 \text{ Exp-3}} = 0.5294PT - 58.82 \quad \text{MW}$$

If  $PT = 500\text{MW}$

$$P_1 = 206\text{MW}$$

Substituting for  $P_1$  and finding  $\lambda$

$$\lambda = 10 + 16 \text{ Exp-3 } (206) = 13.29 \quad \$/MWh$$

Therefore using  $\lambda$  :

$$\lambda = 8 + 18 \text{ Exp-3 } (P2)$$

$$P2 = (13.29 - 8) \div 18 \text{ Exp-3}$$

$$= 5.29 \div 18 \text{ Exp-3}$$

$$= 294 \text{ MW}$$

and the minimum total operating cost/hour will be:

$$CT = C1 + C2 \text{ \$/h}$$

$$= 10P1 + 8 \text{ Exp-3 } (P1)^2 + 8P2 + 9\text{Exp-3 } (P2)^2$$

$$= 2060 + 339 + 2352 + 778$$

$$= 5529$$

The economic solution is shown below for various values of PT from 500 to 1500MW.

PT	P1	P2	dC1/dP1	CT
MW	MW	MW	\$/MWhr	\$/hr
500	206	294	13.29	5529
600	259	341	14.14	6901
700	312	388	14.99	8358
800	365	435	15.84	9899
900	418	482	16.68	11525
1000	471	529	17.53	13235
1100	524	576	18.38	15030
1200	576	624	19.22	16910
1300	629	671	20.07	18875
1400	682	718	20.92	20924
1500	735	765	21.76	23058

**2. EFFECT OF INEQUALITY CONSTRAINTS**

This means interalia each generating unit must not operate above its rating or below some minimum value. That is:

$$P_i \text{ min} < P_i < P_i \text{ max } \quad i = 1, 2 \dots N \quad \text{--- (10)}$$

When inequality constraints are included, the economic dispatch solution is modified, that is, if one or more units reach their limit values, then these units are held at their limits and the remaining units operate at equal incremental operating cost / .

EXAMPLE 2

For the following three units: (Wollenberg 1984, 26)

**Unit 1: Coal-fired Steam Unit:**

Max output = 600 MW  
Min output = 150 MW  
Input-output curve:

$$H1 \left[ \frac{\text{MBtu}}{h} \right] = 510.0 + 7.2P1 + 0.00142P12$$

**Unit 2: Oil-fired Steam Unit:**

Max output = 400MW  
Min output = 100MW  
Input-output curve:

$$H2 \left[ \frac{\text{MBtu}}{h} \right] = 310.0 + 7.85P2 + 0.00194P22$$

**Unit 3: Oil-fired Steam Unit:**

Max output = 200 MW  
Min output = 50 MW  
Input-output curve:

$$H3 \left[ \frac{\text{MBtu}}{h} \right] = 78.0 + 7.97P3 + 0.00482P32$$

Determine the economic operating point for these three units when delivering a total of 850 MW. Before this problem can be solved, the fuel cost of each unit must be specified. Let the following fuel costs be in effect.

Unit 1: Fuel cost = 1.1 \$/MBtu  
Unit 2: Fuel cost = 1.0 \$/MBtu  
Unit 3: Fuel cost = 1.0 \$/MBtu

SOLUTION

Using equation 5,

$$F1 = H1 \text{ times fuel cost for unit 1} \\ = (510 + 7.2P1 + 0.00142P12)1.1 = 561 + 7.92P1 + 0.001562P12 \text{ \$/h}$$

Likewise for units 2 and 3

$$F2 = 310 + 7.85 P2 + 0.00194 P22 \text{ \$/h} \\ F3 = 78 + 7.97 P3 + 0.00482 P32 \text{ \$/h}$$

Therefore for optimum dispatch :

$$\frac{dF1}{dP1} = 7.92 + 0.003124P1 = \lambda$$

$$\frac{dF2}{dP2} = 7.85 + 0.00388P2 = \lambda$$

$$\frac{dF3}{dP3} = 7.97 + 0.00964P3 = \lambda$$

$$P1 + P2 + P3 = 850 \text{ MW}$$

Solving for  $\lambda$ , one obtains:  $\lambda = 9.148$  \$/MWh  
then:

$$P1 = 393.2 \text{ MW}$$

$$P2 = 334.6 \text{ MW}$$

$$P3 = 122.2 \text{ MW}$$

$$PT = 850 \text{ MW}$$

Note that all constraints are met, that is, each unit is within its high and low limit and the total output when summed over all three units meets the desired 850 MW total.

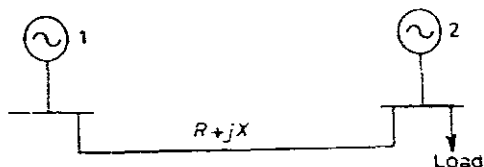
P1, P2 and P3 can be substituted into F1, F2 and F3, and the \$/h cost found for each unit.

### 3. EFFECT OF TRANSMISSION LOSSES

In case of an urban area where the load density is very high and the transmission distances are very small the transmission loss could be neglected and the optimum strategy of generation could be based on the equal incremental cost as outlined above. Whereas if the energy to be transported is over relatively larger distances with low load density, the transmission losses in some cases may amount from 20 to 30%, of the total load and it then becomes very essential to take these losses into account when developing an economic dispatch strategy.

Before an optimum strategy for load scheduling is derived, the need for inclusion of losses is further stressed by the following explanation: (Wadhwa 1991, 653).

