INNOVATIVE TECHNIQUES OF EMPLOYING SMALL HYDROPOWER PLANTS IN DISTRIBUTED ELECTRICITY GENERATION

ABRAHAMAN SALUM GUJI KILIMO

Cape Peninsula
University of Technology

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By

ABRAHAMAN SALUM GUJI KILIMO

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DECLARATION

I, Abrahaman Kilimo, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

Electricity is the most convenient form of energy. It can be easily transported to long distances and converted into other forms of energy that is required for any technological process. The impact of availability of electricity on a society touches health, education, economic prosperity, living standard of people etc. The generation of electricity using hydropower started with waterwheels as prime mover which led to the development of modern day hydraulic turbines which caused rapid construction of large hydro schemes for bulk electricity generation in the 20th century. Later electricity generation was dominated by fossil powered power plants. In this race small hydro schemes were found to be comparatively uneconomical and hence partially abandoned.

Escalation of prices of fossil fuels and environmental concerns has made people to seek alternative energy sources and preferably renewable sources. Hydro power both large and small is the most effective renewable energy source and small hydro causes negligible stress to the environment. Adding to current achievements in the fields of civil engineering works, machines and power electronics, small hydro has become an attractive alternative energy source. For developing countries like Tanzania, small hydro can enhance efforts of electrification of rural communities.

The research study explores techniques of implementing low cost small hydropower plant by using a combination of synchronous and induction generators in an autonomous installation. The control strategies for synchronous generator includes terminal voltage and frequency of power generated. For frequency-load control, tacho-generator, electric servomotor and servo control systems are employed to replace conventional governor to the coupled hydraulic turbine. On the other hand, control strategy for induction generator is to regulate its active power output based on the power supplied to the load connected to the power plant. The regulation is achieved by using power relay to monitor the power output of the plant and electric servomotor interfaced with servo control system to adjust mechanical power output of the turbine coupled to the induction generator. Amongst other conditions, operation of an induction machine as a generator requires the machine to be supplied with reactive power sufficient for its excitation. For this reason Static Var Compensator was included for reactive power generation to supplement that generated by synchronous generator.

A model of the proposed small hydropower plant was developed in MATLAB/Simulink environment by using physical modelling approach in which block models of machines, equipment and circuit elements available in the software toolboxes are used. Simulations of the model has shown that the plant is technically viable and demonstrated stability under

normal operation as well as in fault condition if fault clearance takes place before the critical moment determined by power angle curve for synchronous generator and power speed characteristic for induction generator.

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DEDICATION

I dedicate this thesis to my father Waziri Salimu Kilimo and my mother Mwanamisi bint Ramadhan Mkumbo your teachings and unconditional love has moulded me to who I am today. To my lovely wife Rukia bint Bashir, our cute children Beatrice, Musa and Hadija your affection made my life in Cape Town focused.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Term/Acronym	Definition/Explanation
UNDP	United Nations Development Programme.
URT	United Republic of Tanzania.
ESHA	European Small Hydropower Association.
Small Hydro	Water scheme whose maximum power is not more than 10 MW.
Small Hydropower Plant (SHP)	Small hydro used for electricity generation.
Run of river scheme	Power plant in which electric power is generated using natural runoff without flow regulation.
Weir	Low diversion structure built along the streambed in order to divert a portion of the river flow into a conveyance system.
Sedimentation tank	Container in which silt particles are made to settle at the basin floor and flushed out periodically.
Forebay	Small pond created for receiving water from conveyance system and distributing it to penstocks.
Penstock	Pressure pipe that convey water from forebay to power house.
Head	Difference between elevation of water in the forebay and tailwater (discharged water) elevation.
Power house	Structure that support generating units and their accessories.
Discharge rate	Volume of water flowing through generating units in unit time.
FACTS	Flexible AC Transmission Systems.
SVC	Static Var Compensator.
Load Frequency control (LFC)	Frequency regulation by maintaining active power balance in electric power system.
Governor	Frequency regulator.
Isochronous governor	Governor which adjusts generation frequency back to the nominal or scheduled synchronous value.
Speed-droop governor	Governor whose speed regulation characteristics provide for speed deviation ($\Delta\omega_r$) or frequency deviation (Δf) with change in power output (ΔP) of interfaced generating unit.
Electronic Load Controller (ELC)	An electronic device that maintains a constant electrical load on a generator in spite of changing user loads by varying the amount of power fed into dump load.

Electric Servomotor	A precision electric motor whose function is to cause motion in the form of rotation or linear motion in proportion to a supplied electrical command signal.
Synchronous speed	The rotational speed of the generator such that the frequency of the alternating current is precisely the same as that of the system being supplied
Alternating Current (AC)	Electric current that reveres its polarity periodically

CHAPTER ONE

Introduction

1.1 Background

Electricity is one of the critical inputs for overall development of a country as well as main infrastructural requirement for agricultural, industrial socio-economic development and employment generation in rural and remote areas (Nouni, et al., 2008:1187-1220). In another research, UNDP (2002) came to an observation, that in most parts of the world, areas without electricity are far less developed than those with electricity. This observation is also true in the case of Tanzania which has a population of about 35 million, with only 10% of its populations having access to electricity. Furthermore, rural areas are the most deprived in this matter with the access of about 1% (URT, 2003) despite of being inhabited by 80% of the country's populations and consequently less developed.

Tanzania government recognises the immense benefits of rural electrification as mentioned by Nouni et al. (2008), that supplying electricity to rural areas contributes to poverty reduction by spurring economic growth and fulfilling human needs of health and education. However, the government cannot afford the cost of electrifying rural communities because of shortage of resources which is also aggravated by the approach used in effecting the electrification of the rural areas. Electrification of rural areas in Tanzania like in most of developing countries is mainly undertaken by extension of the existing grids. This approach has proved to be feasible and cost effective only in areas with dense and concentrated populations. In other situations, the approach is physically and economically unviable (Chaurey, Ranganathan and Mohanty, 2004: 1693-1705) as it involves investment in transmission lines, poles, transformers and other infrastructure (Lhendup, 2008). The term 'rural electrification' in this context means the availability of electricity for use by rural communities irrespective of the technologies, source and form of generation (Lhendup, 2008). Therefore generation of electricity from locally available energy resources small hydropower being one of them, and connecting the communities around the generating station can be most cost effective means of electrifying rural areas which has been a concern of Tanzania and many other developing country governments. Generally wherever hydro potential is available, electrification can be effected relative cheaply because hydro energy is the most reliable and cost effective renewable energy source. This is confirmed by global assessment of contribution of renewable sources in electricity generation as depicted in Table 1.1. In addition, comparing its yielding factor with those of other renewable source plants as shown in Table 1.2 indicates that hydropower is the most valuable among renewable energy sources. Yield factor is the ratio of the quantity of energy produced by an installation during its lifetime and energy required in manufacturing the installation, its operation and disposal including secondary energy (Dragu, et al. 2001). In view of electricity generation by means of renewable sources Paish, (2002) indicated that, hydropower large and small, remains by far the most important of the renewable for electrical power production worldwide.

Table1.1: Contribution of Renewable Sources in Electricity Generation

Large hydro (>10MW)	86%
Small hydro (<10MW)	8.3%
Wind and Solar	0.6%
Geothermal	1.6%
Biomass	3.5%

Table1.2: Yield Factors of Renewable Energy Sources

Plant	Yield Factor
Large hydro	100 - 200
Small hydro	80 - 100
Photovoltaic	3 - 5
Solar (Thermal)	20 - 50
Wind power	10 - 30

Tanzania has an estimated feasible small hydro potential of about 314MW (Lyimo, 2006) distributed all over its territory; this could be exploited to generate electricity and connect people in the areas close to respective small hydropower potentials. Had this been the case, such areas would have benefited from convenience advantages the electrical energy has over other forms of energy including long distances transmission and easy conversion to a form required by the process or activity to be performed and impact on their social economic situations and living standards.

Hydro energy is based on the flow of naturally cycled water and its drop from a higher to a lower surface. The exploitation of hydropower started with the wooden waterwheel used in many parts of Europe and Asia for some 2,000 years, mostly for milling grain. Modern-day turbines are the outcome of improved engineering skills in the advent of industrial revolution and higher demand for electricity generation. The power capacity of a hydropower plant is primarily a function of water discharge and the hydraulic head; hence head and discharge are the two decisive factors in hydraulic power determination.

In discussing small hydro, one has to note that, the definition of small hydropower plant is not universal (Voros, Kiranoudis, and Maroulis, 2002:545-564, ESHA, 2004:3), however, Harvey, et al (1993), Paish, (2002) and ESHA, (2004) contend, that 10MW as upper limit of small hydropower is the mostly accepted worldwide. The same understanding of the value of 10 MW as an upper limit was adopted in this study. Also adopted is the view, that within the range of small hydropower, mini-hydro refers to schemes below 1MW and micro-hydro below 100kW.

There are several ways of classifying small hydropower plants, among them includes by their heads, mode of head concentration and flow regulation.

Basing on these classifications, most small hydropower plants are said to be mainly run of river type, although some cases involve diversion. Basically power generation in run of river plants depend on natural runoff. The civil works purely serves the function of regulating the level of water at the intake to a plant.

During their operation, hydro schemes extract water from rivers in a controllable way (Harvey et al, 1993:73) and covey it to hydraulic turbines. Hydraulic turbines that drive the electric generators convert water power into mechanical power via the rate of change of angular momentum of the water which is later converted to electrical power. Normally, it is most cost effective to have minimum number of units at a given installation. However, multiple units are employed to make most effective use of water where flow variation is great thus generators operate in parallel.

Almost all hydroelectric generators which are currently converting the mechanical power to electrical power in small hydro power plants are 3-phase ac synchronous machines with stationary armatures and salient-pole rotating field structures. The rotating magnetic field is typically produced via a dc-excited winding connected to an excitation source.

The rotational speeds of the generator and turbine are usually the same because their shafts are directly connected. In some cases, however, a speed increaser (gearbox) is used to enable the generator to operate at a higher speed than that of the turbine, thus permitting a smaller and less expensive generator to be used (Beaty, & Fink, 2007:9-11).

Induction generators are less common in small hydropower plants but are being used increasingly in micro-hydro schemes (Harvey et al, 1993:278, Boldea and Nasar, 2002:8).

The fundamental difference between induction and synchronous generators is that the magneto motive force for magnetic flux generation is principally the responsibility of rotor dc excitation on synchronous generators, whereas in induction generators, it must be supplied from stator currents.

In order to maintain a frequency of generation (50-Hz), a hydraulic turbine-synchronous generator unit must run at a constant steady state speed and when two or more generating units operate in parallel, they have to maintain synchronism as well; this is a function of respective governor interfaced with each turbine.

1.2 Statement of Research Problem

Small hydro is a renewable energy sources that can effectively answer to the question of how to offer to isolated or rural communities the benefits of electrification as compared to the traditional grid extension which has been difficult to implement in many developing countries.

Until the mid-1970s, the pattern of hydro development was to develop bigger units; small hydro was partially abandoned because of economies of scale of large hydro-schemes and low investment costs of equivalent fossil fuel powered plants. Also, availability of electrical energy from large steam power plants contributed to the status quo (Paish, 2002: 537-556). Recently, with rising cost of fossil fuels and environmental concerns renewable energy sources has come into focus. Change in implementation techniques supported by achievements in research and development on civil engineering works, machines and power electronics, have made small hydropower to be an attractive energy production alternative.

The present small hydropower plant is neither the miniature of large hydro, nor the simple repetition of old small hydropower plant technique, but a more advanced type of technique appropriated to each case (Jiandong et al, 1997). However, relatively high investment cost is still making small hydropower plants to remain unpopular to developers even in countries like Tanzania where small hydro potential is abundant and small hydropower plants could benefit majority of the populations.

1.3 Objective of the Study

The primary objective of this research work was to explore further in techniques of implementing small hydropower plants that would generate electricity with a low up-front investment cost and operated at comparatively lower running costs by introducing a combination of synchronous and induction generators and their respective control strategies and yet meet requirements of electric power generation. In this regard a small hydropower plant was to be designed employing the proposed approach. In addition, the study was to establish advantages of the proposed combination of generators and their control systems in the plant. A model of small hydropower plant which employs synchronous-induction generator combination was to be developed and investigated to determine its technical viability and verify whether operation characteristics of the plant meet power generation requirements.

1.4 Thesis Statement

Electricity generation by using a combination of synchronous and induction generators in parallel is a cost effective way of implementing a stand-alone small hydropower plant at a site whose conditions requires two or more generating units.

When synchronous generator is operated under steady-state, the frequency of the generated voltage is determined by the speed of prime-mover while its terminal voltage and power factor depend on the excitation of field winding and the connected load. Power output of the generator is a function of power angle and the dynamic characteristics are dominated by power angle swings.

Parallel operation of synchronous generators in a power system requires complex control systems to ensure that all generators operate in synchronism.

An induction generator on the other hand, when operated in an isolated power system, reactive power for excitation has to be supplied by external source. Self excitation can be achieved if suitable capacitors are connected to stator terminal of the generator. But neither frequency nor terminal voltage of a self excited induction generator (SEIG) can be controlled easily as they both depend on the speed of prime-mover. However, when connected to an AC source operating at constant voltage and frequency, the excitation reactive power is drawn from the source and active power output of the induction generator become proportional to the slip at the same time the generator exhibit dynamic characteristics that do not affect synchronism.

Application of the synchronous generator which has the ability to regulate terminal voltage, frequency and power factor together with induction generator which is cheap, robust and easy to control in implementing small hydropower plant, result into a plant whose investment cost as well as its maintenance costs are comparatively lower. Such small hydropower plant is capable of effectively generating power at variable flow and can be appropriate for rural electrification.

1.5 Scope and Limitations of the Study

The study focused on the electrical design and particularly on the utilization of a combination of synchronous and induction generators in parallel both driven by hydro turbines at run of river small hydropower station. Dynamic behaviours of the plant were investigated to determine its response to loading conditions that are likely to occur and stability of the plant was also examined. Emphasis was on reduction of investment cost of the plant without compromising the quality of power to be generated.

The study did not include civil and mechanical engineering works of the power plant. Also the environmental aspect was not looked upon.

1.6 Underlying Assumptions

Basic assumptions made during the study included; that the power sector industry was deregulated, and the legal and financial frameworks were conducive for Independent Power Producer (IPP) participation in power industry. The energy generated could be sold to consumers readily available at economical rate. Hydrological studies and surveys at a site where the plant was to be installed had confirmed the availability of hydro potential that is both technical and economical viable; also civil and mechanical engineering works and measures for mitigation of environmental impacts could be implemented.

1.7 Significance and Contributions of the Study

Tanzania has an estimated feasible large hydro potential of 4700MW and about 314MW of small hydro potential located in different parts of the country. Currently it exploits 559MW of large and 2% of small hydro potential while access to electricity is estimated at only 10% of its 35 million populations of which 80% live in rural areas where access to electricity is 1%. Small hydro is a reliable renewable energy source and sites endowed with small hydro potential are mostly in remote rural areas that are yet to be electrified. In this case, utilisation of the small hydro potential for electricity generation can effectively facilitate electrification of the isolated or rural communities, and impact on their social and economic activities raising their living standards. The study explored the possibility of harnessing the distributed small hydro potentials which includes those available in Tanzania at low cost. It was anticipated, that implementation of the proposed plant would stimulate the utilisation of hydropower potential to increase electricity generation capacity and consequently connectivity of rural areas in the country. Therefore the research findings together with innovative construction of distribution networks in areas close to respective plants, were expected to contribute to the electrification of remote rural areas surrounding the hydro potentials at relatively low cost.

1.8 Brief Chapter Overviews

Chapter one introduces the subject matter of the thesis. The chapter gives background of the research subject and elaborates problem statement of the thesis. Also in the chapter, are objectives of the study, thesis statement, scope and limitations, assumptions made during the study and lastly the significance of the research to small hydropower generation industry is highlighted.

In chapter two, general understanding of small hydropower plant as well as brief explanation on development in exploitation of small hydropower in the world has been given. Classification methods and basic structures of small hydropower plants including their main components are identified. The operation principles of electro-mechanical part of small hydropower plant are briefly explained and techniques employed for load frequency control of hydraulic turbine-synchronous generator units are discoursed. The chapter discusses both synchronous and induction generators in the context of three-phase AC machines, their fundamental differences and operation behaviour in normal conditions have been highlighted. Elements of electrical connection of small hydropower plant and principles of their selection are briefly explained. Methods of generating reactive power applied in FACTS are introduced and operation of Static Var Compensator (SVC) is shown. The possibility of applying power relay in the system which control power output of induction generator is introduced. And finally, stability problems of synchronous and induction generators in a power system are discussed.

Chapter three looks at a new type of small hydropower plant proposed. Main components of the proposed power plants are identified which include synchronous and induction generators and Static Var Compensator for generation of reactive power. Operations of the plant and control strategies for the turbines which drive the generators in order to maintain generation voltage and frequency while load connected to the plant changes are also explained. In the same chapter, models of main components of the proposed plant were individually developed.

Chapter four presents a model of the proposed plant implemented using physical modelling approach by means of SimpowerSystems tool box available in MATLAB/Simulink software. The model includes inductive load connected to the plant. The chapter elaborates simulation process and the simulation results when the plant is loaded with constant load to establish the interaction between the two generators installed in the plant and their behaviour when the plant is loaded with variable load. In the chapter, presented also are simulations and simulation results for assessment of small signal stability and transient stability of the synchronous generator and speed stability of the induction generator in the plant. Also included, are simulations aimed at determining effects of speed of induction generator rotor at the moment of connecting the generator into the system.

Chapter five presents conclusions drawn from the research work which have shown that, it is technically viable to install synchronous generator and induction generator in parallel operation in small hydropower plant. Included also, are some recommendations for implementing the project. Some areas for further research to enhance the performance of the proposed small hydropower plant are also identified.

CHAPTER TWO

Literature Review

2.1 Introduction

Small hydro has been serving mankind for centuries, exploitation of hydro energy started with wooden waterwheel whereby people in Asia and Europe converted hydro power to mechanical power used for grain milling. Advancement in technology called upon need for high speed and more powerful machines for generation of electricity. This led to development of current hydro turbines which are now used as prime-movers driving electric generators in hydro electric power plants or hydropower plants in short.

Small Hydropower Plant (SHP) is a facility used to convert hydro energy into electrical energy at a site which has small generation capacity. SHP has no universal meaning; this study adopted the definition used by European Small Hydro Association. Loss of interest in development of SHP occurred during the second half of the 20^{th} century, when SHPs were found to be not cost effective as compared to large hydropower plants and fossil fuel powered plants. The scenario has recently changed due to environmental concerns and rise in cost of fossil fuels thus SHPs are again on the agenda as an energy provision alternative. However, new SHPs are not the repetition of the old ones they employ new technology and techniques aiming at performance improvement and cost reduction.

Majority of SHPs are run of river type in which generation capacity depend upon flow rate which again varies with seasonal conditions. In this case it is sometimes necessary to install multiple generating units in SHPs in order to effectively harness the hydro energy available at a site.

In electric power generation industry, three phase synchronous generators with their respective governing and control systems are dominant converters of the mechanical power supplied by turbines to electrical power except in few micro hydropower plants where induction generators are used.

Main setbacks of induction generator in power generation lie on inability to regulate frequency of generated power and voltage at its terminals. These setbacks are possible to reverse nowadays by using power electronic devices such as static var compensators (SVC) and frequency converters which have surfaced recently and made cheap and robust induction generators to be equal contender in large power generation.

2.2 Small Hydropower Development and Elements

Hydro energy is based on the flow of naturally cycled water and its drop from a higher to a lower surface. The energy of water cycle is driven by the sun causing water to go through a vast global cycle evaporating from lakes, oceans, etc forming clouds, precipitating as rain or snow then flowing back down to the ocean.

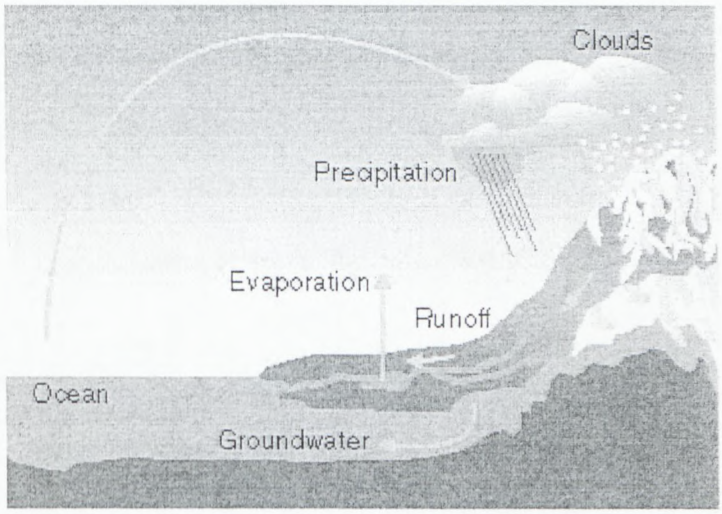


Figure 2.1: Water Cycle

Source: http://wwwl.eere.energy.gov/tribalenergy

Part of the precipitation that reaches the earth's surface is returned to the atmosphere by evaporation from water surfaces, soil and vegetation and through transpiration by plants and in addition, another part seeps into ground forming groundwater. The remaining part flows downstream on earth surface as run-off or stream flow. If at certain point the water falls through an appreciable vertical height, its energy can be converted into mechanical energy by allowing it to flow through hydraulic turbine runner.

The exploitation of hydro energy started with the wooden waterwheel used in many parts of Europe and Asia for some 2,000 years, people converted hydropower into mechanical power used for milling grain. Improved engineering skills and increased energy requirement in the advent of industrial revolution, called for smaller but more powerful and high speed devices with large capacities to generate electricity which led to the development of modern-day turbines. Therefore towards the end of 19th century, many mills were replacing their waterwheels with turbines, at the same time governments started to focus on how they could exploit hydropower for large scale supply of electricity required by industries.