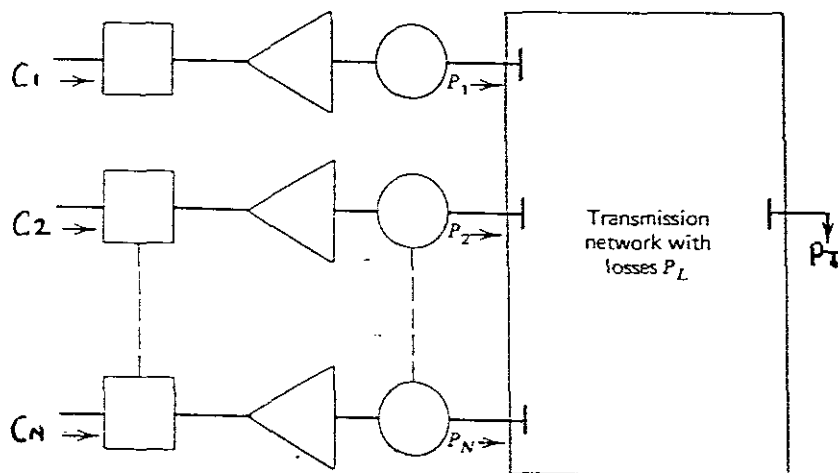
Figure 9 consists of two identical generators each with identical incremental costs.



TWO IDENTICAL GENERATORS CONNECTED THROUGH A TRANSMISSION LINK

FIGURE.9

If generator 2 has a local load, according to equal incremental criterion, the total load must be shared equally by both generators, that is, each generator should supply half of the total load. The common sense tells us that it is more economical to let generator 2 supply most of the local load because generator 1 has to supply in addition to the load, the transmission losses also. Therefore, the criterion of sharing the load by equal incremental cost does not hold good under such situations and a strategy must be evolved which takes into account the transmission losses also. The economic dispatching problem associated with Figure.9 or in general, as shown in Figure.10, is more complicated than the previous cases.



N THERMAL UNITS SERVING LOAD THROUGH TRANSMISSION NETWORK

FIGURE. 10

Where:  $C_1, C_2$  and  $C_N$  are fuel costs  
 $P_1, P_2$  and  $P_N$  are output powers  
 $P_T =$  Total load power  
 $P_L =$  Transmission network losses.



When transmission losses are included in the economic dispatch problem, equation 8 becomes:

$$P_1 + P_2 + \dots + P_N - PL = PT \quad \text{--- (11)}$$

In general: PL is not constant but depends on the unit outputs P1, P2 - - - - PN.

For this "N" number of units system, the economic criterion, including transmission losses becomes:

$$\lambda = \frac{dC_i}{dP_i} \left[ \frac{1}{1 - \frac{PL}{P_i}} \right] \quad i = 1, 2, \dots, N \quad \text{--- (12)}$$

Each unit that is not at a limit value operates such that its incremental operating cost dCi/dPi multiplied by a "PENALTY FACTOR Li" is the same.

NB! Note that when transmission losses are negligible,  $\partial PL / \partial P_i = 0$  and  $L_i = 1$  and equation (12) reduces to equation (10).

NB! Note that when transmission losses are included,  $\lambda$  as given by equation (12) is no longer the incremental operating cost of equation (8), instead  $\lambda$  is the unit incremental operating cost dCi/dPi multiplied by the unit penalty factor Li.

EXAMPLE 3

If total transmission losses for the power-system area given in Example 1 are given by:

$$PL = 1.5E-4P_1^2 + 2E-5P_1P_2 + 3E-5P_2^2 \quad \text{MW}$$

where P1 and P2 are given in megawatts. Determine the output of each unit, total transmission losses, total load demand, and total operating cost CT when the area  $\lambda = 16.00$  \$/MWh.

**SOLUTION**

Using the incremental operating costs from Example 1:

$$\frac{dC_1}{dP_1} \left[ \frac{1}{1 - \frac{PL}{P_1}} \right] = \frac{10 + 16E-3 P_1}{1 - (3E-4 P_1 + 2E-5 P_2)} = 16.00$$

$$\frac{dC_2}{dP_2} \left[ \frac{1}{1 - \frac{PL}{P_2}} \right] = \frac{8 + 18E-3 P_2}{1 - (6E-5 P_2 + 2E-5 P_1)} = 16.00$$

Rearranging the above two equations,

$$20.8E-3 P_1 + 32E-5 P_2 = 6.00$$

$$32E-5 P_1 + 18.96E-3 P_2 = 8.00$$

Solving,

$$P_1 = 282 \text{ MW} \quad P_2 = 417 \text{ MW}$$

Using the equation for total transmission losses,

$$PL = 1.5E-4(282)^2 + 2E-5(282)(417) + 3E-5(417)^2 \\ = 19.5 \text{ MW}$$

From EQ.11, the total load demand is,

$$P_T = P_1 + P_2 - PL = 282 + 417 - 19.5 = 679.5 \text{ MW}$$

Also using the cost formulas given in Example 1, the load operating cost is,

$$C_T = C_1 + C_2 = 10(282) + 8E-3(282)^2 + 8(417) + 9E-3(417)^2 \\ = 8357 \text{ \$/hr}$$

**B COEFFICIENTS**

(Stevenson 1982, 238) (Glover 1987, 367)

In example 2, total transmission losses are expressed as a quadratic function of unit output powers.

**LOSS EQUATION**

The general form of the loss equation for any number of N units is:

$$PL = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j \quad \text{--- (13)}$$

where:  $B_{ij}$  terms are called "LOSS COEFFICIENTS" or "B COEFFICIENTS".

For instance for 3 units:

$$PL = P_1^2 B_{11} + P_2^2 B_{22} + P_3^2 B_{33} + 2P_1 P_2 B_{12} + 2P_2 P_3 B_{23} + 2P_1 P_3 B_{13} \quad \text{--- (14)}$$

**LOSS MATRIX**

The matrix form of the transmission-loss equation is:

$$PL = P T B P \quad \text{--- (15)}$$

where for a total of N units:

$$P = \begin{bmatrix} P_1 \\ P_2 \\ \cdot \\ \cdot \\ P_N \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} B_{11} & B_{12} & B_{13} & \cdot & \cdot & \cdot & B_{1N} \\ B_{21} & B_{22} & B_{23} & \cdot & \cdot & \cdot & B_{2N} \\ \cdot & \cdot & \cdot & & & & \cdot \\ \cdot & \cdot & \cdot & & & & \cdot \\ B_{N1} & B_{N2} & B_{N3} & & & & B_{NN} \end{bmatrix} \quad \text{--- (16)}$$

The B coefficients are not truly constant, but vary with unit loadings. However the B coefficients are often constant in practice since the calculation of  $PL / P_i$  is thereby simplified. Using equation (13):

$$\frac{PL}{P_i} = \sum_{j=1}^N B_{ij} P_j \quad \text{--- (17)}$$

NB! This equation 17 can be used to compute the penalty factor  $L_i$  in equation 12.

Various methods of B coefficients from power flow studies are available. In practice more than one set of B coefficients may be used during a daily load cycle.

When the unit incremental cost curves are linear, an analytic solution to the economic dispatch problem is possible as illustrated by the above examples. However in practice the incremental cost curves are **non-linear** and contain **discontinuities** (see Figure 4).

In this case, an iterative solution by digital computer can be obtained.

TABLE VERSUS POLYNOMIALS

Such an iterative solution (Glover 1987, 367) assumes that the incremental cost curves are stored in **tabular form**, such that a unique value of  $P_i$  can be read for each  $dC_i/dP_i$ .

Instead of having their values stored in **tabular form** for this procedure, the incremental cost curves could instead be represented by non-linear functions such as **polynomials**. This means that each unit output  $P_i$  would be computed from the non-linear functions instead of being read from a table.

EXAMPLE 4

Starting with the same units and fuel costs as in Example 2, we will include a simplified loss expression.

$$PL = 0.00003 P_{12} + 0.00009 P_{22} + 0.00012 P_{32}$$

This simplified loss formula will suffice to show the difficulties in calculating a dispatch for which losses are accounted. Note that real-world loss formulas are more complicated than the one used in this example.

Applying EQ 12:

$$\frac{dF_1}{dP_1} = \lambda \left[ 1 - \frac{PL}{P_1} \right]$$

becomes

$$7.92 + 0.003124P_1 = \lambda [1 - 2(0.00003)P_1]$$

Similar for  $P_2$  and  $P_3$ ,

$$\begin{aligned} 7.85 + 0.00388 P_2 &= \lambda [1 - 2(0.00009)P_2] \\ 7.97 + 0.00964 P_3 &= \lambda [1 - 2(0.00012)P_3] \end{aligned}$$

and

$$P_1 + P_2 + P_3 - 850 - PL = 0$$

We no longer have a set of linear equations as in Example 2. This necessitates a more complex solution procedure as follows.

- Step 1** Pick a set of starting values for P1, P2 and P3 that sum to the load.
- Step 2** Calculate the incremental losses  $\delta PL / \delta P_i$  as well as the total losses PL. The incremental losses and total losses will be considered constant until we return to step 2.
- Step 3** Calculate the value of  $\lambda$  that causes P1, P2 and P3 to sum to the total load plus losses. This is now as simple as the calculations in Example 2 since the equations are again linear.
- Step 4** Compare the P1, P2 and P3 from step 3 to the values used at the start of step 2. If there is no significant change in any of the values, go to step 5, otherwise go back to step 2.
- Step 5** Done.

Using this procedure, we obtain

- Step 1** Pick the P1, P2 and P3 starting values as

$$\begin{aligned} P1 &= 400.0 \text{ MW} \\ P2 &= 300.0 \text{ MW} \\ P3 &= 150.0 \text{ MW} \end{aligned}$$

- Step 2** Incremental losses are

$$\frac{\delta PL}{\delta P1} = 2(0.00003)400 = 0.0240$$

$$\frac{\delta PL}{\delta P2} = 2(0.00009)300 = 0.0540$$

$$\frac{\delta PL}{\delta P3} = 2(0.00012)150 = 0.0360$$

Total losses are 15.6 MW

- Step 3** We can now solve for  $\lambda$  using the following.

$$\begin{aligned} 7.92 + 0.003124 P1 &= \lambda (1 - 0.0240) = \lambda (0.9760) \\ 7.85 + 0.00388 P2 &= \lambda (1 - 0.0540) = \lambda (0.9460) \\ 7.97 + 0.00964 P3 &= \lambda (1 - 0.0360) = \lambda (0.9640) \end{aligned}$$

and

$$P1 + P2 + P3 - 850 - 15.6 = P1 + P2 + P3 - 865.6 = 0$$

These equations are now linear, so we can solve for  $\lambda$  directly.