The golden age of hydropower was the first half of the 20th century, before oil took over as the dominant force in energy provision. The development of hydro-electricity during that period was associated with the building of large dams. Hundreds of massive barriers of concrete, rock and earth were placed across river valleys world-wide to create huge artificial lakes (Dursun and Gokcol 2011:1227-1235) for hydro-electric power generation. Europe and North America built dams and hydropower stations at a rapid rate, exploiting up to 50% of the technically available potential.

The 1960's witnessed decline of the small hydro industry as small hydropower plants were found to be not cost effective as compared to large hydro schemes and fossil fuel powered plants. The high cost of generation in SHPs as compared to then ready available enormous quantity of electrical energy from large steam powered plants and large hydropower plants was found to be on the higher side and this made SHPs to be partially abandoned (Paish, 2002:537-556).

In discussing small hydropower plants, one has to note, that up to present time there is no universal definition of small hydropower plant in terms of generation capacity. Depending on a country, the term small hydropower plant can be defined differently. However, after a survey, European Small Hydro Association (ESHA) has concluded that, 10MW of generation capacity as an upper limit is the most widely accepted value in the world (ESHA, 2004). Voros, Kiranoudis and maroulis (2000:545-563) subdivided further the range of small hydropower to mini-hydro referring to schemes of between 1MW and 100kW while those below 100kW were referred to as micro-hydropower plants. Examples of diversity in the existing definitions of small hydropower plants as applicable to some few countries are presented in Table 2.1 below.

Table 2.1: Definition of Small Hydropower Plants in Some Countries/ Organisations

Country/Organisation	Micro (kW)	Mini (kW)	Small (MW)
U.S.A.	<100	100-1000	1-30
China	-	<500	0.5-25
France	500	501-2000	2-8
Sweden	-	100	0.1-15
India	<100	101-1000	1-15
Peru	5-50	51-500	0.5-5
Philippines	-	-	15
Romania	-	-	0.05-5
Thailand	200	201-6000	6-15
Turkey	100	101-1000	1-5
Columbia	-	-	20

Malaysia	25	25-500	0.5-5
Nepal	-	-	10
Panama	100	101-1000	1-10
Ecuador	50	51-500	0.5-5
Bolivia	100	101-1000	-
Dominica	100	101-1000	1-5
Vietnam	50	51-500	0.5-5
Japan	-	-	10
New Zealand	-	10000	10-50
Indonesia	-	-	5
Zimbabwe	5-500	501-5000	-
Norway	-	-	10
Greece	100	101-1000	1-15
Poland	100	101-1000	1-15
Finland	200	201-2000	-
UNIDO	100	101-1000	1-10

In this study, small hydropower plant as defined by ESHA was referred to a plant with capacity not exceeding 10MW within which mini hydropower plant was the one whose capacity did not surpass 1MW but above 100kW and any plant with capacity of 100kW and below was termed as micro hydropower plant.

The depletion of world oil reserves and escalation of price of fossil fuels in general and the significant environmental degradation accompanying power generation by burning of the fuels, have revived the interest on renewable energy sources (Kaldellis, 2007:2187-2196) this includes the partially abandoned small hydropower plants.

Implementation of an SHP can be divided into two components; first part is normally referred to as civil engineering works. Another component of a small hydropower plant consists of electro-mechanical equipment which among others include hydraulic turbines, governors, gates, generators, control systems, a power substation, electrical and mechanical auxiliary equipment (Forouzbakhsh et al., 2007:1013-1024, Singal et al. 2010:117-126). In terms of cost contribution of the components of SHP, electro-mechanical equipment is next to civil engineering works as it constitute between 30% and 40% of the total cost of a plant (Ogayar and Vidal, 2009) depending on site conditions.

Huang and Yan (2009:1652-1656) contended, that hydropower in general is a clean and renewable energy source that can be commercially developed. They further enumerated some advantages of hydropower compared with other energy sources as:

- Hydropower's fuel is essentially infinite and is not depleted during the production of electricity.
- Hydropower uses water to generate electricity. It is climate friendly and does not produce air pollution or create any toxic by-product.
- Hydropower is the most efficient way to generate electricity. Today's hydro turbines can convert as much as 90% of the available energy into electricity.
- Hydropower can go from zero power to maximum output rapidly and predictably.
- Hydropower has the unique ability to change output quickly.
- Hydropower projects do more than just produce electricity.

In addition, Jiandong et al, (1997) identified advantages that are specific to a small hydropower plant as:

- Its suitability for decentralised development, as it fully uses local materials and appropriate technology with the participation of local people.
- Its technology is mature and involves small investment risk.
- SHP has low operating costs, it is easy to maintain and offer reliable power supply.
- SHP imposes little stress to environment during construction, with some positive impact on the environment.
- SHP offers social benefit to a developing local economy and improvements in the material and spiritual life of local residents.

If properly implemented, small hydro is a cheap method of electricity generation as indicated above which is also characterised by reliable and flexible operation. Small hydropower plants have relatively long lifetime; civil work can perform for a century or more with little maintenance.

Current achievements in research and development in machines, power electronics and relevant technologies in civil engineering works have made small hydropower to be an attractive energy production alternative among renewable. Even some countries that stopped small hydropower development for many years have decided to develop them again. In this aspect, China has shown how valuable SHPs can be as by the end of 2005 small hydro projects in China had an installed capacity of 38 GW, while more than 40,000 SHPs had been built and 653 rural counties had been electrified (Huang and Yang, 2009) through the small hydropower development programme. In Europe where the installed capacity was 8 GW by 2002, new installations were taking place and European Commission projected to achieve an increase of 50% by the year 2010 by exploiting the then estimated potential of 18 GW (Anagnostopoulos,J.S., and Papantonis,D.E. 2007:2663-2670). In 2004, US Department of Energy analysed every two-mile stream segment in the United States for its potential as a hydropower development site. In this process, nearly 500,000 viable small scale hydropower sites were identified, capable of providing more than 100,000 MW of power (Kosnik, 2010:5512-5519).

The present small hydropower plant is neither the miniature of large hydro, nor the simple repetition of old small hydropower plant technique, but a more advanced type of technique appropriated to each case (Jiandong et al, 1997). In spite of all positive attributes mentioned above, high investment cost and low operating costs remains specific for small hydro facility. The generation cost of SHPs is still higher than from larger sized plants due to economy of scale as some instrumentation, control and monitoring systems have no size dependency (Tsoutsos et al. 2007). This has all along been an obstacle for developers to harness the available energy potential and make small hydropower plants to remain unpopular even in countries like Tanzania where majority of its populations could benefit from it.

2.2.1 Classification

Exploitation of small hydropower for electricity generation involves extracting water in a controlled manner from a river at higher land surface, and then conveying it to a lower land surface where its energy is converted into mechanical and lastly into electrical energy. A hydropower plant capacity is primarily a function of water discharge and hydraulic head which have a role in both classification and structure of a hydropower plant.

Hydropower schemes are generally classified according to the head namely:

- High head
- Medium head
- Low head

Jiandong et al (1997:14-17) highlighted two other methods of classifying hydropower schemes based on mode of head concentration and flow regulation.

According to the mode of concentration, hydro schemes are classified as:

- A dam scheme- The head is mainly raised by the dam, which raises the upstream water level. In this case the power station can be placed either behind or parallel with the dam.

- A diversion scheme- The head is mainly concentrated by diversion structure. The diversion structure is an open canal, a tunnel or a pressure pipe line.
- A mixed scheme- The concentrated head is obtained by both the dam and diversion structure.

According to mode of flow regulation, hydropower projects can be classified as:

- A run of river scheme- Power is generated by natural runoff without flow regulation. Firm power is guaranteed by a natural base flow with high reliability.
- A daily regulation scheme- Power is generated by natural daily flow, but with daily regulating pond by which the natural daily flow can be regulated in accordance with the fluctuation of daily load. The power output is thus bigger than that without regulation.
- A seasonal regulation scheme- In this case a reservoir should be built at the intake of the power station to store water in the rainy season and discharge it in the dry season, thus enhancing the firm output the whole year round. Most of these kind hydropower stations are dam and mixed schemes.

Basing on the above classifications, Small hydropower plants are said to be mostly run of river type meaning that the natural flow of the river is maintained with diversion schemes in which power generation depends on natural runoff. This is because such schemes cost less in civil engineering works. Implementation of run of river SHP does not involve construction of dams and reservoirs. Therefore it also brings minimal or ignorable environmental problems (Dursun and Gokcol, 2011). The civil works purely serves the function of regulating the level of water at the intake to the plant.

2.2.2 Civil Engineering Works

Irrespective of the sizes or types, for operation of hydro schemes water has to be supplied to turbines located in power house. This process involves elements of civil engineering works. The extraction of water from rivers is done in a controllable way (Harvey et al, 1993:73). In diversion SHP schemes this is done by weir and intake structures as shown in a typical layout of a small hydropower plant is depicted in Figure 2.2 below. Sometimes a natural permanent pool in the river may provide the same function as a weir.

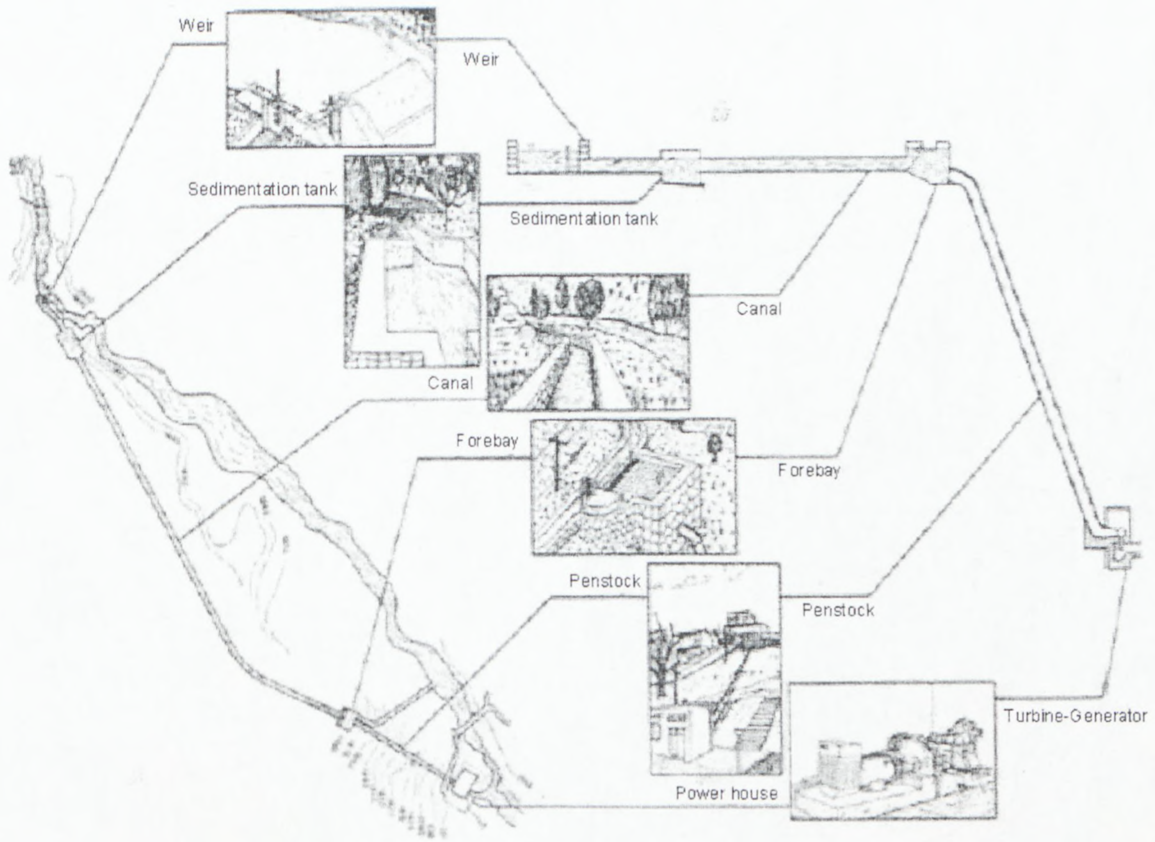


Figure 2.2: Typical Small Hydropower Plant Layout

Source: Hossein et al, 2005

2.2.2.1 Weir and Intake Structure

Water flows in the river vary in its volume through the year, but hydro installation is designed to take a constant flow. Weir or a barrage is a low diversion structure built along the streambed in order to divert a portion of the river flow into a conveyance system (Kosnik, 2010:5512-5519). Weir design is very flexible, it can be constructed perpendicular, angular, or lateral to the to the river's axis. It can be fixed, mobile or even an inflatable structure. Weir forms a small dam to ensure that the correct flow is diverted by the intake structure to the canal whether the river is in low flow or high flow. The main function of weir is to ensure that the canal flow is maintained with the river in low flow. The function of intake structure is to regulate the flow within reasonable limits when the river is in high flow. Further control or regulation of the canal flow is provided by spillways.

2.2.2.2 Sedimentation Tank

The water drawn from the river normally carries a suspension of small particles of solid matter composed of hard abrasive materials such as sand and will cause damage and rapid wear of turbine runner if allowed to go through the turbine. To remove this material the water flow must be slowed in sedimentation tank so that the silt particles settle on the basin flow where the deposits can be periodically flushed out to settle out the sediment both at the canal entry and at the penstock entry, or forebay tank.

2.2.2.3 Canal

For small hydropower plants, it is a worldwide practice to use canals for diversion structure to a forebay. There are various types of canals which may be suitable for a particular installation.

The choice of the correct type of canal for each part of the route and associated lining or sealing material is very important. The canal type and the material of canal determine three basic factors which govern canal dimensions and head namely:

- Side slope and cross-sectional profile.
- Water flow velocity.
- Roughness.

The optimum design of a canal is governed by five principles:

- The velocity of the water must be high enough to ensure that suspended solids (sediments) do not settle on the bed of the canal.
- The velocity of the water in the canal must be low enough to ensure that its side walls are not eroded by the water flow. If this is impossible, without conflict with the previous principle, the use of improved lining of the canal wall must be considered.
- The head loss, or loss of vertical height, due to the canal must be minimised.
- The canal must be durable and reliable, not only free from sedimentation, but also protected from destruction by storm runoff, rock-falls crossing its path, or land slip.
- It must have the minimum possible material cost, construction and maintenance cost.

2.2.2.4 Forebay

Forebay is a collector–distributor, or small pond, receiving water from the canal and distributing it to penstocks. In some cases it functions as a storage pond. A forebay should be long enough to distribute the flow smoothly and uniformly and wide enough to accommodate the intake or penstock and other structures.

During normal operations, the water level in the forebay is in a steady condition. When the plant is suddenly loaded, the water level in front of the intake suddenly draws down while the canal cannot supply enough flow to the plant. Therefore, the forebay should have certain storage volume capable of regulating the flow.

The forebay is the final defence against harmful particles of slit and floating debris. Therefore, sand sluices and trash racks which filter out water-borne debris that might damage the turbine are usually provided in the forebay.

2.2.2.5 Penstock

Penstock conveys water under pressure to a turbine located in a power house. Penstocks are always laid on and towards the slope. Great attention should be paid to the slope stability of the site and the installation condition of the penstock. This means, the layout of the forebay, penstock and powerhouse should be considered comprehensively. There are two layout schemes for the penstock:

- A separate layout in which each generating unit has one penstock.
- A common penstock with branching pipes at its lower end to supply water for more than one generating unit.

Selection of penstock layout must be carried out on the principle of maximum economy, taking into consideration the operating function of plant, the construction conditions etc.

Depending on local conditions of an SHP, any of the following types of penstock can be selected:

a) Wood-stave pipes. The main advantages of wood-stave pipes include:
    - Their cost-effectiveness.
    - Local availability.
    - Appropriate technology.
    - Ease of transportation and installation.
    - Flexibility and freedom from expansion.
    - Fabrication in workshop or factories all year around.
    - Good resistance to abrasion.
    - Resistance to climatic extremes.

   The main disadvantage is decay due to infestation by insects and fungi. If untreated, their service life is about 15-20 years, and if treated they can last more than 30 years.

b) Reinforced concrete pipes. Their advantages are:

- Long service life.
- Little maintenance.
- Less expensive than steel pipes

Their main disadvantages are:

- Difficulty in transportation and installation.
- Partial utilisation of steel strengths due crack prevention.

c) Pre-stressed concrete pipes. Pre-stressed concrete pipes were first developed and applied in China instead of precast reinforced concrete pipes. Their main merits are in cost and steel savings. Their main disadvantage remained to be difficulty in transport and installation.

d) Steel penstocks. Steel penstocks are widely used in hydropower construction.

e) Plastic GRP pipes. Plastic pipes can also be used for penstocks in SHP, but they should be buried in ditches or wrapped in some type of coating to protect them from sunlight.

As a composite material, high-strength glassfibre-reinforced plastic pipes (GRP pipes) were developed in the 1960s. However, their application to SHP penstocks began in the 1980s in Norway, Japan and Malaysia. With the development of the polymer industry in developing countries, GRP pipes have their prospective future in SHP construction.

2.2.2.6 Power House

The power house is where the activity of electricity generation is at. It is in the power house that the flowing water turns a turbine shaft which drives the generator. The function of the power house is to support and house the generating units and their accessories, as well as the water passage through the power house for the purposes of good performance of the plant, cost saving and easy inspection and maintenance.

The layout and dimensions of hydro power houses are determined by the sizes of the generating units and their accessories. .

2.2.3 Hydraulic Turbines

In hydropower plants, hydraulic turbines are also called hydraulic prime-movers as they drive electric generators; turbines convert fluid power into mechanical power through the rate of change of angular momentum of the fluid. The action of the turbine runner is to remove this angular momentum or to straighten out the fluid streamlines. The effect of this change in angular momentum is to induce torque on the shaft of the runner. The speed of rotation is the rate at which this angular momentum is changed.

The relative proportions of power transferred by a change of static pressure and by a change in velocity provide the method of classifying turbines. The ratio of this transfer by means of change in static pressure to the total change in the runner is called reaction. Therefore, if there is any significant pressure change in the runner of a turbine, it is a reaction hydraulic turbine. If there is no change in pressure, only in velocity, it is called impulse hydraulic turbine.

Aside from the most basic category as reaction or impulse, hydraulic turbines are also classified in two separate ways, by the type of runner and by the configuration of the water passages. For reaction turbines, there are different classifications of runners, namely axial, radial, and mixed. These terms denote whether the flow enters the runner either parallel or perpendicular to the shaft, or at some angle in between. Reaction turbines are widely applied in low and medium head power plants while for high head applications; the preferred choice is an impulse turbine.

Definition of head applicable to turbines is relative to the size of the machine: what is low head for a large turbine can be high for a small turbine (Paish, 2002:537-556).

Turbine selection and plant capacity determination require that rather detailed information has been determined on head and possible plant discharge. In practice, different selection procedures are used.

In a theoretical sense, plant output or energy output can be expressed in a functional relation as follows $E = F(h, q, TW, d, n, H_s, P_{\max})$.

Where h = net effective head

q = plant discharge

TW = tailwater discharge

d = diameter of runner

n = generator speed

H_s = turbine setting elevation above tailwater

$P_{\max}$ = maximum output expected or desired at plant.

The general formula for any hydro system's power output as explained in appendix A is:

$$P = \eta \rho g q h \tag{2.1}$$

Where: η is the hydraulic efficiency of the turbine, ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), q is the plant discharge (m^3/s), and h is the net effective head (m).

The best turbines can have hydraulic efficiency in the range 80 to over 90%, although this will reduce with size. Micro-turbines tend to be in the range 60 to 80% efficient. The usual practice in turbine selection is to base on the annual energy output of the plant and the least cost of that energy for the particular scale of hydropower installation.

There are some definite limits of use for each turbine type and it is most cost effective to have a minimum number of units at a given installation. However, multiple units may be necessary to make the most efficient use of water where flow variation is great as is the case of run of river plants.

In accordance with the installed capacity, number of generating units employed in an installation depends on the following factors:

- Average efficiency of the SHP.
- Operation mode of the SHP.
- Investment for electro-mechanical equipment.
- Operation and maintenance.
- Other factors such as the total capacity of the power system, equipment manufacturing, transport conditions, layout of the power house etc.

Engineering consultants select type turbine and number of units in a size or combination of sizes that gives the most economical selection for a particular site and characteristics of a site are the main determinants of type of turbine to be used.

Generally, the more units employed, the more flexible the operation, and the average efficiency of the SHP could improve correspondingly, but the amount of construction work, investment, the number of operating staff, as well as operation cost would also be increased.

2.2.3.1 The Impulse Turbine

Impulse turbines are low-speed, low-discharge capacity turbine. These turbines are often installed on a horizontal shaft with the generator mounted beside. The turbine wheel is spun by directing water from nozzles against the wheel paddles and using the high momentum of the water to drive the wheel as shown in Figure 2.3.