The results are:

$$\lambda = 9.5252 \text{ \$/MWh}$$

and the resulting generator outputs are

$$\begin{aligned} P_1 &= 440.68 \\ P_2 &= 299.12 \\ P_3 &= 125.77 \end{aligned}$$

**Step 4** Since these values for P1, P2 and P3 are quite different from the starting values, we will return to step 2.

**Step 2** The incremental losses are recalculated with the new generation values.

$$\frac{\Delta PL}{\Delta P_1} = 2(0.00003)440.68 = 0.0264$$

$$\frac{\Delta PL}{\Delta P_2} = 2(0.00009)299.12 = 0.0538$$

$$\frac{\Delta PL}{\Delta P_3} = 2(0.00012)125.77 = 0.0301$$

Total losses are 15.78 MW

**Step 3** The new incremental losses and total losses are incorporated into the equations, and a new value of  $\lambda$  and P1, P2 and P3 are solved for

$$\begin{aligned} 7.92 + 0.003124 P_1 &= \lambda (1 - 0.0264) = \lambda (0.9736) \\ 7.85 + 0.00388 P_2 &= \lambda (1 - 0.0538) = \lambda (0.9462) \\ 7.97 + 0.00964 P_3 &= \lambda (1 - 0.0301) = \lambda (0.9699) \end{aligned}$$

$$P_1 + P_2 + P_3 - 850 - 15.78 = P_1 + P_2 + P_3 - 865.78 = 0$$

resulting in  $\lambda = 9.5275 \text{ \$/MWh}$  and

$$\begin{aligned} P_1 &= 433.94 \text{ MW} \\ P_2 &= 300.11 \text{ MW} \\ P_3 &= 131.74 \text{ MW} \end{aligned}$$

·  
·  
·

A summary of the iterative process used to solve this problem is as follows:

Iterative Process Used

Iteration	P1(MW)	P2(MW)	P3(MW)	Losses(MW)	Lambda (\$/MWh)
Start	400.00	300.00	150.00	15.60	9.5252
1	440.68	299.12	125.77	15.78	9.5275
2	433.94	300.11	131.74	15.84	9.5285
3	435.87	299.94	130.42	15.83	9.5283
4	435.13	299.99	130.71	15.83	9.5284

NB! There is no significant change from 3 to 4 therefore problem is solved. (See Step 4 above).

**THE LAMBDA - ITERATION METHOD OR LAMBDA SEARCH METHOD**

This lambda iterative search method of solution is for all thermal dispatching problems neglecting losses. (Wolenberg 1984, 33).

This procedure is an iterative type of computation and converges very rapidly for this particular type of optimization problem.

**EXAMPLE 5**

Assume that one wishes to use cubic functions to represent the input/output characteristics of generating plants as follows:

$$H(\text{MBtu/h}) = A + BP + CP^2 + DP^3 \quad (P \text{ in MW}) \quad [\text{Order 3 Polynomial}]$$

For the three units, find the optimum schedule using the lambda-iteration method, (the lambda search method) if the polynomial has the following ABCD coefficients:

	A	B	C	D
Unit 1	749.55	6.95	9.68E-4	1.27E-7
Unit 2	1285.0	7.051	7.375E-4	6.453E-8
Unit 3	1531.0	6.531	1.04E-3	9.98 E-8

Assume the fuel cost to be 1.0 \$/MBtu for each unit and unit limits as follows:

$$\begin{aligned} 320 \text{ MW} &\leq P_1 \leq 800 \text{ MW} \\ 300 \text{ MW} &\leq P_2 \leq 1200 \text{ MW} \\ 275 \text{ MW} &\leq P_3 \leq 1100 \text{ MW} \end{aligned}$$

In this method, the value for  $\lambda$  on the second iteration is always set at 10% above or below the starting value depending on the sign of the error. The iterations for PT = 2500 MW and if  $\lambda$  start = 8 \$/MWh are:

Iteration	Lambda	Total generation			P3
		(MW)	P1	P2	
1	8.0000	1731.5	494.3	596.7	640.6
2	8.8000	2795.0	800.0	1043.0	952.0
3	8.5781.	2526.0	734.7	923.4	867.9
4	8.5566	2497.5	726.1	911.7	859.7
5	8.5586	2500.0	726.9	912.7	860.4

**4. OTHER TYPES OF UNITS OTHER THAN THERMAL UNITS** (Glover 1987,368)

The economic dispatch criterion has been derived for a power system area consisting of fossil-fuel generating units. In practice however, an area has a mix of different types of units including fossil-fuel, nuclear, pumped storage hydro, hydro and other types.

Nuclear units have low operating costs due to inexpensive nuclear fuel. Hydro power management is especially complex since it is difficult to assign a cost to water (Cegrell 1986, 281).

Hydro-electric units have input-output characteristics similar to steam turbine units and nuclear plants will be treated in this chapter as if they are ordinary thermal-generating units fueled by fossil-fuels. (Wollenberg 1984, 14).



**A. EXPLANATION OF THE USAGE OF THE WOODS-WOLLENBERG PROGRAM "EDC" FOR ECONOMIC DISPATCH**

The "EDC" program allows a user to experiment with two commonly used economic dispatch solution algorithms (lambda search or table lookup) using three different generating heat rate or incremental heat curve representations (POLY, PINC and PIO). See below for further details.

**INPUT DATA  
CREATING, STORING, DISPLAYING, PRINTING,  
UPDATING AND MAXIMUM PROGRAM DIMENSIONS**

On entering into the program, it prompts and asks if you want output on a printer (Y or N) and then asks for the name of the "INPUT FILE" that you will be using.

It is therefore necessary to create an "Input Data File" first before even using this program.

For example : bus16.dat

Before describing the format of a typical "Input Data File" required by this program, the following is introduced.

From above:

**POLY:** Stands for **polynomial curve representation** of the heat rate function. That is, the curve represents the function:

$$H(P) = A + BP + CP^2 + DP^3 + . . . . . - - - (18)$$

The input file must contain the order for this polynomial. If the order is set to 2 the file must specify coefficients A, B, and C. If the order is set to 3 the file must specify A, B, C, and D. Etc.

**PINC** Stands for **piecewise incremental heat rate curve**. The curve is represented by a series of points connected by straight line segments. The number of segments in the curve is determined by the order parameter. Each point requires a MW value and an incremental heat rate value. The input file then must contain points such as the table below:

MW	Inc. Heat Rate
P1	IHR1
P2	IHR2
P3	IHR3

This example has an order of 2 since the three points specify two segments.

The user is cautioned that the first points MW value ought to be equal to the unit low limit and the last MW point equal to the unit high limit.

In addition:

$P(I) < P(I+1)$ $IHR(I) < IHR(I+1)$
--

for all points in the curve.

**PIO:** Stands for piecewise Input/Output curve. Here the unit's heat rate curve is represented as a series of points connected by straight line segments. The number of segments in the curve is determined by the order parameter. Each point requires a MW value and a heat rate value. The input file then must contain points such as the table below:

MW	Inc. Heat Rate
P1	HR1
P2	HR2
P3	HR3
P4	HR4

This example has an order of 3 since the four points specify three segments.

The user is cautioned that the first point's MW value ought to be equal to the unit low limit and the last MW point to the unit high limit.

In addition:

$P(I) < P(I+1)$ $HR(I) < HR(I+1)$
--------------------------------------

for all points in the curve.

**LOSS REPRESENTATION:**

Network losses may be ignored or may be presented by fixed penalty factors or by a loss matrix (B Matrix). The format for entering the loss representation type and values is given in the section on file format.

**INPUT DATA FILE FORMAT:**

The format for the input data file is as follows:

The first two lines are file labels and may be any character string up to 80 characters long.

The third line contains four parameters. They are:

- FIRST PARAMETER = The number of generating units represented.
- SECOND PARAMETER = The type of curve used to represent the unit. This parameter is limited to three different character string values of POLY or PINC or PIO as explained above.
- THIRD PARAMETER = Contains an integer of 1 to 10 giving order of the curve as explained above.
- FOURTH PARAMETER = The loss representation. This parameter is limited to three different character string values of NOLOSS or CONSTPF or LOSSFORM denoting no loss, constant penalty factors and loss matrix respectively.

Next comes the unit data. Each unit has one line of data giving the unit's name (an alphanumeric string up to 9 characters), its low MW limit, its high MW limit and its fuel cost. Each variable is separated by a space. Next each polynomial curve coefficient or each piecewise curve breakpoint is given with each value on a separate line.

Your "EDC" disk contains sample files. "Dir" to determine sample files stored. Existing files can be DISPLAYED and PRINTED. The file below is from such a sample. The arrow <----- will be used together with lower case text to show comments only (nothing to the right of the arrow nor the arrow itself is actually on the file). NB! Make a hard copy from your disk to ensure exact format.

```

FILE EX3A.DAT--DATA FOR EXAMPLE 3A IN TEXT <--1st Header line
-----<--2nd Header line
3 POLY 2 NOLOSS <--No of units/curve type/curve order/loss type
UNIT1 150.0 600.0 1.1 <---- start of first unit's data
510.0      <----- A coefficient for polynomial for first unit
7.2        <----- B coefficient
0.00142    <----- C coefficient
UNIT2 100.0 400.0 1.0 <----- Start of second unit's data
310.0
7.85
0.00194
UNIT3 50.0 200.0 1.0 <----- Start of third unit's data
78.0
7.97
0.00482

```

TABLE.1

LINES 1 AND 2

The first line is a file label. Here "text" refers to Ex.3A in Wollenberg 1984, 26 and which was solved by hand in EXAMPLE 2 in the previous section of this chapter.

Two lines can be used if necessary. In the above format the 2nd header line is merely a line of dashes. (HEADER LINES)

LINE 3

The third line contains four parameters.

FIRST PARAMETER : "3" Generating units. - (NO. OF GEN UNITS)  
SECOND PARAMETER : Type of curve used - "POLY" -(CURVE TYPE)  
THIRD PARAMETER : Curve Order-Order "2" polynomial-(CURVE ORDER)  
FOURTH PARAMETER : Loss Representation - "NOLOSS" - (LOSS TYPE)

LINE 4

Contains Unit Data

FIRST DATA : Unit name - "UNIT 1" (An alphanumeric name, max 9ch)  
- (UNIT NAME)  
SECOND DATA : Low Limit - "150.0" - (LOW MW Limit)  
THIRD DATA : High Limit - 600.0 - (High MW Limit)  
FOURTH DATA : Fuel Cost - 1.1 - (Fuel Cost)

NB! Each variable is separated by a space.

FOLLOWING LINES

Next each polynomial curve coefficient or each piecewise curve breakpoint is given with each value on a separate line.

"A" COEFFICIENT : 510.0  
"B" COEFFICIENT : 7.2 (CURVE COEFFICIENTS)  
"C" COEFFICIENT : 0.00142

Line 4 is then repeated for each of the remaining units.

The next example shows unit data having a piecewise heat curve with five segments is represented on the input file.

```
FILE EDC3.DAT ----- PIECEWISE INPUT/OUTPUT CURVES, NO LOSSES

3 PIO 5 NOLOSS
UNIT1 100.0 200.0 1.0
100.0 10200.0 <-----MW and heat rate point values
120.0 14620.0
140.0 19840.0
160.0 25860.0
180.0 32680.0
200.0 40300.0
UNIT2 50.0 300.0 1.0
50.0 10000.0
100.0 15000.0
150.0 22500.0
200.0 32500.0
250.0 45000.0
300.0 60000.0
UNIT3 200.0 700.0 1.0
200.0 10000.0
300.0 15000.0
400.0 21000.0
500.0 28000.0
600.0 36000.0
700.0 45000.0
```

The next example shows how to input constant penalty factors into the data file.

```
FILE EDC4.DAT --- POLYNOMIAL CURVES, CONSTANT PENALTY FACTORS

3 POLY 2 CONSTPF
UNIT1 100.0 200.0 1.0
100.0
1.0
1.0
UNIT2 50.0 150.0 1.0
100.0
1.0
1.0
UNIT3 200.0 450.0 1.0
10.0
1.0
1.0 <----- Last line of unit 3 data
1.0 1.2 1.0 <----- Penalty factors listed in order of units.
                        (Unit 1 penalty factor = 1.0, unit 2
                        penalty factor = 1.2, etc.)
```

Finally the next example shows how to enter a lossformula with the unit data.