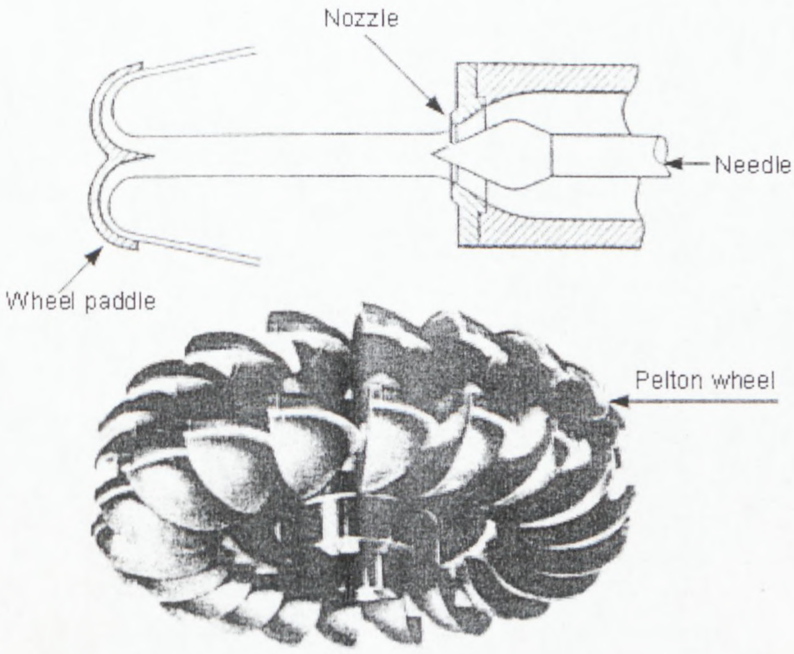


Figure 2.3: Impulse Turbine

Speed regulation of the impulse turbine is accomplished by adjusting the flow of water through the nozzle by means of a needle that can be moved back and forth to change the size of the nozzle opening. In order to abruptly cut off the water jet, water stream is mechanically deflected by means of a jet deflector. Thus, the governor of an impulse wheel control the nozzle for normal changes, and recognize a load rejection by quickly moving the jet deflector.

There are several designs of impulse turbine runners. The most common is the Pelton and a variation of the basic Pelton design is the Turgo impulse turbine. Another design of impulse turbine is the cross-flow turbine (Beaty and Fink, 2007: pp 9-7 to 9-9).

2.2.3.2 The Reaction Turbine

The reaction turbine is a high-speed, high-discharge capacity turbine. In the impulse turbine, the high pressure in the penstock at the nozzle is changed to momentum so that no pressure drop is experienced at the turbine inlet. However, in reaction turbine there is a partial pressure drop at the nozzle, the remainder taking place in the rotating runner. Thus, water completely fills the cavity occupied by the runner, flows across this pressure drop, and transfers both pressure energy and kinetic energy to the runner blades. Since much of the turbine blades are active in this energy transfer, the diameter of the reaction turbine is smaller than an impulse turbine of similar rating. Figure 2.4 shows typical reaction turbine.

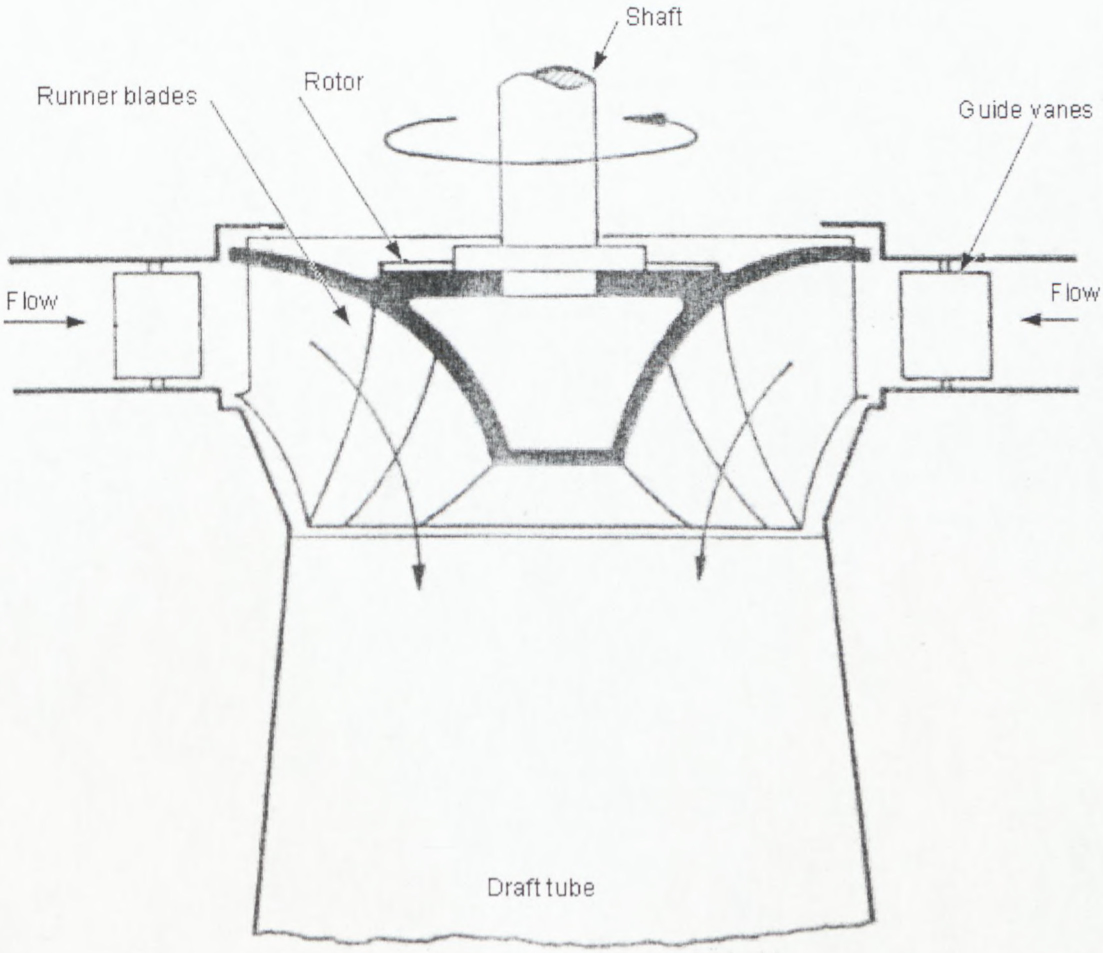


Figure 2.4: Reaction Turbine

Reaction turbines used for medium heads are of Francis type, they have fixed runner blades and adjustable guide vanes. Propeller type reaction turbines are used for low head plants, these may have fixed blades or if the pitch angle of the blades can be adjusted, they are called Kaplan. Reaction turbines are installed either in a horizontal or vertical shaft arrangement, with the vertical turbines being the most common.

The control for a reaction turbine is in a form of movable guide vanes called wicket gates through which the water flows before reaching the runner.

The draft tube is an integral and important part of the reaction turbine design formed in reinforced concrete. It serves two purposes: It allows the turbine runner to be set above the tailwater level and reduces the discharge velocity, thereby reducing the kinetic energy losses at discharge.

2.2.4 Load Frequency Control

Power systems operate at a particular frequency and voltage which are among important factors in determining the quality of power supply. Thus controls are required during power generation to maintain these parameters within the predefined variation limits. Voltage at generator bus in a power plant is maintained by the controller of excitation system of a synchronous generator and frequency is maintained by eliminating the mismatch between generation and load demand (Hanmandlu, M. and Goyal, H. 2008:272-282), in other words, the frequency of a system is dependent on active power balance. In addition, for stability of the system and effective operation of electrical equipment, all parallel operating synchronous generators in power system should maintain synchronism at a predetermined frequency of generation (50-Hz), thus each synchronous generator-turbine generating unit in the system must run at a constant speed. For hydraulic turbine-generator units, speed maintenance is achieved by regulating water fed to the turbine in accordance with the load variations. This function is the responsibility of a governor which is on each generating unit in the system. There are various types and methods of governing systems employed to hydraulic turbine driving a generator in hydropower plant, depending on size and function of the unit.

2.2.4.1 Conventional Governor

Conventional governor systems fulfil the function of keeping each unit operating at its proper speed through a high pressure hydraulic system that operates wicket gates of the reaction turbine or needle in the case of impulse turbine, which control water flow into a turbine to which it is attached. When there are load changes or disturbances in the power network, the governors respond by increasing or decreasing power output of their respective generating units to meet power demands and keep the frequency of the power network at 50-Hz.

The principles of speed governing are illustrated by considering an isolated synchronous generating unit supplying a local load. Figure 2.5 on page 25 depicts the said situation.

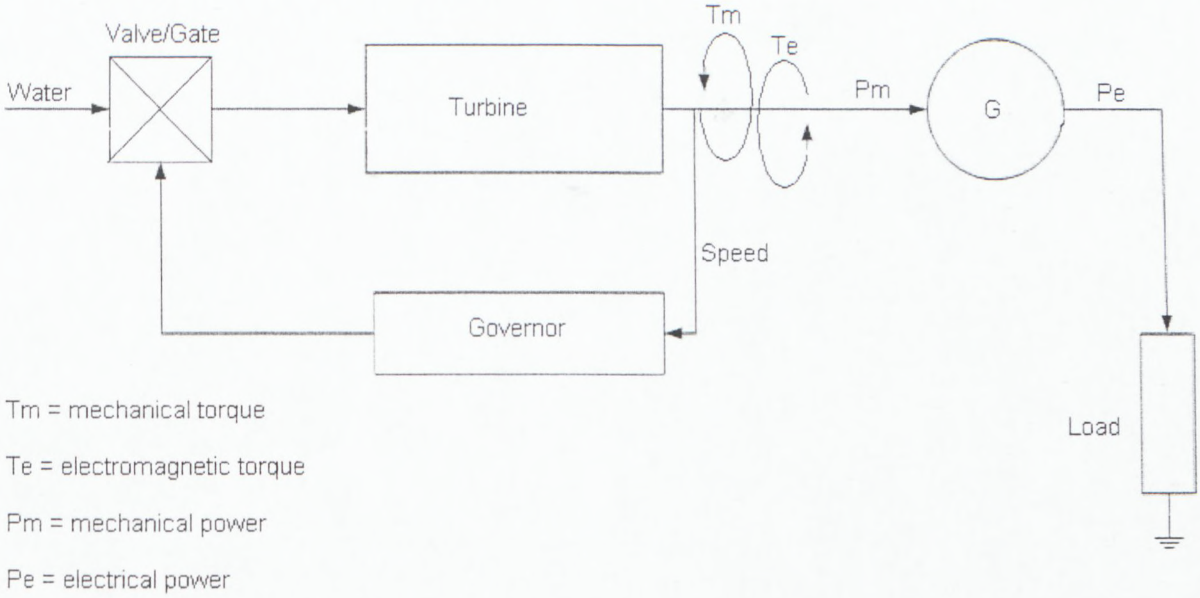


Figure 2.5: Speed Governing Principle for an Isolated Synchronous Generating Unit

In case of a load change, it is reflected as a change in electromagnetic torque T_e of the generator which will cause mismatch with the mechanical torque T_m of the turbine resulting into variations of generating unit speed according to the equations of motion explained hereunder.

The effect of unbalance between the electromagnetic and the mechanical torques acting on the rotor is the acceleration of the combined rotor mass of the generator and the turbine. Hence, the equation of motion is

$$J\frac{d\omega_m}{dt} = T_a = T_m - T_e \tag{2.2}$$

Where

J = combined moment of inertia of generator and turbine, kg.m^2

ω_m = angular velocity of the rotor, mech. rad. /s

t = time, s

T_a = accelerating torque, N-m

When Equation 2.2 is normalised in terms of per unit inertia constant H, defined as the kinetic energy in Watt-second at synchronous speed divided by the VA_{base}, and using ω_{sm} to denote synchronous angular velocity in mechanical radians per second, the inertia constant is

$$H = \frac{1}{2}\frac{J\omega_{sm}^2}{VA_{base}} \tag{2.3}$$

Then the moment of inertia J in terms of H becomes

$$J = \frac{2H}{\omega_{sm}^2} VA_{base} \tag{2.4}$$

Therefore

$$\frac{2H}{\omega_{sm}^2} VA_{base} \frac{d\omega_m}{dt} = T_m - T_e \tag{2.5}$$

Rearranging yields

$$2H \frac{d}{dt}\left(\frac{\omega_m}{\omega_{sm}}\right) = \frac{T_m - T_e}{VA_{base}/\omega_{sm}} \tag{2.6}$$

Since $T_{base} = VA_{base}/\omega_{sm}$, the equation of motion in per unit form is

$$2H \frac{d\bar{\omega}_r}{dt} = \bar{T}_{sm} - \bar{T}_e \tag{2.7}$$

In Equation 2.7,

$$\bar{\omega}_r = \frac{\omega_m}{\omega_{sm}} = \frac{\omega_r/P}{\omega_s/P} = \frac{\omega_r}{\omega_s}$$

Where ω_r angular velocity of rotor is in electrical radians per second, ω_s is its synchronous value, and P is number of field poles.

Introducing the Laplace operator in Equation 2.7, the relationship between rotor speed as a function of the electrical and mechanical torques is represented by the transfer function depicted in Figure 2.6

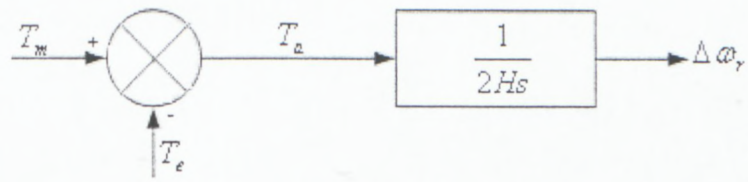


Figure 2.6: Transfer Function Relating Speed and Torques

Where

s = Laplace operator

T_m = mechanical torque, per unit

T_e = electrical torque, per unit

T_a = accelerating torque, per unit

H = inertia constant, MW-sec/MVA

$\Delta\omega_r$ = rotor speed deviation, per unit

In other words, the operation of governor is based on measuring the speed of the rotor ω which is compared with the reference speed ω_s. The error signal $\Delta\omega_r$ is then amplified and integrated to produce a control signal which actuates the valve/gate of a hydraulic turbine. Due to the reset action of the controller, the control signal reaches a new steady state only when the speed error $\Delta\omega_r$ is zero. Such a governor which adjusts the turbine valve/gate to bring the frequency back to the nominal or scheduled synchronous value is known as isochronous (constant speed) governor. Figure 2.7 and Figure 2.8 shows schematic diagram of an isochronous governor and a response of generating unit with isochronous governor respectively.

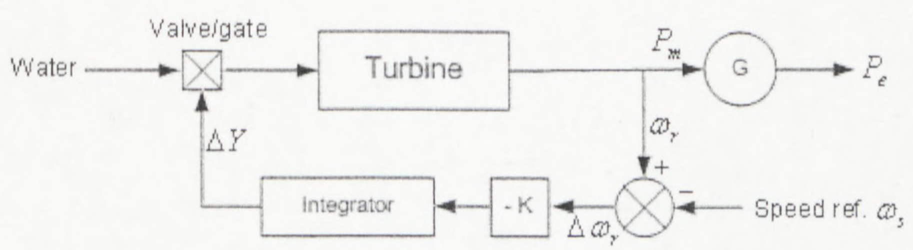


Figure 2.7 Schematic Diagram of an Isochronous Governor

ω_r is rotor speed, Y is valve/gate position and P_m is the mechanical power.

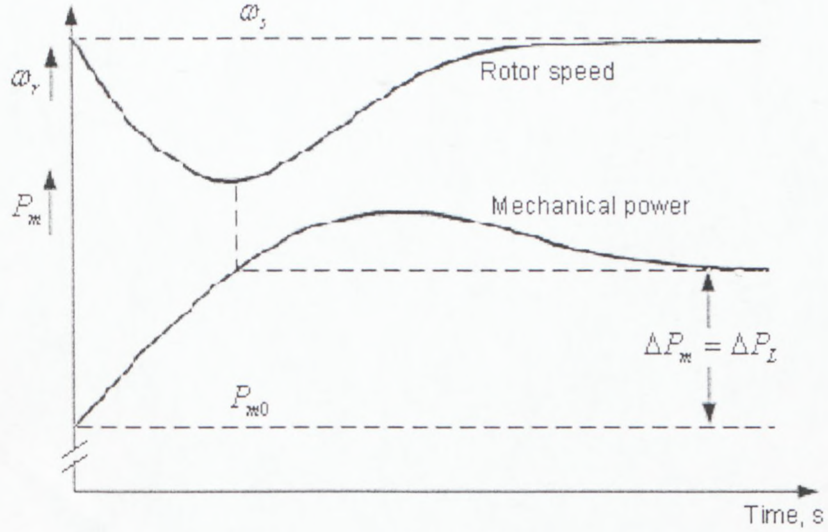


Figure 2.8: Response of Generating Unit with Isochronous Governor

An isochronous governor works satisfactorily when a controlled synchronous generator is supplying an isolated load or when only one generator in a multi-generator system is required to respond to changes in load. When there are two or more units connected to the system which are required to respond to changes in load, they should have to have precisely the same speed setting. Otherwise, they would fight each other, each trying to control system frequency to its own setting. For stable load division between two or more units operating in parallel, the governors are provided with a characteristic so that the speed drops as the load is increased.

The speed droop or regulation characteristic is obtained by addition of a steady state feedback loop around the integrator as shown in Figure 2.9. This type of governor is characterised as a proportional controller with a gain of $\frac{1}{R}$.

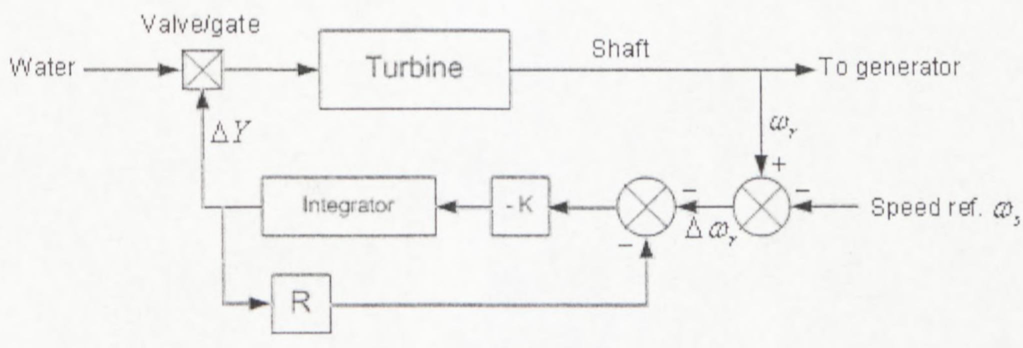


Figure 2.9: Governor with Steady State Feedback

The transfer function of the governor of Figure 2.9 is represented in Figure 2.10.

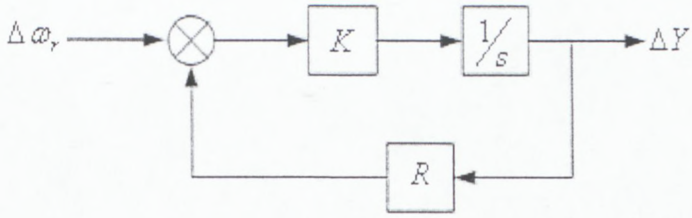


Figure 2.10a: Block Diagram of Governor with Steady Feedback

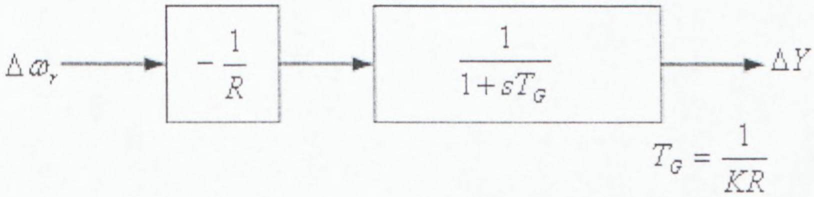


Figure 2.10b: Reduced Block Diagram of Governor with Steady State Feedback

The parameter R is the speed regulation or droop of which value, is the ratio of speed deviation ($\Delta\omega_r$) or frequency deviation (Δf) to change in valve/gate position (ΔY) or power output (ΔP), it determines the steady state speed versus load characteristic of the generating unit as shown in Figure 2.11.

An increase in power output of a generating unit with a speed-droop governor is accompanied by a steady state speed and consequently frequency deviation, the property makes parallel operation of such units possible. Figure 2.12 shows the time response of a generating unit with a speed-droop governor subjected to an increase in load.

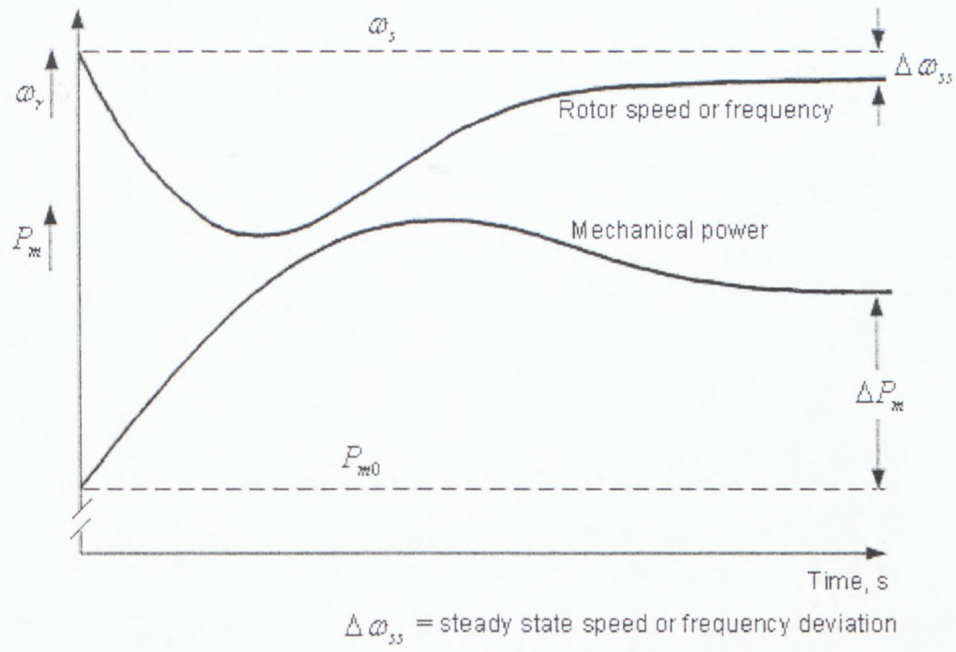


Figure 2.11: Response of a Generating Unit with a Droop-Speed Governor

If two or more synchronous generators with drooping governor characteristics in a system work in parallel, when a system load change, there will be a unique frequency at which they will share the load change. The amount of load picked up by each unit depends on the droop characteristic. Figure 2.12 depicts two generating units operating in parallel at initial nominal frequency f_0, with outputs P_1 and P_2. The increase in system load by ΔP_L causes the units to slow down, while the governors increase output until they reach a new common operating frequency f' at which sum of the amount of power output increase by each unit equals the load increase $\Delta P_L = \Delta P_1 + \Delta P_2$.