FILE EDC5.DAT----- POLYNOMIAL CURVES, B MATRIX LOSS FORMULA				
3	POLY	2	LOSSFORM	
UNIT1	100.0	200.0	1.0	
	100.0			
	1.0			
	1.0			
UNIT2	50.0	150.0	1.0	
	100.0			
	1.0			
	1.0			
UNIT3	200.0	450.0	1.0	
	10.0			
	1.0			
	1.0			<-----Last line of unit 3 data
	0.005			<-----BOO Coefficient
	0.005	0.005	0.01	<-----B1, B2, B3 coefficients
	0.01	0.005	0.005	<-----B11, B12, B13
	0.005	0.01	0.005	<-----B21, B22, B23
	0.005	0.005	0.02	<-----B31, B32, B33

Note that the Loss formula coefficients are entered as follows: The first line contains the BOO coefficient. The second contains the B(I) coefficients for I = 1 to the number of generators, the matrix portion of the formula is stored row by row. There will be as many rows as there are units.

Once the data has been created it is saved and "STORED" in its "Input Data File" (e.g. bus16.dat) ready for use by the EDC program.

Once a file has been created it can be "UPDATED" by calling up the "Input Data File", making the necessary changes, additions or subtractions, then saving it by storing it in its file. Alternately an existing file can be copied over into a created file which is then updated and stored.

NB! It is not possible to update an "Input Data File" when running the EDC program. The program however prints the Input Data File as part of its printout facility.

**PROGRAM MAXIMUM DIMENSIONS:**

Maximum no. of generator units	= 20
Maximum no. of points of piecewise linear curve segments	= 10
Maximum no. of polynomial coefficients	= 10

**RUNNING THE PROGRAM**

**USER OPTIONS :**

When a data file is complete the user runs the EDC program by entering EDC and then hitting enter.

First the program asks if the user wants to display the program output on the printer or the CRT.

The program then prompts for the data file to be read. The user should enter the file name followed by the ENTER key. (Note all entries into the program assume the user enters a number or letter(s) followed by ENTER).

The solution method allows the user to select either lambda search or table lookup. Note that search is appropriate for polynomial or piecewise incremental heat rate curves and table lookup should be used for piecewise heat rate curve.

Diagnostic printout can be obtained by answering Y or N to the next question and will show the results of the lambda search.

The schedule type allows the program to match total generation to a fixed total generation value (option 1) or matches the total generation to the load plus losses (option 2).

If option 1 is selected the user is prompted for the MW total generation to use.

If option 2 is selected the user enters the total load. If the loss formula is used the program calculates the losses and adds it to the load MW as the target total generation.

The program then prints the file header followed by a printout of the unit and loss formula data. After the solution is complete the program prints out a summary of the generation. The user is asked if another run of EDC is desired and can enter Y or N to continue or not. If Y entered, the user can opt to read a new data file or use the one previously read.

**OUTPUT DATA**

**NB!** In order to understand the above and to explain the output data provided, a program execution sample is given by way explanation.

**PROGRAM EXECUTION SAMPLE  
COMPUTER SOLUTION OF  
EXAMPLE 2 OF THE PREVIOUS SECTION  
OF THIS CHAPTER 4**

The example is a 3 unit system having no-losses but having maximum and minimum output power constraints. Its heat rate, input-output curves are order 2 polynomials having A, B, and C coefficients. Fuel costs for each unit are also given. The total generation is 850 MW. Obtain the economic dispatch solution.

Before executing the EDC program, "DIR" the EDC directory and obtain a list of the data files. Call up these data files one by one and determine which one matches the above input data (for example Ex3A.DAT). Exit and execute the EDC program. Follow the following steps:

**SAMPLE PROGRAM EXECUTION:**

edc <----- user starts program

Do you want output on the printer? (y or n) y <-----user asks for printer

Enter name of input file? ex3a.dat <----- user enters file name  
(On some disks ex3A.dat is called DAT1.dat)

Please enter solution method:

- 1 = lambda search
- 2 = table lookup (pio curves only)

Enter 1, or 2 : ? 1 <----- user enters solution option

Do you want diagnostic printout? (y or n):? y <--- user selects diagnostics

Please enter schedule type

- 1 = total generation (MW)
- 2 = total load (MW)

Enter schedule type ? 1 <-----user selects schedule type

Enter total generation (MW):? 850 <-----user selects total MW

The output below appears on either the crt or the printer.



FILE EX3A.DAT-DATA FOR EXAMPLE3A IN TEXT <-start of data printout

-----  
Number of generator units = 3  
Unit curve type = poly  
Curve order = 2  
Network loss representation = no loss  
UNIT1 Limits = 150 600 fuelcost = 1.1  
Curve coefficients

510.0000  
7.2000  
0.0014

UNIT2 limits = 100 400 fuelcost = 1  
Curve coefficients

310.0000  
7.8500  
0.0019

UNIT3 limits = 50 200 fuelcost = 1  
Curve coefficients

78.0000  
7.9700  
0.0048

Using lambda search

Total generation schedule = 850.0

Loss neglected

Lambda limits = 8.238 9.898 <--start of diagnostic output

Lambdastart deltalambda = 9.068 .83

Targetgen = 850

Lambda	= 9.068	totalgen = 795.2956	<--iteration on lambda
Lambda	= 9.898	totalgen = 1200	
Lambda	= 9.483	totalgen = 1057.27	
Lambda	= 9.275499	totalgen = 936.7207	
Lambda	= 9.171749	totalgen = 866.0078	
Lambda	= 9.119874	totalgen = 830.6513	
Lambda	= 9.145811	totalgen = 848.3291	
Lambda	= 9.15878	totalgen = 857.1684	
Lambda	= 9.152296	totalgen = 852.749	
Lambda	= 9.149054	totalgen = 850.539	
Lambda	= 9.147432	totalgen = 849.4342	
Lambda	= 9.148243	totalgen = 849.9868	

Generator	output mw	limit	inc cost \$/mwhr	penalty fact	op.cost \$/hr	<-output
Unit1	393.2		9.148	1.000	3916.31	
Unit2	334.6		9.148	1.000	3153.80	
Unit3	122.2		9.148	1.000	1124.13	
-----	-----				-----	
totals	850.0				8194.24	
Lambda	=	9.14824				

(NB! Confirms Example 2.) This is not part of program solution.

Do you want to run EDC again? (Y or N): ? N <--user does not re-execute.

NB! Note that all constraints are met and that the answers obtained by the computer agree with those obtained by hand calculations.

**PROGRAM OUTPUT DATA**

From the above it can be seen that the economic dispatch solution is given in terms of the headings:

GENERATOR	OUTPUT	LIMIT	INC COST	PENALTY	FACT	OPERATING	COST
	MW		\$/MWh			\$/h	

It also gives lambda value.

**B. EXPERIMENTATION USING THE PROGRAM**

**INFORMATION AVAILABLE:**

The one-line diagram of the 16 bus, 3 generator, 14 line and 5 transformer system as shown in Figure 1 as well as Tables 1 to 6 form the basis of the information available.

**EXPERIMENTAL REQUIREMENTS:**

**PART ONE**

- a. Create an "Input Data File" (16bus.dat) from the information available and obtain a printout of its format. Explain why you have chosen the specific format and the value for its parameters?
- b. Use the "EDC" program and the base load condition results obtained by the "LOADFLOW" program in Chapter One and obtain:
  - (1) A printout of the Input Data confirming "a" above.
  - (2) The lambda limits, lambda start and delta lambda values.
  - (3) The lambda values for each iterative step and its corresponding total generation value. How many iterations has the program taken for its solution?
  - (4) The economic dispatch solution. What are the MW outputs, the incremental costs (\$/MWh) and the operating costs (\$/hr) for each of the 3 units for this solution. Is equation 10 satisfied, if so, what is the value for lambda which satisfies this equation?
  - (5) The value for the total operating cost in \$/h for this 16 bus power system.

**PART TWO  
SELF EVALUATION**

- c. Repeat the "PART ONE" experimental requirements but for a reduction in the coal price from 1 to 0.9 \$/MBTU. Compare the total operating costs in \$/h for these two case studies.

**NB! Note that unit 1 is a fossil-fuel unit, that unit 2 is a nuclear unit and that unit 3 is a hydro unit.**

SOLUTION

PART ONE

a. CREATION - INPUT DATA FILE

The 16 bus power system has 3 generators (Table 1):

Unit 1 - G1	- FOSSIL	- 270 MVA	- 50MW(MIN)	- 200MW(MAX)
Unit 2 - G2	- NUCLEAR	- 245 MVA	- 35MW(MIN)	- 300MW(MAX)
Unit 3 - G3	- HYDRO	- 260 MVA	- 25MW(MIN)	- 250MW(MAX)

The input-output curves, curve order, A, B, C coefficients and fuel costs (Table 5 b) are:

No	Input/Output Curve	Order	Coefficients	Fuel Cost
1	Polynomial	2	a = 105 b = 1.5 c = 0.0015	1.0
2	Polynomial	2	a = 225 b = 1.6 c = 0.00142	1.0
3	Polynomial	2	a = 130 b = 1.35 c = 0.004	1.0

The format for the "Input Data File" is as follows:

```
FILE BUS16.DAT ----- DATA FOR 16 BUS POWER SYSTEM  
  
3 POLY 2 NOLOSS  
UNIT1 50.0 200.0 1.0  
105.0  
1.5  
0.00150  
UNIT2 35.0 300.0 1.0  
225.0  
1.6  
0.00142  
UNIT3 25.0 250.0 1.0  
130.0  
1.35  
0.00400
```

The above format is chosen as the input-output curves are polynomial. No-loss is selected as the scheduled total MW generation for the 16 bus system is to be used. It is not necessary to determine the losses for the system as this is available from the "LOADFLOW" results.

The values chosen for the parameters are derived from Tables 1 and 5b. (See above for a summary of the required parameters).

**b. ECONOMIC DISPATCH SOLUTION**

The above created file is stored on the EDC disk.

A:\>EDC

(1) Input Data:

Do you want output on the printer ? (y or n) : y

Enter name of input file: bus16.dat

Please enter solution method:

1 = lambda search

2 = table lookup (pio curves only)

Enter 1 or 2 : 1

Do you want diagnostic printout ? (y or n) : y

Please enter schedule type

1 = total generation (mw)

2 = total load (mw)

Enter schedule type : 1

**NB!** At this point the program will prompt for the total MW generation. The total generation to be used is obtained from the "LOADFLOW" program base load conditions in Chapter One.