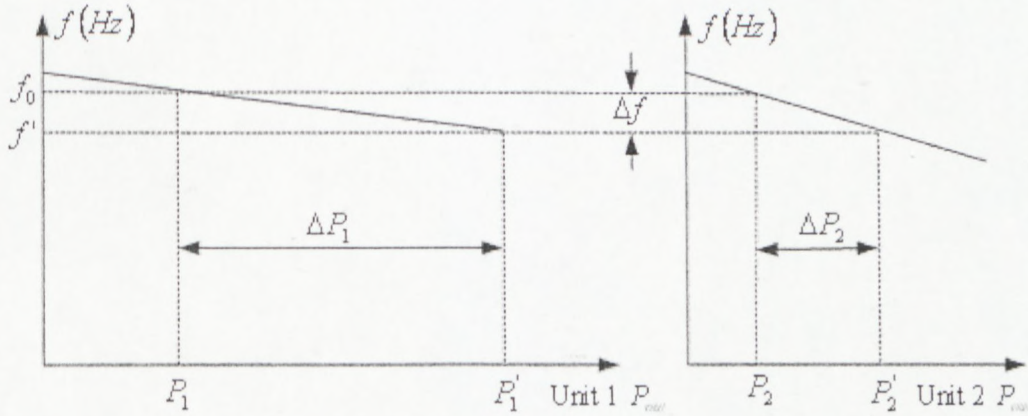


Figure 2.12: Load Change Sharing By Parallel Units with Drooping Governor

$$\Delta P_i = \frac{\Delta f}{R_i}; i = 1, 2 \ldots n.$$

Older governors use mechanical speed sensing and control interfaced to the hydraulic system to govern turbine speed. Improved versions incorporate electronic or digital speed sensing and controls with a hydraulic interface to the turbine governor. The new governor designs use high-speed electronic logic to control electro-hydraulic force-stroke amplifiers. The electro-hydraulic systems have high sensitivity and fast response.

The governors mentioned can be used with plants of all sizes. However, they require regular maintenance such as:

- Leaking seals and worn pins and bushings must be replaced;
- All bolts and connections should be checked regularly for looseness;
- All levers should be checked for friction or binding;
- All pivots, cam surfaces and linkage rod ends should be oiled frequently and any accumulated grit, rust or dust removed;
- Dust, which serves as an insulation on electrical parts, must be guarded against;
- Governor characteristics, such as servomotor timing, should be checked periodically and appropriate adjustment made;
- Pistons should be checked for wear;
- The hydraulic oil must be kept very clean and filters changed regularly.

In practice, governors designed to operate as proportional control systems, operate at a widespread characterized droop of 4 to 6% across the operational range as shown in Figure 2.13. Usually there is an inbuilt facility within a governor that allows an operator to adjust the set point frequency. For the line A, the set point is 1.04 p.u and the frequency will be 1.00 p.u when the load has increased to rated generator power. Changing the set point to 1.02 p.u moves the line to B. Set point adjustment allows power system operators to decide how the demand is shared by the generators in the system.

The under frequency protection normally incorporated in plant protection systems, activate load shedding when the system frequency falls below the designated minimum allowable value.

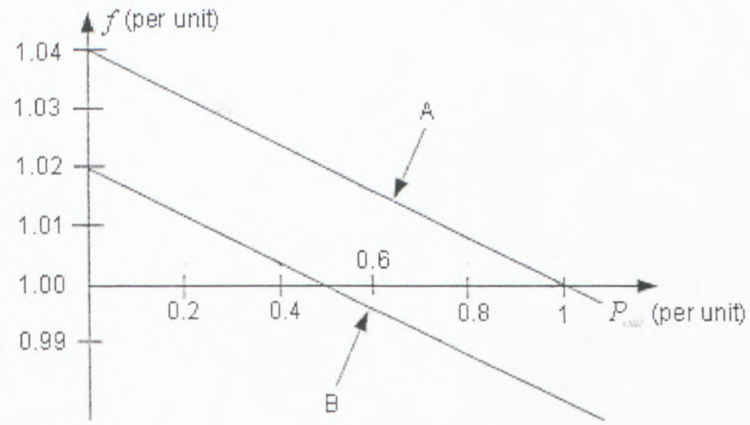


Figure: 2.13: Frequency/Power Characteristic of a Governed Turbine

The cost and sophistication of these governors detract them from their appropriateness to small hydropower plants. It has been observed that, conventional governors have never been an ideal option for small plants because cost of the governors and their controls do not decrease proportionally as the generator size reduces (Singh, 2004: 107-114). Therefore in these lines Naibo, et al. (1989. 77-102) contends that when conventional governors are used in SHPs, the cost of electricity unit become comparatively high.

2.2.4.2 Electronic Load Controller

Electronic load controllers using solid-state power electronics were developed in the UK in the early 1980's as a low-cost means of running off-grid turbines at a fixed speed regardless of the increase or decrease in load. The concept has since been copied worldwide and has greatly improved the long-term sustainability of micro hydro schemes in developing countries (Paish, O. 2002: 537-556).

Principally, the electronic load controller is an electronic device that maintains a constant electrical load on a generator in spite of changing user loads by varying the amount of power fed to dump load. This permits the use of a turbine with no flow-regulating devices and their governor control system. The flow through the turbine is set at a constant value and the load controller ensures that a constant electrical load is supplied by the generator. The turbine power output is then constant and thus its speed is constant. A complete mathematical model for an improved load controller when applied for micro/mini hydro or wind or diesel electric system is discussed in detail in several publications.

The main setback of electronic load controllers' application is based on the limitation of amount of energy to be generated by the power plant due to limitation of capacity of the dump load to dissipate the excess energy and the method of dissipation. Doolla, and Bhatti, (2006: 889-896) attests the limitation in size of the available dump loads as one of main reasons for non exploiting isolated small hydro power systems in the higher capacity range.

2.2.4.3 Servomotor as Governor

An electric servomotor is a precision electric motor whose function is to cause motion in the form of rotation or linear motion in proportion to a supplied electrical command signal in this way they transform electric power into mechanical dynamics. Servomotors can be categorised into direct current (dc) motors and alternating current (ac) motors. However, dc servomotors are frequently used within feedback loops to control position or velocity and the most common are the dc servomotors in which there is constant field excitation, and position or velocity control is achieved by variation of voltage applied to armature winding.

The control of a servomotor requires error detecting devise, an amplifier, and error correcting device. Since the motor respond to the error signal abruptly and accelerate the load, the torque-inertia ratio is an important value. The fundamental characteristics of any servomotor are: output torque is proportional to the applied voltage which is the control voltage developed by the amplifier in response to an error signal and the direction of the torque developed depend on the instantaneous polarity of the control voltage. Lee and Wang (2004: 737-754) confirm that with progress in power electronics and microelectronics, the commercially available servomotors nowadays have sufficient capacity for industrial applications.

The idea of employing electric servomotor in small hydropower plant was tested by Doolla, and Bhatti, (2006: 889-896) who proposed and simulated a scheme in which the servomotor was operated as a governor. However, the objective of the work was to save water and there was only one generating unit to be controlled. The penstock water flow was regulated through two longitudinal small sections of pipes, one fitted with on/off control valve with 50% of flow rate under maximum rated load conditions in on state and the second pipe fitted with a valve which was controlled by a servomotor. The flow rate in the second pipe was continuously controlled by controlling the input signal to the servomotor. It had been anticipated that whenever deviation in frequency due to load variation or disturbance occurred, the servomotor controlled valve would change the flow rate so as to maintain the system frequency constant. In this way the possibility of electric servomotor to operate valve and regulate the flow in turn was well illustrated.

According to their observation, simulation results showed, that the technique effectively eliminate the frequency deviations due to load disturbances for nominal loadings of the system. Additionally, the system was found to be more dynamically stable if the on/off control valve has the rate of closing or opening initially low and later on high.

Hanmandlu, and Goyal, (2008: 272-282) contend that electric servomotors are preferable for the small hydropower systems as they have a simple design, require less maintenance and less expensive than conventional governors. Modern servomotors are lightweight, compact, easily integrated, efficient, controllable, and less noisy, also they are implanted with digital signal processors for motion control to meet the increasingly stringent performance criteria (Lee, and Wang, 2004: 737-754). Amongst advantages of electric servomotors include linear speed-torque characteristics, quick response and their availability at all power ranges (Doolla and Bhatti, 2006).

2.2.5 Generators

Generators convert mechanical power supplied by prime-movers into electrical power through electromagnetic torque mechanism resulting from the tendency of magnetic flux caused by armature current and that due to field current to align themselves.

Most of generators used in hydropower plants are 3-phase synchronous machines with stationary armatures and salient-pole rotating field structure.

Induction generators are less common but are being used increasingly in micro-hydro schemes. The fundamental difference is that the mmf flux generation is principally the responsibility of rotor dc excitation on synchronous generators, whereas in induction generators, it must be supplied from stator currents.

2.2.5.1 Three Phase ac Machine Theory

Theory of ac machine is well documented in many publications whereby working principles based on interaction of magnetic fields of armature winding on the stator and the field winding on the rotor are established. In construction the clearance between the rotor and stator which is also called air gap allows free rotation of the rotor. There are two rotor structures: concentric cylindrical and salient-pole rotor.

The $mmf\,(F)$ in a magnetic structure with a concentric cylindrical rotor having a uniform air gap of length g at radius r (r much greater than g) causes magnetic field in the air gap in radial direction across it with a constant magnitude $H = \frac{F}{g}$.

$F = Ni$

Where N = number of turns and i = instantaneous current. Due to symmetry, the air gap fields H on opposite sides of the rotor are equal in magnitude but opposite in direction and the air gap mmf distribution has amplitude $\pm Ni/2$.

In the design of ac machines, the windings are distributed so as to produce a close approximation to a sinusoidal space distribution of mmf. However, even the rectangular mmf wave of the concentrated full-pitch coil can be resolved into a Fourier series comprising a fundamental component and a series of odd harmonics. The fundamental component

$$F_1 = \frac{4}{\pi} \frac{Ni}{2} \cos\theta \tag{2.8}$$

Where θ is measured from the axis of the stator coil and F_1 is a sinusoidal space wave of amplitude

$$F_{1peak} = \frac{4}{\pi} \frac{Ni}{2}$$

The peak is aligned with the magnetic axis of the coil.

The three phase windings are identical and are located with their magnetic axes 120 electrical degrees apart; for a start, mmf of phase a alone is considered.

The resultant fundamental mmf wave of a distributed winding is less than the sum of the fundamental components of the individual coils because the magnetic axes of individual coils are not aligned with the resultant.

Therefore for distributed P-pole winding having N_{ph} series turns per phase

$$F_{a1} = \frac{4}{\pi} k_w \frac{N_{ph}}{P} i_a \cos\theta \tag{2.9}$$

In which the factor $\frac{4}{\pi}$ rises from the Fourier series analysis of the saw-tooth mmf wave of a concentrated full-pitch coil, and the winding factor k_w takes into account the distribution of the winding.

The mmf wave in the machine is a standing wave whose spatial distribution around the periphery is described by $\cos\theta$. Its peak is along the magnetic axis of phase a and its peak amplitude is proportional to the instantaneous current i_a. Accordingly, if the current $i_a = I_m \cos \omega t$, the time maximum of the peak is

$$F_{\max} = \frac{4}{\pi} k_w \frac{N_{ph}}{P} I_m \tag{2.10}$$

As for distributed armature windings, the fundamental mmf wave of a P-pole rotor winding

$$F_{r1} = \frac{4}{\pi} k_r \frac{N_r}{P} I_r \cos\theta \tag{2.11}$$

Its peak amplitude is

$$F_{1peak} = \frac{4}{\pi} k_r \frac{N_r}{P} I_r \tag{2.12}$$

The mmf distribution of the air gap is equal to line integral of H across the air gap. For the case of radial gap and constant radial H, this integral is equal to Hg thus

$$H = \frac{F}{g}.$$

For the distributed winding, the air gap magnetic field intensity is obtainable once F is known. The fundamental component of H is found from

$$H_{a1} = \frac{4}{\pi} k_w \frac{N_{ph}}{Pg} i_a \cos\theta \tag{2.13}$$

Where N_{ph} = number of series turns per phase, θ = electrical angle measured with respect to magnetic axis of winding and k_w = winding factor.

2.2.5.2 Rotating mmf Waves in the Machine

As established in Equation (2.3), space fundamental mmf wave distribution of phase a winding is

$$F_{a1} = \frac{4}{\pi} k_w \frac{N_{ph}}{P} i_a \cos\theta$$

When this winding is excited by sinusoidal varying current in time

$$i_a = I_a \cos\omega t$$

The mmf distribution is given by

$$F_{a1} = (F_{\max} \cos\theta)\cos\omega t$$

The mmf remains fixed in space but its amplitude varies in sinusoidal with time at frequency ω. The mmf distribution can also be expressed as

$$F_{a1} = F_{\max} [\frac{1}{2}\cos(\theta - \omega t) + \frac{1}{2}\cos(\theta + \omega t)] \qquad (2.14)$$

Which means F_{a1} is sum of two travelling waves, with one F_{a1}^{+} travelling in the $+\theta$ direction and the other F_{a1}^{-} travelling in the $-\theta$ direction, both with angular velocity ω.

$$F_{a1}^{+} = \frac{1}{2} F_{\max} \cos(\theta - \omega t) \qquad (2.15)$$

$$F_{a1}^{-} = \frac{1}{2} F_{\max} \cos(\theta + \omega t) \qquad (2.16)$$

In a three phase machine, as mentioned before the windings of the individual phases are displaced from each other by 120 electrical degrees in space around the air-gap circumference. The windings produce sinusoidal mmf waves centred on the magnetic axes of respective phases. The three-component sinusoidal mmf waves are accordingly displaced 120 electrical degrees in space and each phase is excited by an alternating current magnitude of which varies in sinusoidal with time.

Under balanced three phase conditions the instantaneous current currents are

$$i_a = I_m \cos\omega t,$$
$$i_b = I_m \cos(\omega t - 120^0)$$
$$i_c = I_m \cos(\omega t - 240^0)$$

The current I_m is the maximum value of current and the time origin is arbitrarily taken as the instant when the phase a current is a positive maximum. The phase sequence is assumed to be abc.

The phase a mmf has been shown to be

$$F_{a1} = F_{a1}^{+} + F_{a1}^{-}$$

While

$$F_{a1}^{+} = \frac{1}{2} F_{\max} \cos(\theta - \omega t)$$
$$F_{a1}^{-} = \frac{1}{2} F_{\max} \cos(\theta + \omega t)$$

And

$$F_{\max} = \frac{4}{\pi} k_w \frac{N_{ph}}{P} I_m .$$

Similarly, for phases b and c,

$$F_{b1} = F_{b1}^{+} + F_{b1}^{-}$$
$$F_{b1}^{+} = \frac{1}{2} F_{\max} \cos(\theta - \omega t)$$
$$F_{b1}^{-} = \frac{1}{2} F_{\max} \cos(\theta + \omega t - 120^{0})$$

And finally

$$F_{c1} = F_{c1}^{+} + F_{c1}^{-}$$
$$F_{c1}^{+} = \frac{1}{2} F_{\max} \cos(\theta - \omega t)$$
$$F_{c1}^{-} = \frac{1}{2} F_{\max} \cos(\theta + \omega t - 240^{0})$$

The total mmf

$$F(\theta,t) = F_{a1} + F_{b1} + F_{c1} = F^{+}(\theta,t) + F^{-}(\theta,t) . \qquad (2.17)$$

Sum of the negative travelling waves is

$$F^{-}(\theta,t)=F_{a1}^{-}+F_{b1}^{-}+F_{c1}^{-}=0$$

The positive travelling waves reinforce, and their sum is given by

$$F^{+}(\theta,t)=F_{a1}^{+}+F_{b1}^{+}+F_{c1}^{+}=\frac{3}{2}F_{\max}\cos(\theta-\omega t)$$

Thus the result of displacing the three winding by 120^{0} in space phase and displacing the winding current by 120^{0} in time phase is a single positive travelling wave that can be expressed as

$$F(\theta,t)=\frac{3}{2}F_{\max}\cos(\theta-\omega t) \qquad (2.18)$$

This wave is a sinusoidal function of the space angle θ. It has constant amplitude and a space-phase angle ωt which is a linear function of time. The angle ωt provides rotation of the entire wave around the air gap at the constant angular velocity $\omega=2\pi f$ electrical radians per second.

For a P-pole machine the rotational speed is

$$\omega_{m}=\frac{2}{P}\omega\, rad/s$$

Or

$$n=\frac{120f}{P}rev/\min.$$

2.2.5.3 Three Phase Synchronous Generator

A synchronous machine is an ac machine whose speed under steady state conditions is proportional to the frequency of the ac current in its armature. The machine can be operated as a motor or generator and it consists of two essential elements: the field and the armature. The field winding carries direct current and produces a magnetic field which induces alternating voltages in the armature windings.

The three phase armature windings on the stator, are distributed 120^0 apart in space so that with uniform rotation of the magnetic field, voltages displaced by 120^0 in time will be produced in the windings. The theory and performance of synchronous machines have been covered in a number of books.

Under balanced loading, as shown in the previous section, the armature currents will produce the magnetic field rotating at synchronous speed. The field produced by the direct current in the rotor winding, on the other hand revolves with the rotor. For production of a steady torque, the rotor also rotates at the synchronous speed. In practice cylindrical-rotors are used for 2- and 4-pole generators. The salient-pole construction is adapted to multi-polar slow-speed hydroelectric generators and most synchronous motors. The shaping of salient-pole faces is used to minimise harmonics in the flux produced. Therefore for most analyses of the machine performance, it is reasonable to assume that each phase winding produces a sinusoidal distributed *mmf* wave.

To start with, let us look at a simplified three-phase synchronous machine with one pair of field poles shown in a schematic diagram of a three-phase synchronous machine Figure 2.14.

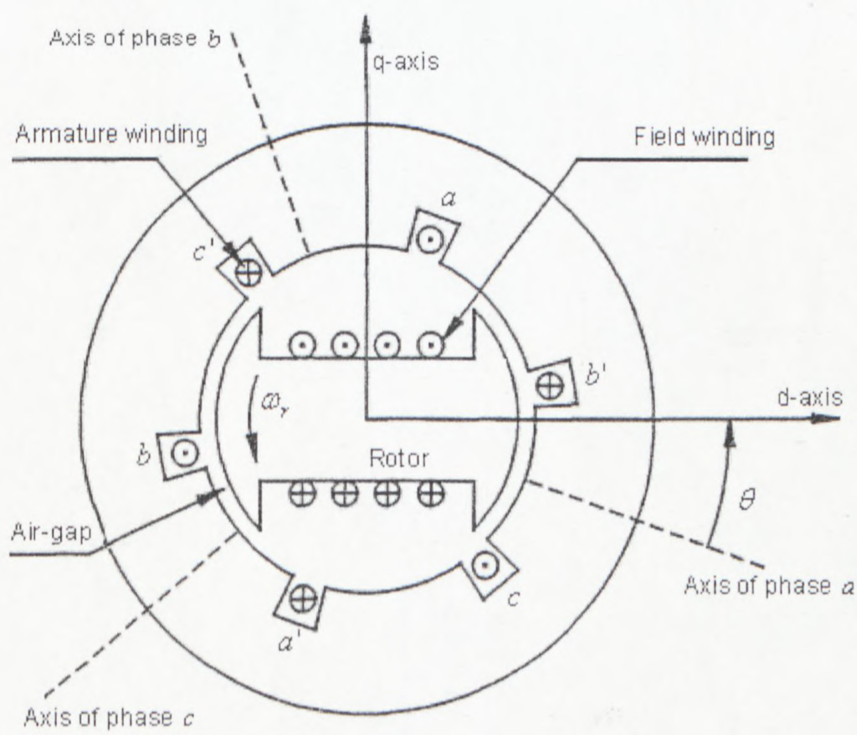


Figure 2.14: Schematic Diagram of a Three-Phase Synchronous Machine

Source: Kundur, 1994

It is observed, that the magnetic circuits and all rotor windings are symmetrical with respect to both polar axis and inter-polar axis. Thus, for the identification of synchronous machine characteristics, two axes are defined as:

- The direct (d) axis, centred magnetically in the centre of the north pole;

- The quadrature (q) axis, 90 electrical degrees ahead of the d-axis.

The position of the rotor relative to the stator is measured by the angle θ between the d-axis and the magnetic axis of phase a winding.

The synchronous machine equations to be developed are based on the following assumptions:

- The stator winding are sinusoidal distributed along the air-gap as far as the mutual effects with the rotor are concerned.
- The stator slots cause no appreciable variation of the rotor inductance with the rotor position
- Magnetic hysteresis is negligible
- Magnetic saturation effects are negligible.

In order to simplify the analysis, stator and rotor circuits in which only one amortisseur circuit is assumed in each circuit as shown in Figure 2.15 is considered. However, implicitly an arbitrary number of such circuits are considered; the subscript k is used to denote this.

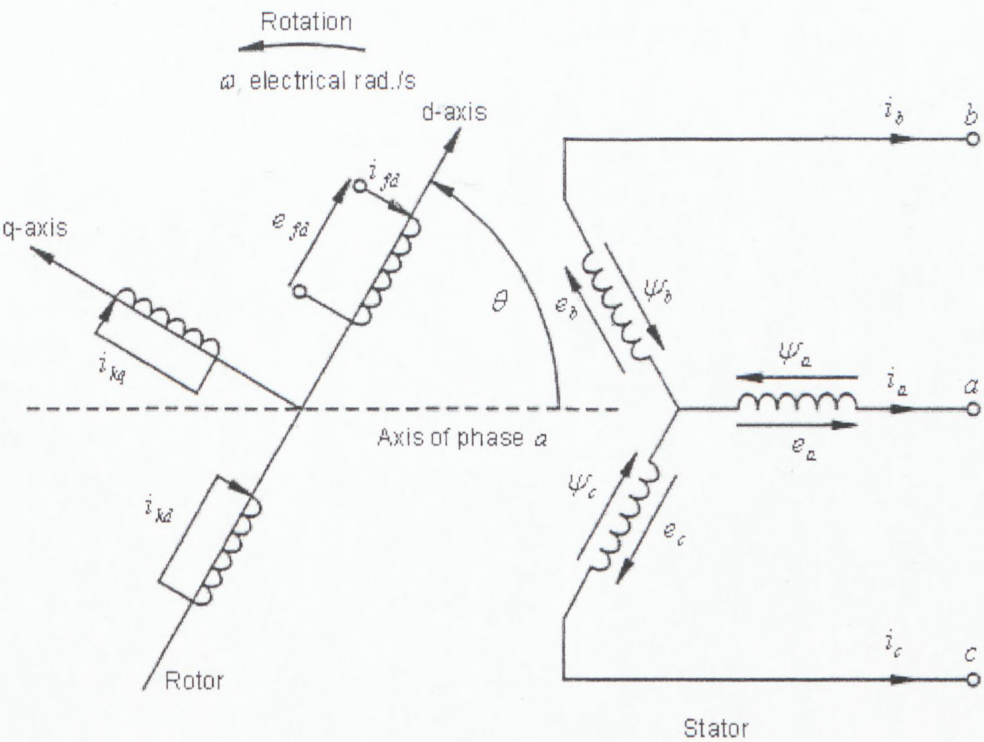


Figure 2.15: Stator and Rotor Circuits of a Synchronous Generator

Source: Kundur, 1994

a, b, c: Stator phase winding

fd : Field winding

kd : d-axis amortisseur circuit

kq : q-axis amortisseur circuit

θ: Angle by which d-axis leads magnetic circuit axis of phase a

k = 1, 2, ...n: Number of amortisseur circuits

ω : Rotor angular velocity

Angle θ is continuously increasing and is defined in terms of the rotor angular velocity ω_r and time t as

$$\theta = \omega_r t$$

The equations for stator and rotor circuits will be written using the following notations:

e_a, e_b, e_c = instantaneous stator phase to neutral voltages

i_a, i_b, i_c = instantaneous stator currents in phases a, b, c

e_{fd} = field voltage

i_{fd}, i_{kd}, i_{kq} =field and amortisseur circuit currents

R_{fd}, R_{kd}, R_{kq} = rotor circuit resistances

l_{aa}, l_{bb}, l_{cc} = self-inductances of stator windings

l_{ab}, l_{bc}, l_{ca} = mutual inductances between stator windings

$l_{afd}, l_{akd}, l_{akq}$ = mutual inductances between stator and rotor windings

$l_{ffd}, l_{kkd}, l_{kkq}$ = self-inductance of rotor circuits

R_a = armature resistance per phase

p = differential operator d/dt

For the stator circuits, voltage equations of the three phases are

$$e_a = \frac{d\psi_a}{dt} - R_a i_a \quad = p\psi_a - R_a i_a \tag{2.19}$$

$$e_b = p\psi_b - R_a i_b \tag{2.20}$$

$$e_c = p\psi_c - R_a i_c \tag{2.21}$$

The flux linkages ψ_a, ψ_b, ψ_c in phases $a, b,$ and c respectively, are evaluated through inductances and currents involved in the stator circuits. For instance, the flux linkage in the phase a winding at any instant is given by

$$\psi_a = -l_{aa} i_a - l_{ab} i_b - l_{ac} i_c + l_{afd} i_{fd} + l_{akd} i_{kd} + l_{akq} i_{kq} \tag{2.22}$$

The negative sign associated with stator winding currents is due to their assumed direction. Similar expressions apply to flux linkages in the other two phases.

The self inductance l_{aa} is equal to the ratio of flux linking phase a winding to the current i_a with currents in all other circuits equal to zero. Phase a has an mmf that is sinusoidal distributed in space with its peak equal to $N_a i_a$ centred on the phase a axis, N_a being the effective turns per phase. The mmf can be resolved into two other sinusoidal distributed mmf's, centred on the d- and q-axes respectively. The peak values of the two component waves are peak

$$mmf_{ad} = N_a i_a \cos\theta \tag{2.23}$$

And $mmf_{aq} = N_a i_a \cos(\theta + 90) = -N_a i_a \sin\theta$ (2.24)

Air gap fluxes per pole along the two axes are

$$\Phi_{gad} = (N_a i_a \cos\theta) P_d \tag{2.25}$$

And $\Phi_{gaq} = (-N_a i_a \sin\theta) P_q$ (2.26)

where P_d and P_q are the permeance coefficients of the d- and q-axis, respectively. The total air gap flux linking phase a is

$$\begin{aligned}\Phi_{gaa} &= \Phi_{gad}\cos\theta - \Phi_{gaq}\sin\theta \\ &= N_a i_a \left(P_d \cos^2\theta + P_q \sin^2\theta\right) \\ &= N_a i_a \left(\frac{P_d + P_q}{2} + \frac{P_d - P_q}{2}\cos 2\theta\right)\end{aligned} \tag{2.27}$$

The self inductance l_{gaa} of phase a due to air gap flux is

$$\begin{aligned}l_{gaa} &= \frac{N_a \Phi_{gaa}}{i_a} \\ &= N_a^2 \left(\frac{P_d + P_q}{2} + \frac{P_d - P_q}{2}\cos 2\theta\right) \\ &= L_{g0} + L_{aa2}\cos 2\theta\end{aligned} \tag{2.28}$$

The total self inductance l_{aa} is given by adding to the above the leakage inductance L_{al} which represents the leakage flux not crossing the air gap:

$$\begin{aligned} l_{aa} &= L_{al} + l_{gaa} \\ &= L_{al} + L_{g0} + L_{aa2}\cos 2\theta \\ &= L_{aa0} + L_{aa2}\cos 2\theta \end{aligned} \tag{2.29}$$

Since the windings of phases b and c are identical to that of phase a and are displaced from it by 120^0 and 240^0 respectively, we have:

$$l_{bb} = L_{aa0} + L_{aa2}\cos 2(\theta - \frac{2\pi}{3}) \tag{2.30}$$

And

$$l_{cc} = L_{aa0} + L_{aa2}\cos 2(\theta + \frac{2\pi}{3}) \tag{2.31}$$

The mutual inductance l_{ab} can be found by evaluating the air gap flux Φ_{gab} linking phase b when only phase a is excited by replacing θ by $\theta - \dfrac{2\pi}{3}$ in Equation 2.27.

$$\begin{aligned} \Phi_{gab} &= \Phi_{gad}\cos(\theta - \frac{2\pi}{3}) - \Phi_{gaq}\sin(\theta - \frac{2\pi}{3}) \\ &= N_a i_a \left[P_d \cos\theta \cos\left(\theta - \frac{2\pi}{3}\right) + P_q \sin\theta \sin\left(\theta - \frac{2\pi}{3}\right) \right] \\ &= N_a i_a \left[-\frac{P_d + P_q}{4} + \frac{P_d - P_q}{2} \cos\left(2\theta - \frac{2\pi}{3}\right) \right] \end{aligned}$$

The mutual inductance between phases a and b due to the air gap flux is

$$\begin{aligned} l_{gab} &= \frac{N_a \Phi_{gab}}{i_a} \\ &= -\frac{1}{2}L_{g0} + L_{ab2}\cos\left(2\theta - \frac{2\pi}{3}\right) \end{aligned}$$

There is a very small amount of mutual flux around the ends of windings which does not cross the air gap. With this flux included, the mutual inductance between phases a and b can be written as

$$l_{ab} = l_{ba} = -L_{ab0} + L_{ab2}\cos(2\theta - \frac{2\pi}{3}) \\ = -L_{ab0} - L_{ab2}\cos\left(2\theta - \frac{\pi}{3}\right) \tag{2.32}$$

Similarly,

$$l_{bc} = l_{cb} = -L_{ab0} - L_{ab2}\cos(2\theta - \pi) \tag{2.33}$$

$$l_{ca} = l_{ac} = -L_{ab0} - L_{ab2}\cos(2\theta - \frac{\pi}{3}) \tag{2.34}$$

From the Equations 2.28 to 2.34 above, it can be readily seen that $L_{ab2} = L_{aa2}$ and also that L_{ab0} is nearly equal to $\frac{1}{2}L_{aa0}$.

Mutual inductance between stator and rotor windings when the variations in air gap due to stator slots are neglected varies due to relative motion between the windings themselves. When a stator winding is lined up with a rotor winding, the maximum flux is linking the two windings and the mutual inductance is of maximum value. When the two windings are displaced by 90^0 no flux links the two circuits and the mutual inductance is zero.

With a sinusoidal distribution of mmf and flux waves,

$$l_{afd} = L_{afd}\cos\theta \tag{2.35}$$

$$l_{akd} = L_{akd}\cos\theta \tag{2.36}$$

$$l_{akq} = L_{akq}\cos(\theta + \frac{\pi}{2}) \\ = -L_{akq}\sin\theta \tag{2.37}$$

For considering the mutual inductance between phase b and the rotor circuits, θ is replaced by $\theta - \frac{\pi}{3}$; for phase c winding θ is replaced by $\theta + \frac{\pi}{3}$.

Knowing the expressions for all the stator inductances, on substituting them into Equation 2.22, we obtain

$$\psi_a = -i_a\left[L_{aa0} + L_{aa2}\cos 2\theta\right] + i_b\left[L_{ab0} + L_{aa2}\cos(2\theta + \frac{\pi}{3})\right]$$
$$+ i_c\left[L_{ab0} + L_{aa2}\cos(2\theta - \frac{\pi}{3})\right] + i_{fd}L_{afd}\cos\theta \tag{2.38}$$
$$+ i_{kd}L_{akd}\cos\theta - i_{kq}L_{akq}\sin\theta$$

Similarly,

$$\psi_b = i_a\left[L_{ab0} + L_{aa2}\cos(2\theta + \frac{\pi}{3})\right] - i_b\left[L_{aa0} + L_{aa2}\cos 2(\theta - \frac{2\pi}{3})\right]$$
$$+ i_c\left[L_{ab0} + L_{aa2}\cos(2\theta - \pi)\right] + i_{fd}L_{afd}\cos(\theta - \frac{2\pi}{3}) \tag{2.39}$$
$$+ i_{kd}L_{akd}\cos(\theta - \frac{2\pi}{3}) - i_{kq}L_{akq}\sin(\theta - \frac{2\pi}{3})$$

And

$$\psi_c = i_a\left[L_{ab0} + L_{aa2}\cos(2\theta - \frac{\pi}{3})\right] + i_b\left[L_{ab0} + L_{aa2}\cos(2\theta - \pi)\right]$$
$$- i_c\left[L_{aa0} + L_{aa2}\cos 2(\theta + \frac{2\pi}{3})\right] + i_{fd}L_{afd}\cos(\theta + \frac{2\pi}{3}) \tag{2.40}$$
$$+ i_{kd}L_{akd}\cos(\theta + \frac{2\pi}{3}) - i_{kq}L_{akq}\sin(\theta + \frac{2\pi}{3})$$

Looking at rotor circuits, the rotor voltage equations are

$$e_{fd} = p\psi_{fd} + R_{fd}i_{fd} \tag{2.41}$$

$$0 = p\psi_{kd} + R_{kd}i_{kd} \tag{2.42}$$

$$0 = p\psi_{kq}i_{kq} \tag{2.43}$$

The rotor circuit flux linkages are determined as follows:

$$\psi_{fd} = L_{ffd}i_{fd} + L_{fkd}i_{kd} - L_{afd}\left[i_a\cos\theta + i_b\cos(\theta - \frac{2\pi}{3}) + i_c\cos(\theta + \frac{2\pi}{3})\right] \tag{2.44}$$

$$\psi_{kd} = L_{fkd}i_{fd} + L_{kkd}i_{kd} - L_{akd}\left[i_a\cos\theta + i_b\cos(\theta - \frac{2\pi}{3}) + i_c\cos(\theta + \frac{2\pi}{3})\right] \tag{2.45}$$

$$\psi_{kq} = L_{kkq} i_{kq} + L_{akq} \left[i_a \sin\theta + i_b \sin(\theta - \frac{2\pi}{3}) + i_c \sin(\theta + \frac{2\pi}{3}) \right] \tag{2.46}$$

2.2.5.4 The dq0 Transformation

The concept of resolving armature quantities into two rotating components, one aligned with the field winding axis, the direct axis component, and one in quadrature with the field winding axis, the quadrature axis component, was introduced as a means of simplifying analysis in salient pole machines. The usefulness of the concept comes from the fact that although each of the stator phases sees a time varying inductance due to the saliency of the rotor, the transformed quantities rotate with the rotor and hence see constant magnetic paths (Fitzgerald et al. 1985: 364-365).

Since the resultant mmf wave to the currents in the armature phases travels along the periphery of the stator at a synchronous speed, for a balanced synchronous operation, the armature mmf wave appears stationary with respect to the rotor and has sinusoidal space distribution. Therefore, the armature mmf wave can be resolved into two sinusoidal distributed mmf waves, one with its peak over the d-axis and the other having its peak over the q-axis. Thus all stator variables can be referred to rotor. The full transformation of the abc phase variables to d- and q-axis is facilitated by the Park's transformation and the variables are said to have been transformed into dq0 variables. For currents dq0 variables can be obtained as:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.47}$$

The inverse transformation is given by:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{2.48}$$

The above transformations also apply to stator flux linkages and voltages.

2.2.5.5 Synchronous Generator Equations in dq0 Components

Kundur (1994:69) has shown, that transforming expressions 2.38, 2.39, and 2.40 for ψ_a, ψ_b, and ψ_c into dq0 components and with relevant reduction of terms involving trigonometric terms results to the following expressions

$$\psi_d = -(L_{aa0} + L_{ab0} + \frac{3}{2}L_{aa2})i_d + L_{afd}i_{fd} + L_{akd}i_{kd}$$

$$\psi_q = -(L_{aa0} + L_{ab0} - \frac{3}{2}L_{aa2})i_q + L_{akq}i_q$$

$$\psi_0 = -(L_{aa0} - 2L_{ab0})i_0$$

With introduction of new inductances

$$L_d = L_{aa0} + L_{ab0} + \frac{3}{2}L_{aa2} \tag{2.49}$$

$$L_q = L_{aa0} + L_{ab0} - \frac{3}{2}L_{aa2} \tag{2.50}$$

$$L_0 = L_{aa0} - 2L_{ab0} \tag{2.51}$$

Then flux linkage equations become

$$\psi_d = -L_d i_d + L_{afd}i_{fd} + L_{akd}i_{kd} \tag{2.52}$$

$$\psi_q = -L_q i_q + L_{akq}i_{kq} \tag{2.53}$$

$$\psi_0 = -L_0 i_0 \tag{2.54}$$

The dq0 components of stator flux are seen to be related to the components of stator and rotor currents through constant inductances.

Rotor flux linkages in dq0 components are obtained by substituting the expressions for i_d and i_q in Equations 2.44 to 2.46 which yields

$$\psi_{fd} = L_{ffd} i_{fd} + L_{fkd} i_{kd} - \frac{3}{2} L_{afd} i_d$$

$$\psi_{kd} = L_{fkd} i_{fd} + L_{kkd} i_{kd} - \frac{3}{2} L_{akd} i_d$$

$$\psi_{kq} = L_{kkq} i_{kq} - \frac{3}{2} L_{akq} i_q$$

Even in rotor circuits, all inductances are seen to be constant independent of rotor position.

Equations 2.19 to 2.21 express stator phase voltages in terms of phase flux linkages and currents, transforming them to expressions in terms of dq0 components flux linkages and currents gives:

$$e_d = p\psi_d - \psi_q p\theta - R_a i_d \tag{2.55}$$

$$e_q = p\psi_q + \psi_d p\theta - R_a i_q \tag{2.56}$$

$$e_0 = p\psi_0 - R_a i_0 \tag{2.57}$$

The term $p\theta$ represents the angular velocity ω_r of the rotor. In Equations 2.55 and 2.56, those terms result from transformation from a stationary to a rotating reference frame. They represent the fact that a flux wave rotating in synchronism with the rotor creates voltages in stationary armature coil. The terms $\psi_d p\theta$ and $\psi_q p\theta$ are referred to as speed voltages while the terms $p\psi_d$ and $p\psi_q$ as transformer voltages.

The speed voltages terms are the dominant components of the stator voltages. In fact, under steady-state conditions the transformer voltage terms and i_0 is equal to zero, therefore

$$e_d = -\psi_q p\theta - R_a i_d = -\omega_r \psi_q - R_a i_d \tag{2.58}$$

$$e_q = \psi_d p\theta - R_a i_q = \omega_r \psi_d - R_a i_q \tag{2.59}$$

$$e_0 = 0 \tag{2.60}$$

In a balanced steady-state working condition, synchronous generator's stator phase voltages may be written as

$$e_a = E_m \cos(\omega_s t + \alpha) \tag{2.61}$$

$$e_b = E_m \cos(\omega_s t - \frac{2\pi}{3} + \alpha) \tag{2.62}$$

$$e_c = E_m \cos(\omega_s t + \frac{2\pi}{3} + \alpha) \tag{2.63}$$

In Equations 2.61 to 2.63, ω_s is the angular frequency and α is the phase angle of e_a with respect to the time origin. The dq0 transformation of the above phase voltages gives

$$e_d = E_m \cos(\omega_s t + \alpha - \theta) \tag{2.64}$$

$$e_q = E_m \sin(\omega_s t + \alpha - \theta) \tag{2.65}$$

The angle θ by which the d-axis leads the axis of phase a is evaluated as

$$\theta = \omega_r t + \theta_0 \tag{2.66}$$

The angle θ_0 is the value of θ at $t = 0$.

In steady state, rotor rotates at synchronous speed, thus $\omega_r = \omega_s$, substituting for θ in Equations 2.64 and 2.65 yields

$$e_d = E_m \cos(\alpha - \theta_0) \tag{2.67}$$

$$e_q = E_m \sin(\alpha - \theta_0) \tag{2.68}$$

Using E_t to denote per unit RMS value of the armature (stator) terminal voltage and noting that in per unit RMS and peak values are equal

$$e_d = E_t \cos(\alpha - \theta_0) \tag{2.69}$$

$$e_q = E_t \sin(\alpha - \theta_0) \tag{2.70}$$

Despite of being scalar quantities, in view of their trigonometric relationship the armature voltages can be expressed as phasors in a complex plane having d-and q-axes as coordinate axes in figure 2.16.

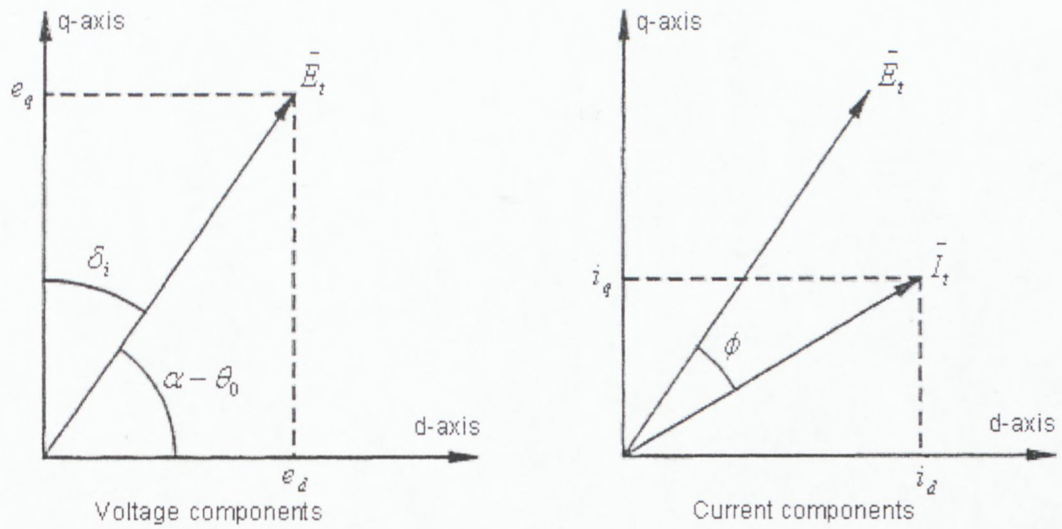


Figure 2.16: Phasor Representations of dq0 Components of Armature Voltage and Current

Therefore, the armature terminal voltage may be expressed in complex form as

$$\bar{E}_t = e_d + je_q \tag{2.71}$$

By denoting δ_i as the angle by which the q-axis leads the phasor $\bar{E}_t$, Equations 2.69 and 2.70 become

$$e_d = E_t \sin\delta_i \tag{2.72}$$

$$e_q = E_t \cos\delta_i \tag{2.73}$$

Similarly, the dq0 components of armature terminal current I_t can be expressed as phasors. If ϕ is the power factor angle, they can be expressed as

$$i_d = I_t \sin(\delta_i + \phi) \tag{2.74}$$

$$i_q = I_t \cos(\delta_i + \phi) \tag{2.75}$$

And the terminal current as

$$I_t = i_d + ji_q \tag{2.76}$$

The relationships between dq0 components of armature terminal voltage and current are defined by Equations 2.52, 2.57, 2.59 and 2.60. Thus

$$
\begin{aligned}
e_d &= -\omega_r \psi_q - R_a i_d \\
&= \omega_r L_q i_q - R_a i_d \\
&= X_q i_q - R_a i_d
\end{aligned}
\tag{2.77}
$$

$$
\begin{aligned}
e_q &= \omega_r \psi_d - R_a i_q \\
&= -X_d i_d + X_{ad} i_{fd} - R_a i_q
\end{aligned}
\tag{2.78}
$$

The reactance X_d and X_q are direct-axis and quadrature-axis synchronous reactance, respectively. They represent the inductive effects of the armature mmf wave by separately accounting for its d- and q-axis components.