**See d(iv) solution of Chapter One, namely:**

$$\begin{aligned} \text{MW GEN} &= \text{MW LOAD} + \text{MW LOSSES} \\ &= 300 + 0.84 \\ &= 300.84 \text{ MW} \end{aligned}$$

As the MW losses are known it is not necessary to use the program to determine these losses. "No-loss" was therefore included in the input data file.

Now proceeding:

Enter total generation (MW) : 300.84  
and the program automatically prints out the Input Data, namely:

```

FILE BUS16.DAT-----DATA FOR BUS 16 POWER SYSTEM

Number of generator units = 3
Unit curve type           = poly
Curve order               = 2
network loss representation = noloss

UNIT1 Limits 50.00 200.00 fuelcost = 1.0000
polynomial coefficients
105.0000
 1.5000
 0.0015

UNIT2 Limits 35.00 300.00 fuelcost = 1.0000
polynomial coefficients
225.0000
 1.6000
 0.0014

UNIT3 limits 25.00 250.00 fuelcost = 1.0000
polynomial coefficients
130.0000
 1.3500
 0.0040
using lambda search

Total generation schedule = 300.8
losses neglected

```

The above printout confirms "a".

(11)

```

lambda limits = 1.5500 3.3500
lambdastart deltalambda = 2.4500 0.9000
targetgen = 300.8

```

(111)

```

lambda = 2.4500 totalgen 636.8
lambda = 1.5500 totalgen 110.0
lambda = 2.0000 totalgen 388.8
lambda = 1.7750 totalgen 206.4
lambda = 1.8875 totalgen 297.6
lambda = 1.9437 totalgen 343.2
lambda = 1.9156 totalgen 320.4
lambda = 1.9016 totalgen 309.0
lambda = 1.8945 totalgen 303.3
lambda = 1.8910 totalgen 300.4
lambda = 1.8928 totalgen 301.9
lambda = 1.8919 totalgen 301.1
lambda = 1.8915 totalgen 300.8
lambda = 1.8917 totalgen 301.0
lambda = 1.8916 totalgen 300.9
lambda = 1.8915 totalgen 300.8

```

**16 Iterations  
taken for the  
solution**

(1V)

generator	output mw	limit	inc cost \$/mwhr	penalty fact	op cost \$/hr
UNIT1	130.5		1.8915	1.0000	326.30
UNIT2	102.6		1.8915	1.0000	404.19
UNIT3	67.7		1.8915	1.0000	239.71
-----	-----				-----
totals	300.8				970.20
lambda	1.8915				

Equation 10 is satisfied as  $\lambda = 1.8915$  is the same for each unit.

(V) Total operating cost = 970.6 \$/hr

PART TWO

C. ECONOMIC DISPATCH SOLUTION - REDUCED COAL PRICE

Only unit 1 uses coal, therefore only its fuel price is reduced to 0.9.

FILE BUS16A.DAT-DATA FOR 16 BUS POWER SYSTEM REDUCED FUEL PRICE

3	POLY	2	NOLOSS
UNIT1	50.0	200.0	0.9
	105.0		
	1.5		
	0.00150		
UNIT2	35.0	300.0	1.0
	225.0		
	1.6		
	0.00142		
UNIT3	25.0	250.0	1.0
	130.0		
	1.35		
	0.00400		

FILE BUS16A.DAT-DATA FOR BUS 16 POWER SYSTEM REDUCED FUEL PRICE

Number of generator units = 3  
Unit curve type = poly  
Curve order = 2  
network loss representation = noloss

UNIT1 Limits = 50.00 200.00 fuelcost = 0.9000  
polynomial coefficients  
105.0000  
1.5000  
0.0015

UNIT2 Limits = 35.00 300.00 fuelcost = 1.0000  
polynomial coefficients  
225.0000  
1.6000  
0.0014

UNIT3 limits = 25.00 250.00 fuelcost = 1.0000  
polynomial coefficients  
130.0000  
1.3500  
0.0040  
using lambda search

Total generation schedule = 300.8  
losses neglected

lambda limits = 1.4850 3.3500  
lambdastart dotalambda = 2.4175 0.9325  
targetgen = 300.8

lambda =	2.4175	totalgen	621.3
lambda =	1.4850	totalgen	110.0
lambda =	1.9512	totalgen	398.8
lambda =	1.7181	totalgen	224.0
lambda =	1.8347	totalgen	322.7
lambda =	1.7764	totalgen	273.3
lambda =	1.8055	totalgen	298.0
lambda =	1.8201	totalgen	310.4
lambda =	1.8128	totalgen	304.2
lambda =	1.8092	totalgen	301.1
lambda =	1.8074	totalgen	299.6
lambda =	1.8083	totalgen	300.4
lambda =	1.8087	totalgen	300.7
lambda =	1.8090	totalgen	300.9
lambda =	1.8088	totalgen	300.8



generator	output mw	limit	inc cost \$/mwhr	penalty fact	op cost \$/hr
UNIT1	169.9		1.8088	1.0000	362.91
UNIT2	73.5		1.8088	1.0000	350.34
UNIT3	57.4		1.8088	1.0000	220.59
-----	-----				-----
totals	300.8				933.84
lambda	1.8088				

NB! It can be seen that the total operating costs decrease from 970.20 to 933.84 \$/h

-----END-----

**BIBLIOGRAPHY**

**SOFTWARE PROGRAMS**

GLOVER:

- a. "POWERFLOW" PROGRAM.
- b. "SYMMETRICAL SHORT CIRCUITS" PROGRAM.
- c. "SHORT CIRCUITS" PROGRAM.
- d. "TRANSIENT STABILITY" PROGRAM.

WOODS-WOLLENBERG:

- a. "LOADFLOW" PROGRAM.
- b. "EDC" ECONOMIC DISPATCH PROGRAM.

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