For identification of the d-and q-axis positions relative to $\bar{E}_t$, let us define a voltage $\bar{E}_q$ as

$$
\begin{aligned}
\bar{E}_q &= \bar{E}_t + (R_a + jX_q)\bar{I}_t \\
&= (e_d + je_q) + (R_a jX_q)(i_d + ji_q)
\end{aligned}
\tag{2.79}
$$

Substitution of Equations 2.77 and 2.78, followed by reduction of the resulting expression, gives the expression for $\bar{E}_q$ in phasor form with d, q axes as reference:

$$
\bar{E}_q = j\left[X_{ad} i_{fd} - (X_d - X_q) i_d\right] \tag{2.80}
$$

The corresponding phasor diagram is shown in Figure 2.17 bellow. The position of the q-axis with respect to $\bar{E}_t$ can be identified by computing $\bar{E}_q$ and the voltage behind $R_a + jX_q$.

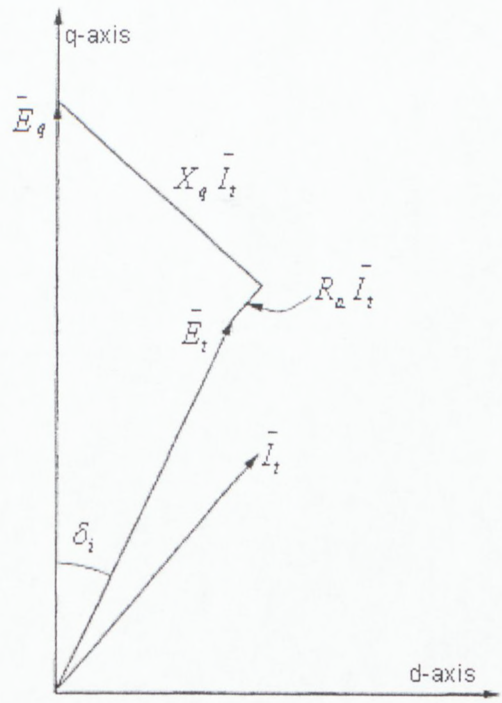


Figure 2.17: Phasor $\bar{E}_q$ in dq Complex Plane

Under no-load conditions, the current $i_d = i_q = 0$. Substituting in Equations 2.52, 2.53, 2.58, and 2.59 yields

$$\psi_d = L_{ad} i_{fd}$$

$$\psi_q = 0$$

$$e_d = 0$$

$$e_q = X_{ad} i_{fd}$$

Therefore,

$$\begin{aligned} \bar{E}_t &= e_d + je_q \\ &= jX_{ad} i_{fd} \end{aligned} \tag{2.81}$$

Under no-load, $\bar{E}_t$ has only the q-axis component and hence $\delta_i = 0$. As the machine is loaded, δ_i increases. Therefore, the angle δ_i is referred to as the internal rotor angle or load angle. It represents the angle by which the q-axis leads the stator terminal voltage phasor $\bar{E}_t$.

2.2.5.6 Steady-State Equivalent Circuit of Synchronous Generator

In a synchronous generator, the effect of saliency is not significant as far as the relationships between terminal voltages, armature current; power and excitation over the normal operating range are concerned. Therefore if saliency is neglected,

$$X_d = X_q = X_s$$

The reactance X_s is the synchronous reactance. Therefore,

$$\bar{E}_q = \bar{E}_t + (R_a + jX_s) \tag{2.82}$$

With $X_d = X_q$, from Equation 2.80, the magnitude of $\bar{E}_q$ is given by

$$E_q = X_{ad} i_{fd} \tag{2.83}$$

Considering Equations 2.82 and 2.83, equivalent circuit of the generator is as depicted in Figure 2.18.

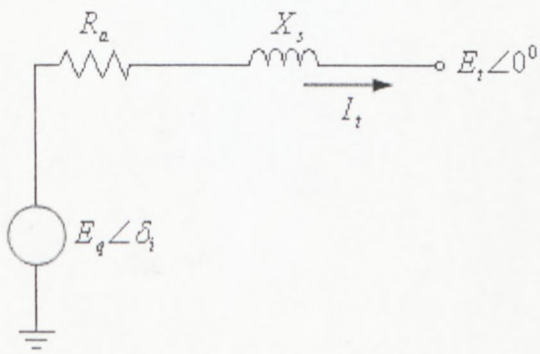


Figure 2.18: Steady-State Equivalent Circuit of Synchronous Generator

The voltage E_q is the effective internal voltage of the generator which is equal to $X_{ad} i_{fd}$ hence is the excitation voltage due to the field current. The value of resistance R_a is relatively small, normally less than 0.1 per unit compared to that of reactance X_s which ranges between 1.0 and 2.0 per unit. In addition, the resistance decreases while the reactance increases with increasing size of the generator. Therefore, the resistance can be neglected in the equivalent circuit. With regulation of field current, synchronous generator is capable of regulating its terminal voltages.

2.2.5.7 Power Output of Synchronous Generator

Total power a synchronous generator can deliver at its terminals is determined as

$$
\begin{aligned}
S &= \bar{E}_t \bar{I}_t^* \\
&= (e_d + je_q)(i_d + ji_q) \\
&= (e_d i_d + e_q i_q) + j(e_q i_d - e_d i_q)
\end{aligned}
\tag{2.84}
$$

From Equation 2.84, active power P_t and reactive power Q_t components respectively are deduced as

$$P_t = e_d i_d + e_q i_q \tag{2.85}$$

And

$$Q_t = e_q i_d - e_d i_q \tag{2.85}$$

The steady-state electromagnetic torque in per unit is given by

$$
\begin{aligned}
T_e &= \psi_d i_q - \psi_q i_d \\
&= (e_d i_d + e_q i_q) + R_a (i_d^2 + i_q^2) \\
&= P_t + R_a I_t^2
\end{aligned}
\tag{2.86}
$$

The maximum active power a synchronous generator can deliver is determined by the maximum torque which can be applied without loss of synchronism with the external system to which it is connected.

Since the machine can be represented by simple impedance, the study of power limits becomes merely a special case of the more general problem of the limitation of power flow through inductive impedance which is expressed by the power-angle characteristic equation.

Therefore, if, as is usually the case, the resistance R_a is neglected, the power output of the generator is said to be

$$P_t = \frac{E_q E_t}{X_s} \sin \delta_i \tag{2.87}$$

In this case δ_i is referred to as power angle.

For constant voltages, the maximum power $P_{t\max} = \dfrac{E_q E_t}{X_s}$ occurs when $\delta_i = 90^0$.

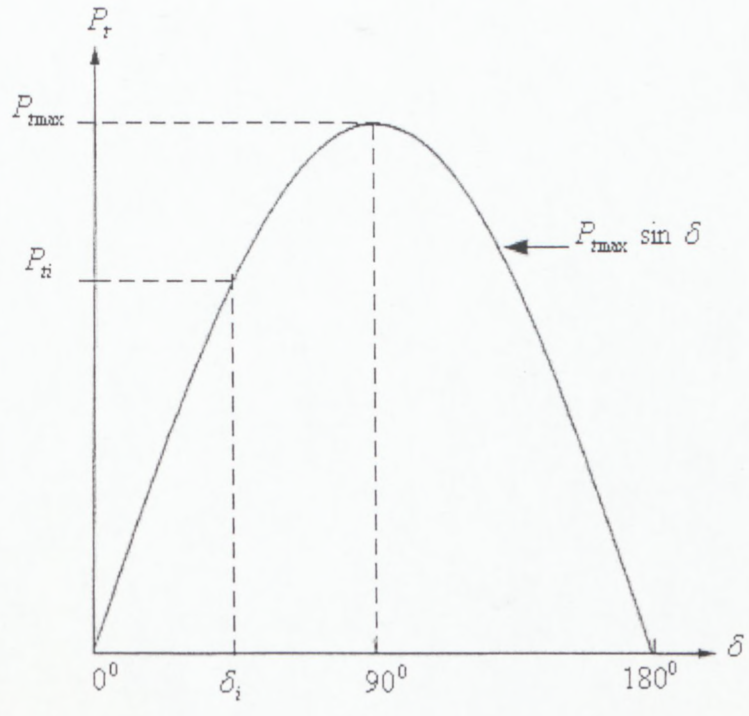


Figure 2.19: Power Angle Curve

For successful operation, stability considerations dictate that synchronous generators achieve steady-state at a power angle δ_i less than 90^0, Figure 2.19 shows power angle curve.

2.2.5.8 Synchronous Generator Rating

Synchronous generators are usually rated in terms of the maximum kVA load at a specific voltage and power factor which they can carry continuously without overheating. The active power of the generator is limited to a value within the kVA rating by the capability of its prime mover. When the active power loading and voltage are fixed, the allowable reactive power loading is limited by either armature or field heating (reactive capability curves).

The interrelations between terminal voltage, armature current, power and excitation in the normal operating range for the salient-pole machine, can be similarly treated as that of cylindrical-rotor machine with satisfactory accuracy. Only at small excitations the difference between cylindrical-rotor and salient-pole theory will become important.

2.2.5.9 Parallel Operation of Synchronous Generators

The dynamics characteristics of power systems are dominated by aspects of electromechanical energy interchange of the synchronous generators in the system. The requirement of a reliable supply for a power system is that all the synchronous generators in the system must maintain synchronous operation. The active power distribution among them depends on the set-point of the drooping speed-power characteristics of their individual prime movers as depicted in Figure 2.9 and Figure 2.10. The terminal voltage and reactive power supplied by the generators to the system are affected by changes in their respective excitation systems. In addition, the excitation systems contribute in improvement of operation stability of the synchronous generators.

2.2.5.10 Induction Generator

The distinctive feature of the induction machine being a motor or generator is that the rotor currents are induced by electromagnetic induction from the stator. The induction machine of interest in this study was an induction machine with cage rotor; the attractive feature of this particular induction machine is its simplicity and ruggedness in construction.

The stator windings of a three phase induction machine are similar to those of a synchronous machine. When the stator armature winding of an induction machine is connected to an ac system, a synchronously rotating flux is established in the air-gap as established earlier. With rotor stationary, each rotor phase senses a flux linkage varying between positive and negative maxima at supply frequency. The induced phase voltages in the rotor phases cause supply frequency currents to flow, the mmf opposing the stator mmf. In addition however, due to positioning of the windings and the time displacement between the phase currents, the resultant rotor field will rotate in step with the stator field. The force on the conductors will be in the direction of the field motion. If the resultant torque developed is greater than the mechanical resisting torques, the rotor will accelerate to some speed n rev/s, where the developed torque and the opposing mechanical torque are balanced. In this case the machine is operated as a motor. The equivalent circuit of an induction machine in motor operation regime is shown in Figure 2.20.

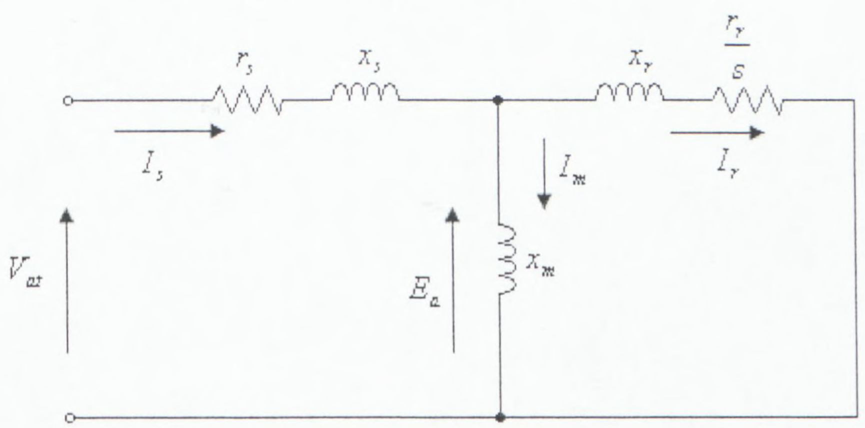


Figure 2.20: Equivalent Circuit of an Induction Machine as a Motor

The difference in speed of rotation between the flux and the rotor, expressed as percentage of synchronous speed n_s, is called slip s.

$$s = \frac{n_s - n}{n_s} \tag{2.88}$$

The slip is positive when the machine is operated as a motor and the rotor speed is always less than that of the flux. This relative motion of flux and rotor conductors induces voltages of frequency sf. The field produced by the rotor currents revolves at the same speed as the stator field. The stator and rotor fields are therefore stationary with respect to each other, a steady torque is produced and rotation is maintained. The rotor current is determined by the voltage induced in the rotor at its leakage impedance, both at slip frequency. At no load, the machine operates with negligible slip. If a mechanical load is applied, the slip increases such that the induced voltage and current produce the torque required by the load.

Under normal running conditions the slip is small so as the slip frequency, consequently the rotor impedance is largely resistive, and rotor current is nearly proportional to and in phase with the rotor voltage and is therefore very proportional to slip.

When rotor currents and voltages are reflected into the stator, their frequency is also changed to stator frequency, because the stator winding sees only mmf and flux waves travelling at synchronous speed.

As a generator, the induction machine is driven by a prime-mover; and as the rotor speed is increased to equal synchronous speed, there is no relative motion between rotor conductors and the flux hence no voltage or current is induced in the rotor bars. A further increase in speed causes a reversal in relative direction of rotation between the rotor bars and the flux, and the rotor voltage and current are correspondingly reversed. The slip under this condition is said to be negative. Shaft torque, supplied by the prime-mover is transferred across the air-gap to the stator, from which is delivered to the system as generated power. The net power output is the shaft input less the losses within the machine and is a function of the slip.

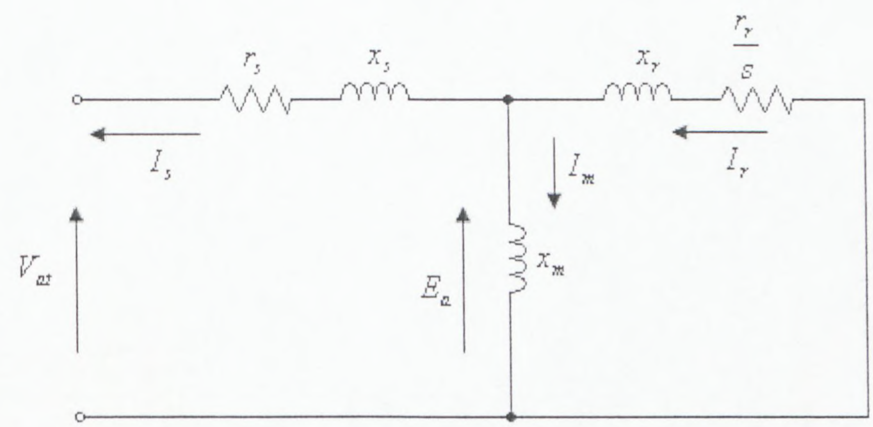


Figure 2.21: Equivalent Circuit of an Induction Machine as a Generator

Where rotor resistance, reactance and current are r_r, x_r, I_r expressed in terms of stator voltage and frequency; r_s, x_s, I_s are stator resistance, reactance and current; x_m, I_m are magnetizing branch reactance and magnetizing current; and finally V_t, E_a, s are terminal voltage, air-gap voltage and slip respectively.

Both equivalent circuits contain two variables; the slip s which is a function of speed, and the magnetizing reactance x_m which is determined by saturation and is a function of the air-gap voltage E_a. For terminal voltage variations within the narrow limits, which are normally encountered on power systems, it is sufficiently accurate to consider the magnetizing reactance a constant. Simplification of the induction machine equivalent circuits were obtained after omitting the shunt conductance and the associated core-loss effect deducted from input power, the equivalent circuits then become as shown in Figure 2.20 and Figure 2.21, the error introduced is negligible(Barkle and Ferguson, 1954, 12-19).

The dynamics of the induction machine can be derived from the equivalent circuit of motor operation regime. When the slip is known or assumed and the magnetizing reactance is known, the power transferred across the air gap to the rotor is

$$P_g = \frac{r_r}{s} I_r^2 \tag{2.89}$$

The rotor resistance loss is

$$P_{lr} = r_r I_r^2 \tag{2.90}$$

Therefore, the mechanical power transferred to the shaft per phase is

$$\begin{aligned} P_{sh} &= P_g - P_{lr} \\ &= \frac{r_r}{s} I_r^2 - r_r I_r^2 \\ &= r_r \left(\frac{1-s}{s} \right) I_r^2 \end{aligned} \tag{2.91}$$

For this mater, the induction machine can be represented by an alternative equivalent circuit shown in Figure 2.22.

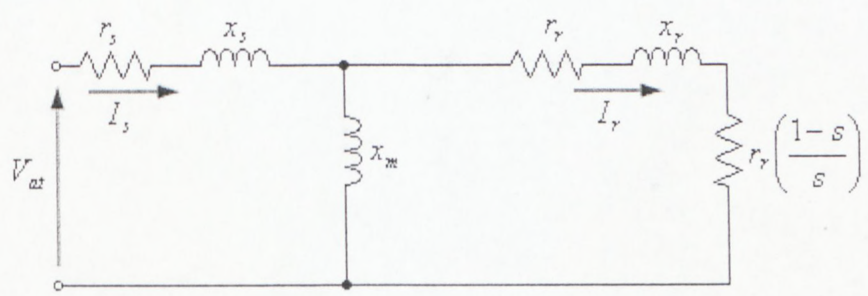


Figure 2.22: Alternative Form of Induction Machine Equivalent Circuit

For a three-phase motor, the electromagnetic torque developed by the motor is

$$T_e = \frac{3P_{sh}}{\omega_m}$$

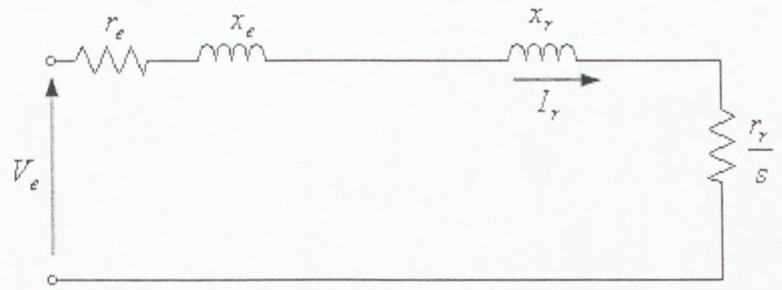
The angular velocity of the rotor in mechanical rad/s, ω_m is determined as

$$\begin{aligned} \omega_m &= \omega_r \frac{2}{P} \\ &= \omega_s (1-s) \frac{2}{P} \end{aligned}$$

Hence

$$T_e = 3 \frac{P}{2} \frac{r_r}{s\omega_s} I_r^2 \tag{2.92}$$

Equation 2.92 shows, that the electromagnetic torque T_e is dependent of slip s. However, for analysis of the torque-slip relationship, the equivalent circuit of Figure 2.21 may be simplified by replacing the part of the stator and magnetising circuit by its Thevenin's equivalent. Figure 2.23 shows the resulting simplified equivalent circuit.



$$r_e + jx_e = \frac{jx_m(r_s + jx_s)}{r_s + j(x_s + x_m)}$$

$$V_e = \frac{jx_m V_{at}}{r_s + j(x_s + x_m)}$$

Figure 2.23: Simplified Equivalent Circuit of an Induction Machine

From Figure 2.23, the rotor current is

$$I_r = \frac{V_e}{(r_e + r_r/s) + j(x_e + x_r)} \tag{2.93}$$

From Equation 2.92, the torque is

$$T_e = 3\frac{P}{2}\left(\frac{r_r}{s\omega_s}\right)\frac{V_e}{(r_e + r_r/s)^2 + (x_e + x_r)^2} \tag{2.94}$$

A typical relationship between torque and slip/speed is depicted in Figure 2.24. Between zero and synchronous speed n_s, the machine performs as a motor. Beyond synchronous speed, slip s is negative, representing generator operation.

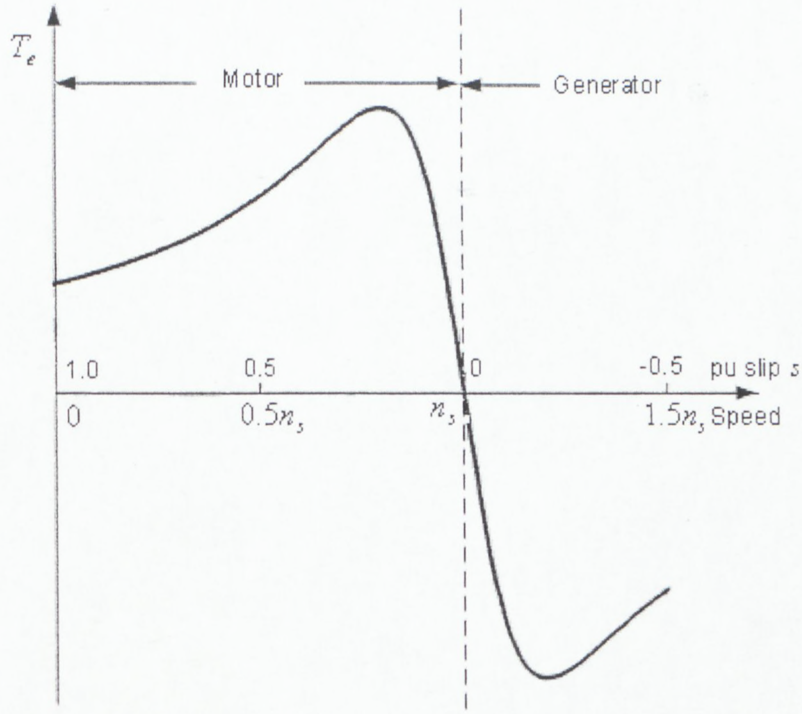


Figure 2.24: Typical Torque-Speed Characteristic of an Induction Machine

The maximum torque occurs when

$$\frac{r_s}{s} = Z' \tag{2.95}$$

Where

$$Z' = \sqrt{r_e^2 + (x_e + x_r)^2} \tag{2.96}$$

Therefore, per unit slip at maximum torque is

$$s_{T\max} = \frac{r_r}{Z'} \tag{2.97}$$

From Equation 2.94, the maximum torque is

$$\begin{aligned} T_{\max} &= 3\frac{P}{2\omega_s}\frac{0.5V_e^2}{r_e + Z'} \\ &= 3\frac{1}{\omega_{ms}}\frac{0.5V_e^2}{r_e + Z'} \end{aligned} \tag{2.98}$$

In Equation 2.98, $\omega_s = 2\pi f$ and ω_{ms} is the synchronous speed in mechanical radians per second.

From Figure 2.24, we observe that the torque-speed characteristic of an induction machine is symmetrical about zero-slip axis where the machine is about to change the operation regime from motor to generator or vice versa. Therefore, the maximum torque and slip also reflect the maximum power-input and speed respectively, which can be subjected to the machine by a prime mover when operated as a generator.

The equivalent circuit in Figure 2.21 can be reduced to single impedance.

$$Z = r_s + jx_s \frac{\left(\frac{r_r}{s} + jx_r\right)(jx_m)}{\frac{r_r}{s} + j(x_r + x_m)} \tag{2.99}$$

The stator current

$$I_s = -\frac{V_{at}}{Z} \tag{2.100}$$

The air-gap voltage is $E_a = V_{at} + I_s(r_s + jx_s)$ (2.101)

Therefore, the magnetising current to be supplied to the machine is

$$I_m = -\frac{E_a}{jx_m}$$

The exciting current I_m is the additional stator current required to create the resultant air-gap flux as combined effect of mmf 's of the stator and rotor currents and is a function of the e.m.f E_a.

De Mello(1981:2610-2618) showed that introduction of induction generators in power systems could affect the dominant type of stability problem which is the loss of synchronism resulting to break of networks and interruption of power supply because dynamic characteristics of induction generators differ from those of synchronous generators since energy interchange with induction generator depends on slip. However, setbacks of the machines were also mentioned including that induction generators absorb reactive power and are incapable of controlling voltage reasons which contributed to their modest size applications where grid could take care of the voltage and reactive power demands.

With recent development in power electronics especially invention of static var sources, the opportunity of employing large scale induction generators was indicated to be in the coming. It was also shown that the added cost of controlled var generation required, could be offset if account is taken of economics inherent in induction versus synchronous generator design and manufacture.

The work successfully investigated dynamic characteristics of a hypothetical power system composed of induction generators through two types of simulations, one where rotor, stator and network transients are treated by differential equations to confirm the feasibility of flux build up through the process of discharge of a three phase capacitor bank. The second simulation took into account the rotor winding differential equations but treated the stator and network in algebraic fashion as is done for fundamental frequency analysis. The result showed that systems containing induction generators as well as a mixture of induction and synchronous generator with large percentage of induction machine were both feasible.

In another study Parsons (1984:497-503) showed that, in spite of their similarities in electrical and mechanical construction induction generators and induction motors differ in voltage ratings. As a generator, a machine will be rated at a slightly higher voltage level than it would as a motor. But it is the opposite when efficiency of operation is considered. Comparing to synchronous generators, it had been realised that, in large sizes synchronous generators have higher efficiency than induction generators. A large synchronous generator can have efficiency as high as 98 percent, but it was also noted that, at certain range both machines may have the same efficiency. For example a 3000kW two pole machine, being either induction or synchronous generator has an efficiency of about 98.3 percent.

In the work induction generator was also associated with little contribution to system short current since its fault contribution decays as fast as the rotating magnetic field collapses and its stored energy dissipated. It was mentioned that induction generator do not introduce harmonic voltages to the system, in the opposite, the squirrel cage rotor tend to dampen out harmonic disturbances. On maintenance requirements, the work indicated that, induction generator would have the same maintenance requirements as would induction motor of comparable size. Due to its simple rugged construction, induction generator is inherently a low-maintenance machine compared to synchronous generator.

2.2.5.11 Self Excited Induction Generator

The description of operation of induction generator shows that the only requirements for obtaining an output are source of magnetising vars and suitable load below the power limit (Barkle and Ferguson, 1954. 12-19). Self excitation of an induction generator by employing external capacitor was introduced by Basset and Potter (1935. 540-545). If an appropriate capacitor bank is connected across the induction generator, the induced voltage and current would rise until the var demanded by machine and that supplied by the capacitor balance. The voltage and frequency are determined by the value of the capacitor, speed of the prime mover, parameters of the machine and the load (Basset and Potter, 1935. 540-545).

In spite of a number of advantages attributed to self excited induction generator encompassing low cost, high reliability, absence of DC source for excitation, ruggedness, self protection against severe over loads, and ease of maintenance, it suffers from inherent poor voltage regulation due to the difference between the vars supplied by the capacitors and the vars required by the machine and load (Singh, 2004. 107-114). With capacitor bank, voltage regulation proves to be difficult because most of system load is dynamic which demand the introduction of changing capacitance or variable var source to the terminals of the generator.

2.2.5.12 Voltage Control and Reactive Power Distribution between Parallel Generators

Maintaining the voltage level and distribution of reactive power between parallel operated generators in a stable way are the fundamental roles of excitation systems of generators.

In the normal operation of a synchronous generator, the terminal voltage tends to vary as the load current it supplies varies due to armature reaction. An automatic voltage regulator (AVR) provided to control excitation system, automatically increase or decrease the excitation current respectively as the load current increase or decrease and maintain the terminal voltage level.

Induction generator has no ability to generate reactive power consequently suffers from voltage regulation capability. For its operation, it has to be supplied with reactive power from an external source; the case of induction generator connected to the grid or in parallel with synchronous generator, the regulation is taken care of by the synchronous generators involved. As for self excited induction generator with load current variations, the terminal voltage can be maintained only by using variable var source as voltage regulator, the fact previously established by Ooi, and David (1979: 69-74) in their study on the use of synchronous condenser in conjunction with induction generator for improved voltage regulation.

2.2.6 Electrical Connection Equipment

Electrical main connections consist of generators, transformers, switchgears and instrument transformers as well as conductors between them. Basically, the electrical main connections are the principal part of electrical equipment in a hydropower plant. They directly affect the investment, operation and maintenance of the plant. Hence the selection of a scheme for main connections and the equipment form the key factor of electrical design for a hydropower plant.

2.2.6.1 Bus bar

The functions of bus bars are to collect and redistribute the electrical energy. On the generator voltage side, generators are connected to the bus through circuit breakers and isolators. The leading-out lines of the bus are either the leading-in lines on the low voltage side of the step-up transformers or the transmission line on the generator voltage side.

On the high voltage side of step-up transformer, the leading out lines are the feeders. On this side, both step-up transformers and feeders have their respective circuit breakers and isolators.

Single bus scheme is frequently adopted on high voltage side of a step-up transformer in small hydropower plants while on generator voltage side, is when number of generating units is less than three. Depending on degree of reliability and flexibility required, busbar can be sectionalized using an isolator or circuit breaker.

2.2.6.2 Transformers

For small hydropower plant the nearby load connected on the generator voltage side and the auxiliary power are generally small. Then the main transformer capacity could be selected according to the installed capacity of the hydroelectric generating units.

One main transformer is mostly adopted in a hydropower plant with one to three units.

2.2.6.3 High Voltage Circuit Breakers and Isolators

High voltage equipment refers to that with a voltage exceeding 1kV. High voltage circuit breaker is an important apparatus in small hydropower plant. It does not only make and break the electrical circuit in normal load, but also interrupts the short circuit current in fault conditions.

Main technical parameters of the high voltage circuit breaker include:

- Rated voltage
- Rated current
- Rated interrupting current
- Rated interrupting capacity
- Dynamic stability current and
- Thermal stability current

Isolator is installed between circuit breaker and busbar or transmission line. An isolator is a no-load operated switch.

2.2.6.4 Selection of High Voltage Electrical Equipment

Except for circuit breakers, all high voltage electrical equipment in small hydropower plant are selected for normal operations and checked under short-circuit conditions.

Normal operation refers the condition when the equipment is operating at the rated voltage and current. Under short-circuit conditions the equipment is verified for thermal and dynamic stability.

2.2.6.5 Relay Protection

In electrical energy production, continuity is the major requirement. Relay protection ensures safe and reliable operation of an electrical power system, as well as the quality of the electrical energy. In a three phase electrical system, faults or abnormal operating conditions often occur. Most dangerous fault is short-circuit, which can cause:

- The significant drop of supply voltage and jeopardize the normal operation of consumers.
- A tremendous short-circuit current flow through a faulty point leading to burning away of the faulty element.
- The heat and electro-dynamic forces generated by short-circuit current cause the faulty element to be damaged.
- Disturbance of stability of parallel operations between generators in the hydropower plant.

Apart from short-circuit, over current and over voltages also occur which often lead to damage of insulation of electrical equipment as a fault occurs to a small hydropower plant. Therefore relay protection in the plant should have both automatic protection of the equipment and sound alarm. In this regard, relay protection in small hydropower plant to a reasonable extent has to meet the basic requirements for a relay protection system namely selectivity, speediness, sensitivity and reliability.

2.3 Static Shunt Compensators

By definition, capacitors generate and reactors (inductors) absorb reactive power when connected to an ac power source. They have been used with mechanical switches for (coarsely) controlled var generation and absorption since the early days of ac power transmission. Continuously variable var generation or absorption for dynamic system compensation was originally provided by over- or under-excited rotating synchronous machines and, later, by saturating reactors in conjunction with fixed capacitors.

Line-commutated thyristors in conjunction with fixed capacitors and reactors have been employed in various circuit configurations to produce variable reactive output. These in effect provide variable shunt impedance by synchronously switching shunt capacitors and/or reactors "in" and "out" of the network. Using appropriate switch control, the var output can be controlled continuously from maximum capacitive to maximum inductive output at a given bus voltage. Recently, gate turn-off thyristors and other power semiconductors with internal turn-off capability have been used in switching converter circuits to generate and absorb reactive power without the use of ac capacitors or reactors. These perform as ideal synchronous compensators (condensers), in which the magnitude of the internally generated ac voltage is varied to control the var output.

All of the different semiconductor power circuits, with their internal control enabling them to produce var output proportional to an input reference, are collectively termed by the joint IEEE and CIGRE definition, static var generators (SVG). Thus, a static var compensator (SVC) is, by the IEEE CIGRE co-definition, a static var generator whose output is varied so as to maintain or control specific parameters (e.g., voltage, frequency) of the electric power system. The control input to the var generator can be arbitrary (within the operating range) reactive current, impedance, or power reference signal that the SVG is to establish at its output. According to the IEEE-CIGRE definition, an SVG becomes an SVC when it is equipped with external controls which derive the necessary reference for its input, from the operating requirements and prevailing variables of the power system, to execute the desired compensation. SVCs have been used in conventional power systems where continuous and fast control of reactive power is required (Bansal, 2005. 292-299). SVCs are shunt-connected static source or sink of reactive power.

Modern SVGs are based on high power semiconductor switching circuits which are of two types: those which employ thyristor-controlled reactors with fixed and/or thyristor-switched capacitors to realize variable reactive impedance (SVCs) and those which employ a switching power converter to realize a controllable synchronous voltage source (STATCOM) or (STATCON).

2.3.1 Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR)

An elementary single-phase thyristor-controlled reactor (TCR) is shown in Figure 2.25. It consists of a fixed reactor of inductance L, and a bi-directional thyristor valve (or switch) *SW*. Currently available large thyristors can block voltage up to 4000 to 9000 volts and conduct current up to 3000 to 6000 amperes. A thyristor valve can be brought into conduction by simultaneous application of a gate pulse to all thyristor of the same polarity. The valve will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied.

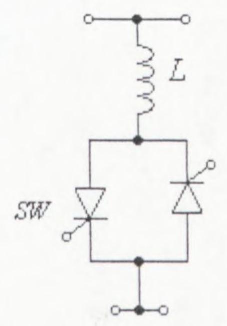


Figure 2.25: Elementary Single-Phase Thyristor-Controlled Reactor

The current in the reactor can be controlled from maximum to zero by the method of firing delay angle control. That is, the closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled. When the gating of the valve is delayed by an angle $\alpha(0 \le \alpha \le \pi/2)$ with respect to the crest of the voltage, the current in the reactor can be expressed with $v(t) = V\cos\omega t$ as follows:

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)dt = \frac{V}{\omega L}(\sin\omega t - \sin\alpha) \tag{2.102}$$

Since the thyristor valve, by definition, opens as the current reaches zero, Equation 2.102 is valid for the interval $\alpha \le \omega t \le \pi - \alpha$. For subsequent positive half-cycle intervals the same expression remains valid. For subsequent negative half-cycle intervals, the sign of the terms in Equation 2.102 become opposite. As the valve automatically turns off at the instant of current zero crossing, this process controls the conduction interval of the thyristor valve. That is, the delay angle α defines the conducting angle $\sigma : \sigma = \pi - 2\alpha$. Thus, as the delay angle α increases, the correspondingly increasing offset results in the reduction of the conduction angle σ of the valve, and consequently the reduction of the reactor current. When the maximum delay of $\alpha = \pi/2$, the offset also reaches its maximum of $V/\omega L$, at which both the conduction angle and the reactor current become zero. It is evident that the current in the reactor can be varied continuously by this method of delay angle control from maximum $(\alpha = 0)$ to zero $(\alpha = \pi/2)$.

If the TCR switching is restricted to a fixed delay angle, then it becomes a thyristor-switched reactor (TSR). The TSR provides a fixed inductive admittance and thus, when connected to the ac system, the reactive current in it will be proportional to the applied voltage.

2.3.2 Thyristor-Switched Capacitor (TSC)

A single-phase thyristor-switched capacitor (TSC) is shown in Figure2.26 consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor. This reactor is needed primarily to limit the surge current in the thyristor valve under abnormal operating conditions; it may also be used to avoid resonances with the ac system impedance at a particular frequency.

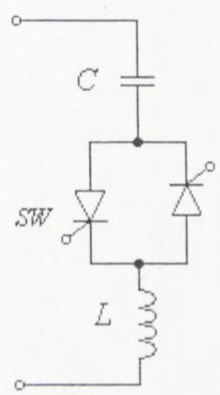


Figure 2.26: Thyristor- Switched Capacitor

Under steady-state conditions, when the thyristor valve is closed and TSC branch is connected to a sinusoidal ac voltage source, $v = V \sin \omega t$, the current in the branch is given by

$$i(\omega t) = V \frac{n^2}{n^2 - 1} \omega C \cos \omega t$$

Where

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$$

The amplitude of the voltage across the capacitor is

$$V_C = \frac{n^2}{n^2 - 1} V$$

The TSC branch can be disconnected (switched out) at any current zero by prior removal of the gate drive to the thyristor valve. At the current zero crossing, the capacitor voltage is at its peak value

$$v_{C,i=0} = Vn^2 / (n^2 - 1)$$

The disconnected capacitor stays charged to this voltage and, consequently, the voltage across the non-conducting thyristor valve varies between zero and peak-to-peak value of the applied ac voltage.

If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again, without any transient, at the appropriate peak of the applied ac voltage, for a positively and negatively charged capacitor respectively. Normally, the capacitor bank is discharged after disconnection. Thus, the reconnection of the capacitor may have to be executed at some residual capacitor voltage between zero and $Vn^2/(n^2 - 1)$. It follows that the maximum possible delay in switching in a capacitor bank is one full cycle of the applied ac voltage. It also follows that firing delay angle control is not applicable to capacitors; the capacitor switching must take place at that specific instant in each cycle at which the conditions for minimum transients are satisfied, that is, when the voltage across the thyristor valve is zero or minimum. For this reason, a TSC branch can provide only a step-like change in the reactive current it draws (maximum or zero). In other words, the TSC branch represents a single capacitive admittance which is either connected or disconnected from the ac system.

To approximate continuous current variation, several TSC branches in parallel may be employed, or the TSC branches have to be complemented with a TCR.

2.3.3 Fixed Capacitor, Thyristor-Controlled Reactor type SVC

A basic var arrangement using a fixed capacitor with a thyristor-controlled reactor (FC-TCR) is shown in Figure 2.27. The current in the reactor is varied by the method of firing delay angle control. The fixed capacitor in practice is usually substituted, fully or partially, by a filter that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power required, but it provide low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR.

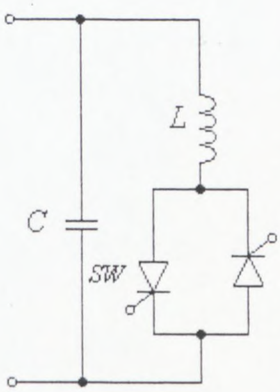


Figure 2.27: Fixed Capacitor with Thyristor-Controlled Reactor

The fixed capacitor, thyristor-controlled reactor type var generator may be considered essentially to consist of a variable reactor (controlled by delay angle) and a fixed capacitor. The FC-TCR type var generator can be considered as a controllable reactive admittance which, when connected to the ac system faithfully follows an arbitrary input reference signal. The *V-I* operating area of the FC-TCR var generator is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of capacitor, reactor and thyristor valve.

2.3.4 Thyristor-Switched Capacitor, Thyristor-Controlled Reactor type SVC

The thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR) type compensator was developed primarily for dynamic compensation of power transmission systems with the intention of minimizing standby losses and providing increased operation flexibility.

A basic single-phase TSC-TCR arrangement is shown in Figure 2.28. For a given capacitive output range, it typically consists of several TSC branches and one TCR.

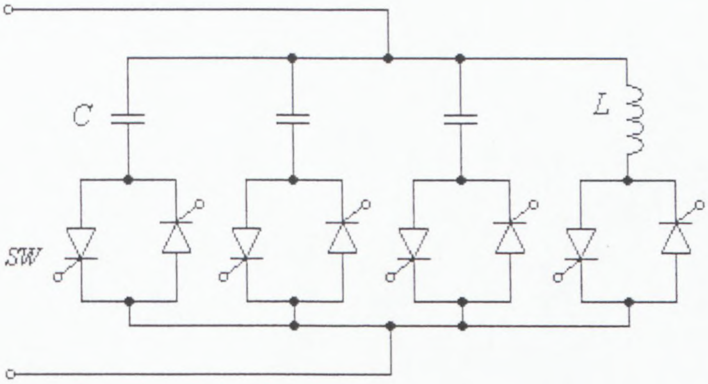


Figure 2.28: Thyristor-Switched Capacitor, Thyristor-Controlled Reactor

The number of TSC branches, is determined by practical considerations that include the operating voltage level, maximum var output, current rating of the thyristor valves, bus bars work and installation cost, etc. The inductive range also can be expanded to any maximum rating by employing additional TCR branches.

2.3.5 Switching Converter type Var Generators

Static var generators discussed in previous sections generate or absorb controllable reactive power (var) by synchronously switching capacitor and reactor banks "in" and "out" of the network. The aim of this approach is to produce variable reactive shunt impedance that can be adjusted to meet the compensation requirements of the transmission network. The possibility of generating controllable reactive power directly, without the use of capacitors or reactors, by various switching power converters was disclosed by Gyugyi in 1976. These (dc to ac or ac to ac) converters are operated as voltage and current sources and they produce reactive power essentially without reactive energy storage components by circulating alternating current among the phases of the ac system. Their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control. They can also exchange real power with the ac system if supplied from an appropriate, usually dc source. Due to these similarities with a rotating synchronous generator, they are termed static synchronous generators (SSGs). When SSG is operated without an energy source, and with appropriate controls to function as a shunt-connected reactive compensator, it is termed, a static synchronous compensator (condenser) or STATCOM (STATCON).

Controllable reactive power can be generated by all types of dc to ac and ac to ac switching converters. The former group is generally called dc to ac converters or just converters, whereas the later one is referred to as frequency changers or frequency converters or cycloconverters. The normal function of converters is to change dc power to ac and that of the frequency changers to change ac power of one frequency to ac power of another frequency. A power converter of either type consists of an array of solid-state switches which connect the input terminal to the output terminals. Consequently, a switching power converter has no internal energy storage and therefore the instantaneous input power must be equal to the instantaneous output power. Also the termination of the input and output must be complementary, that is, if the input is terminated by voltage source (active voltage source like a battery or a passive voltage source like a capacitor) then the output must be terminated by a current source (in practice means a voltage source with an inductive source impedance or a passive inductive impedance) and vice versa. In the case of dc to ac converters the dc terminals are considered as "input" and therefore voltage-sourced and current-source converters are distinguished according to whether these are shunted by a voltage source (capacitor) or by a current source (inductor).

Converters presently employed in FACTS controllers are the voltage-sourced type. The major reasons for the preference of the voltage-sourced converters are:

- A current-sourced converter requires power semiconductors with bi-directional voltage blocking capability. The available high power semiconductors with gate turn-off capability (GTOs, IGBTs) either cannot block reverse voltage at all or can only do it with detrimental effect on other important parameters (e.g., increased conduction losses).
- Practical current source termination of the converter dc terminals by a current-charged reactor causes much loss than complementary voltage source termination by a voltage-charged capacitor.
- The current-sourced converter requires a voltage source termination at ac terminals, usually in the form of a capacitive filter. The voltage-sourced converter requires a current source termination at the ac terminals that is naturally provided by the leakage inductance of the coupling transformer.
- The voltage source termination (i.e., a large dc capacitor) tends to provide an automatic protection of the power semiconductors against transmission line voltage transients. Current-sourced converters may require an additional over voltage protection or higher voltage rating for the semiconductors.

2.3.5.1 Reactive Power Generation

The basic principle of reactive power generation by voltage-sourced converter is akin to that of the conventional synchronous capacitor shown schematically in Figure 2.29. The reactive current I drawn by the synchronous compensator is determined by the magnitude of the system voltage V, that of the internal voltage E, and total circuit reactance (synchronous machine reactance plus transformer leakage reactance plus system short-circuit reactance) X:

$$I = \frac{V - E}{X}$$

The corresponding reactive power Q exchanged can be expressed as follows:

$$Q = \frac{I - \frac{E}{V}}{X} V^2$$

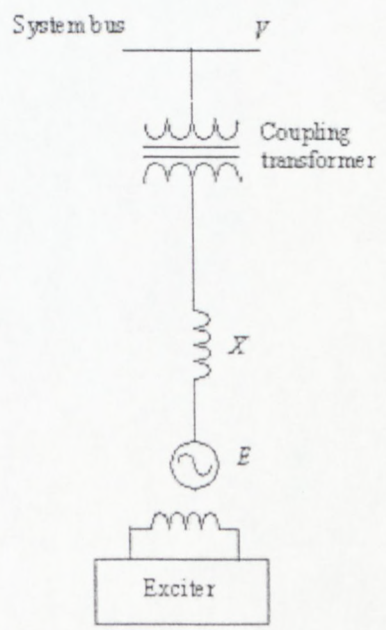


Figure2.29: Conventional Synchronous Capacitor

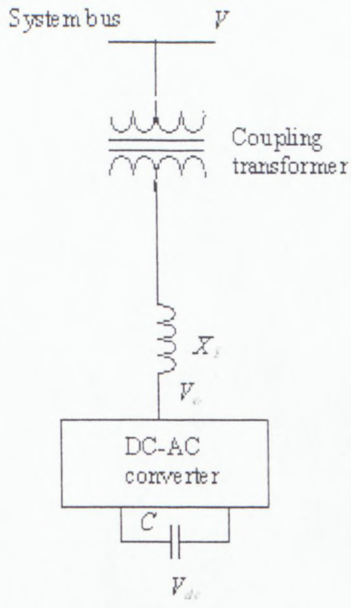


Figure 2.30: Schematic Diagram of Synchronous Var Compensator

By controlling the excitation of the machine, and hence the amplitude E of its internal voltage relative to the amplitude V of the system voltage, the reactive power flow can be controlled, increasing E above V results in a leading current, that is, the machine is "seen" as a capacitor by the ac system.

The basic voltage-sourced converter scheme for reactive power generation is shown schematically, in the form of a single-line diagram, in Figure 2.30. From a dc input voltage source, provided by the charged capacitor C, the converter produces a set of controllable three-phase out voltage with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relative small (0.1-0.15 p.u.) tie reactance (which in practice is provided by the per phase leakage inductance of coupling transformer).

By varying the amplitude of output voltages produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine. The three-phase output voltage is generated by a voltage-sourced dc to ac converter operated from an energy storage capacitor.

2.3.5.2 Basic Control Strategy of STATCOM

A STATCOM comprises a large number of gate-controlled semiconductor power switches (GTO thyristors). The gating commands for these devices are generated by the internal converter control in response to the demand of reactive and/or real power reference signal(s). The reference signals are provided by the external or system control, from operator instructions and system variables, which determine the functional operation of the STATCOM.

The internal control is an integral part of the converter. Main function of the control is to operate the converter power switches so as to generate a fundamental output voltage waveform with the demanded magnitude and phase angle in synchronism with the ac system. In this way the power converter with internal control can be viewed as a sinusoidal, synchronous voltage source behind a tie reactor, the amplitude and phase angle of which is controlled by the external control via appropriate reference signal(s).

The magnitude and angle of the output voltage are those internal parameters which determine the real and reactive power exchanges with the system. If the converter is restricted for reactive power exchange, which means it is strictly operated as var generator, and then the reference input to the internal control required is the reactive current. From this the internal control derives the necessary magnitude and angle for the converter output to establish the required dc voltage on dc capacitor since the magnitude of the ac output voltage is direct proportional to the dc capacitor voltage. Because of this proportionality, the reactive output current, as on approach, can be controlled indirectly via controlling the dc capacitor voltage or, as another approach, directly by the internal voltage control mechanism (e.g., PWM) of the converter in which case the dc voltage is kept constant (Hingorani,N.G., et al., 2000:135-176).

SVCs as well as STATCOM are invaluable sources of reactive power needed for magnetization of induction generators and operation of normally inductive load in power systems.

2.3.5.3 STATCOM in Micro Hydro Scheme

Tamrakar, et al. (2007: 743-750) Conducted experiments and simulations on parallel operation of synchronous and induction generators with STATCOM connected to a common bus in a micro hydropower plant. The purpose of the exercises was to analyse dynamic characteristics of the plant in which STATCOM was used for terminal voltage regulation and employing dump load for frequency control. In the experiment, synchronous generator's exciter provided constant excitation to produce rated terminal voltage at full resistive load and also reactive power when need arise. Induction generator had neither speed controller nor excitation controller and both machines were driven by constant mechanical inputs at their full capacities.

When the consumers load changed, the chopper on the DC side of STATCOM controlled the active power consumed by the dump load hence load of the synchronous generator remained constant and consequently its speed too.

Both simulation and experiment results concurred that the induction generator followed the synchronous generator with negative slip. The transients in stator terminal voltage, stator current of synchronous generator and induction generator at the switching instants were found to be acceptable for practical implementation. STATCOM showed the perfect control of system bus voltage and the frequency was maintained within 49-51Hz range. The work proved that voltage control hence reactive power supply to the system bus in small hydropower plant can be accomplished by STATCOM. However, the challenge of controlling frequency by employing dump load is likely to rise as the capacity of the power plant increases due to possible limits of damp capacity in absorbing and method of dissipation of the absorbed energy. Therefore, application of electronic load control method for frequency control has limitations.

2.4 Power Relay

In A.C power systems, induction type relays are the mostly used for protective relaying. Power relay like other induction type relays, is split-phase induction motor with contacts. Actuating force is developed in a movable element, which may be a disc or other form of rotor of non-magnetic current-conducting material, by the interaction of electromagnetic fluxes with eddy currents that are induced in the rotor by these fluxes.

Power relay use principle of induction wattmeter. Which require both current and voltage element. For this two separate A.C magnets are used, which produce two fluxes, which have the required phase difference. Basic arrangement of the magnets is shown in Figure 2.31.

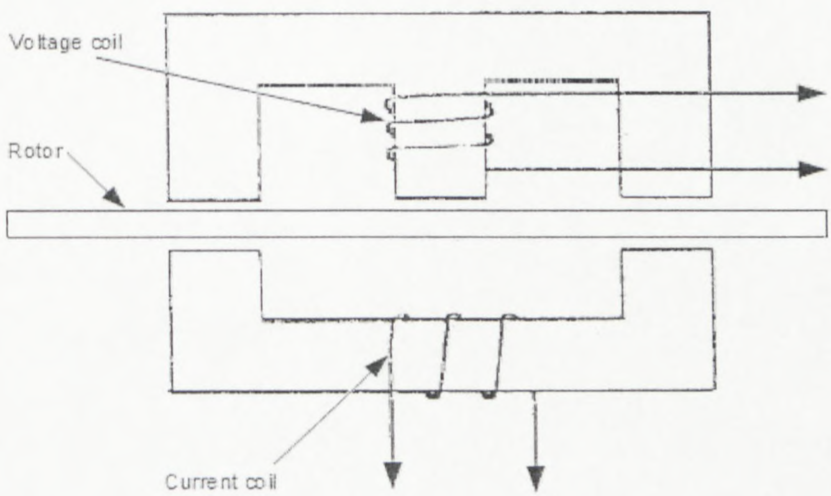


Figure 2.31: Power Relay

The winding of current coil carries line current I so that $\Phi_1 \propto I$ and is in phase with I. The other coil, voltage coil is made highly inductive having an inductance L and negligible resistance. This is connected across the supply voltage V. The current in the voltage coil is therefore, equal to $\frac{V}{\omega L}$. Hence $\Phi_2 \propto \frac{V}{\omega L}$ and lags behind the voltage by 90^0 as shown in Figure 2.32 below.

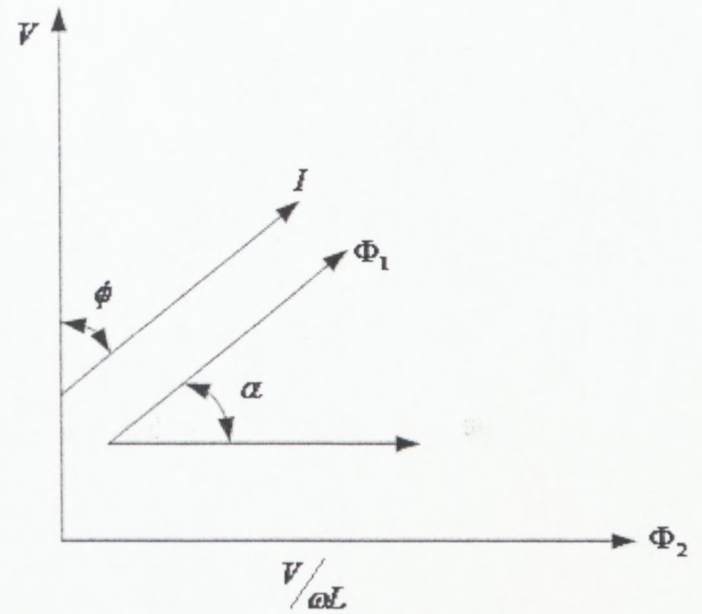


Figure 2.32: Phasor Representation of Voltage, Current and Fluxes in Power Relay

Let the current I lag behind V by ϕ i.e., let the load power factor angle be ϕ. As shown in Figure 2.31 the phase angle between Φ_1 and Φ_2 is $\alpha = (90-\phi)$. The value of the torque acting on the disc/rotor is given by

$T = k\omega\Phi_{1m}\Phi_{2m}\sin\alpha$ or

$T = k\omega I \frac{V}{\omega L}\sin(90-\phi) \propto VI\cos\alpha \propto$ power. Hence deflection torque is proportional to the power in the load circuit.

For spring control, the controlling torque T_c is proportional to the angle of deflection θ i.e. $T_c \propto \theta$, therefore $\theta \propto$ power in the load circuit.

2.5 Power Plant Stability

A power plant is part of power system which consists of power generation, power utilisation and equipment in between that facilitate the delivery of generated power to consumers or loads. Therefore stability of a power plant can only be discussed in the context of power system stability as summarised in figure2.33. Electricity generation in power plants is mainly by use of synchronous generators hence stability problem is discussed based on dynamic characteristics of electromechanical energy exchange of these machines in the system.

Kundur et al (2004:1387-1401) defined power system stability as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most variables bounded so that practically the entire system remains intact. In this work, Kundur et al (2004:1387-1401) classified power system stability into:

a) Rotor stability; referring to ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. The rotor angle stability involves the study of mechanical oscillations inherent in power systems. The rotor stability was further divided into two subcategories:
   - Small-disturbance (or small-signal) rotor angle stability, and
   - Large-disturbance rotor angle (or transient) stability.
b) Voltage stability; referring to ability of a power system to maintain steady voltage at all buses in the system after being subjected to a disturbance from a given initial operating condition. Voltage stability is also subdivide into:
   - Large-disturbance voltage stability, and
   - Small-disturbance voltage stability.
c) Frequency stability which was referred to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.

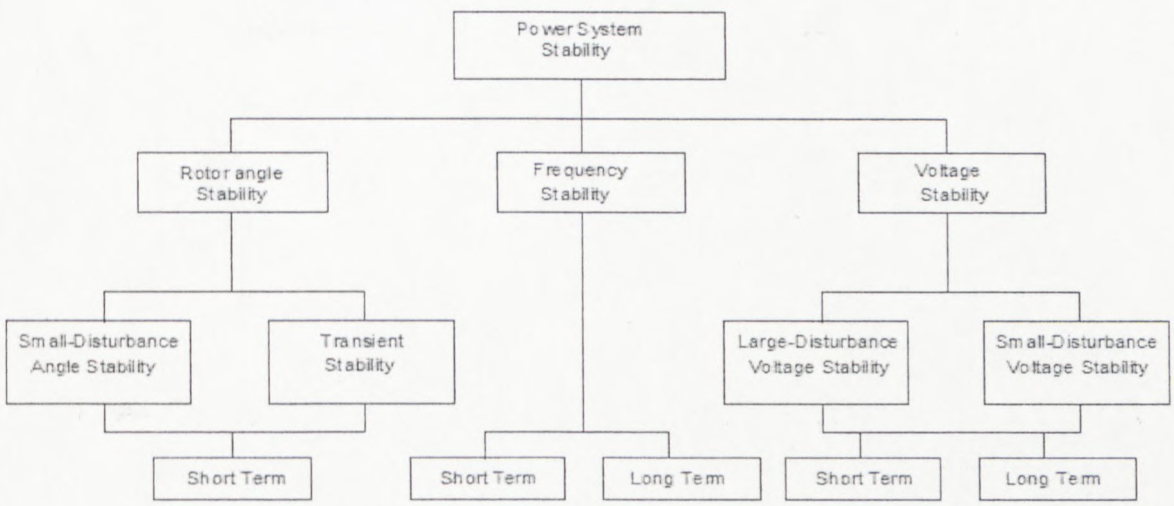


Figure 2.33: Summary of Power System Stability Problem

Source: Kundur et al, 2004

2.5.1 Rotor Angle Stability

Electromagnetic torque T_e in Equation 2.86 multiplied the rotor speed ω results to the electrical power developed by synchronous generator. Basler and Schaefer (2005:46-67) showed that change in electromagnetic torque following a disturbance can be resolved into two components as follows:

$$\Delta T_e = K_s \Delta\delta + K_D \Delta\omega \quad (2.103)$$

Where:

$K_s \Delta\delta$ = the component of torque that is in phase with the rotor angle. This is known as synchronising torque.

$K_D \Delta\omega$ = the component of torque that is in phase with the speed change. This is known as the damping torque.

System stability depends on the existence of both components torque for each of the synchronous generators. Lack of sufficient synchronising torque results in aperiodic or non-oscillatory instability leading to loss of synchronism, whereas lack of damping torque results in oscillatory instability.

2.5.1.1 Small Signal Rotor Stability

Small signal stability was defined as the ability of the power system to remain stable in presence of small disturbances. Small disturbances could be minor variations in load or generation on the system (Basler and Schaefer, 2005:46-67). If sufficient damping torque doesn't exist, the result can be rotor angle oscillations of increasing amplitude.

Damping torque results from the phase lag or lead of the excitation current. The excitation current acting to improve synchronising torque normally is time delayed by characteristics of the excitation system and the time delay of exciter field (if used). These time delays cause the effect of high initial response excitation system to cause negative damping, resulting in loss of small-signal stability. A solution to this is to add a power system stabiliser (PSS) acting through the voltage regulator. Working together, the excitation output is modulated to provide positive damping torque to the system.

2.5.1.2 Transient Stability

Transient stability is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. Figure 2.34 illustrate typical behaviour of a synchronous generator to fault condition.

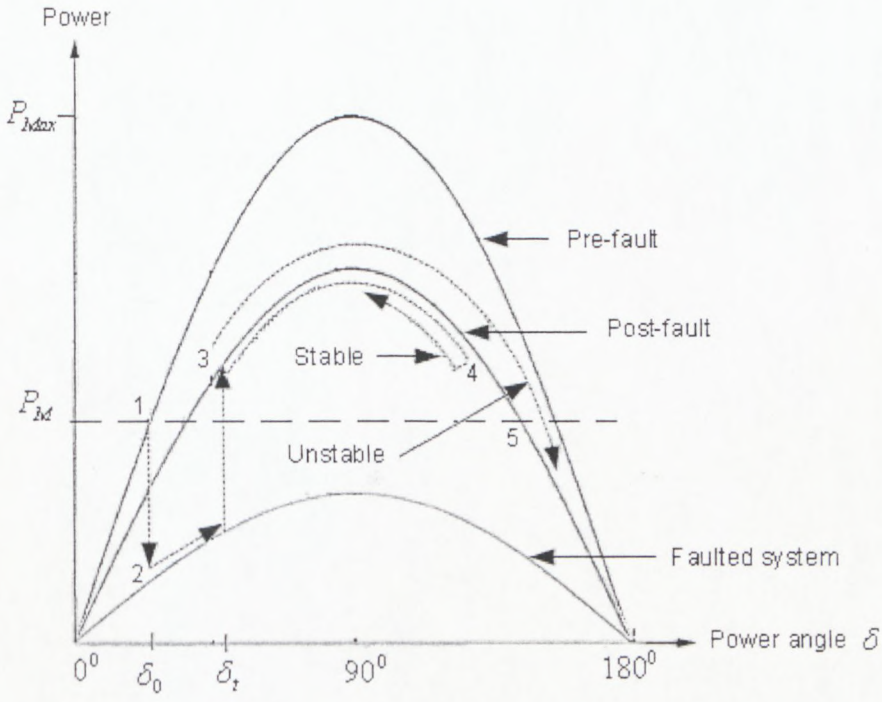


Figure 2.34: Typical Behaviour of Synchronous Generator in Fault Condition

Before the occurrence of fault the power system will be operating at initial steady state condition (point 1) on pre-fault power angle curve corresponding to power angle δ_0. A fault on the system causes the synchronous generator power output P_e to be reduced (point 2) on faulted system power angle curve. The mismatch between electrical power and mechanical power P_M supplied by the prime mover (turbine) causes the generator rotor to accelerate with respect to the system, increasing the power angle. When the fault is cleared by the action of protective devices at time t, the electrical power is restored to a level corresponding to the appropriate point on post-fault power angle curve (point 3). After fault clearing, the power output of the generator becomes greater than the mechanical power. This causes the generator rotor to decelerate, reducing the momentum gained during fault. If there is enough retarding torque after fault clearing to make up for the acceleration during fault, the generator will be stable on the first swing and will move back toward its operating point (point 4). If the retarding torque is insufficient, on the first swing the rotor will move beyond the limit (point 5) and power angle will continue to increase and the generator will lose synchronism with the system.

Transient stability of the synchronous generator depends on:

- How heavily the generator is loaded.
- The generator output during the fault. This depends on the fault location and type.
- The fault clearing time.
- The post-fault system reactance.
- The generator reactance. A lower reactance increases peak power and reduces initial rotor angle.
- The generator inertia. The higher the inertia, the slower the rate of change in angle. This reduces the kinetic energy gained during fault.
- The generator internal voltage magnitude (E_q). This depends on the field excitation.
- The infinite bus voltage magnitude.

2.5.1.3 Power System Stabiliser

Power system stabiliser (PSS) is a device that improves the damping of generator electromechanical oscillations. PSS have been employed on large generators for decades; permitting utilities to improve stability constrained operating limits (Basler and Schaefer, 2005:46-67).

Action of synchronous generator excitation system can produce transient changes in the generator's electrical power output. Fast-responding exciters equipped with high-gain automatic voltage regulators (AVRs) use their speed and forcing to increase a generator's synchronising torque coefficient(K_s), resulting in improved steady-state and transient stability limits. Unfortunately improvements in synchronising torque are often achieved on the expense of damping torque, resulting in reduced levels oscillatory or small-signal stability. To counteract this effect, units that utilise high-gain AVRs are also equipped with power system stabilisers to increase the damping coefficient (K_D) and improve oscillatory stability (Basler and Schaefer, 2005:46-67).

2.5.2 Voltage Stability

Kundur, et al (2004:1387-1401) identified voltage instability as a result of progressive fall or rise of voltages of some buses and its possible outcome is loss of load in an area and operation of protection systems leading to cascading outage. They further mentioned that the driving force for voltage instability is the loads and a major contributing factor is the voltage drop that occurs when active and reactive power flow through inductive reactance of the transmission network.

2.5.3 Frequency Stability

Frequency instability occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.

Severe system upsets generally results in large excursions of frequency, power flows voltage and other system variables. During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds, corresponding to the response of devices such as under-frequency load shedding and generator controls and protections, to several minutes, corresponding to the response of devices such as prime mover energy supply systems and load voltage regulators.

2.5.4 Speed Stability

Speed stability is the concept introduced by Samuelsson and Lndahl (2005:1179-1180) in their analysis of behaviour of induction generator when subjected to a nearby fault. They observed, that voltage sag at nearby fault significantly reduce the induction generator's terminal voltage and its capability to deliver power during the fault is severely impaired. The reduction of active power delivery during fault causes the generating unit to accelerate. They contend that after clearing the fault, the speed may deviate significantly from the pre-fault speed and the reactive power consumption of the generator may be significantly higher than the pre-fault value. They also observed that if the speed increase is too high, the generator may not return to the pre-fault state. They mentioned that the turbine may reach steady state at elevated speed, but it is not desirable since it is accompanied by reduced active power, increased reactive power consumption, and depressed voltage near the generating unit.

In another work, Grilo, et al (2007:1861-1869) devise an analytical method for analysis of large-disturbance stability of the induction generators. Their work was based on the fact, that induction generators are increasingly being used in distributed power generation usually connected to distribution networks. In this regard they saw importance of mitigating the phenomenon related to induction generator operation and its dynamic behaviour during faults.

Grilo, et al (2007:1861-1869) also shared the observation, that during faults induction generators may accelerate to high speeds due to the abrupt reduction in electrical torque. Consequently, the reactive power consumed by the generator increases considerably. This may reach an extent which may lead to the system voltage collapse. However, they asserted that the large-disturbance stability of an induction generator could be determined by analysing the responses of the rotor speed in time after the occurrence of short-circuit.

The analysis showed that, condition whether the generator will be stable or unstable after large-disturbance will depend on the fault clearance time. More specifically, it will depend on whether the fault will be eliminated before the generator rotor reaches the maximum critical speed.

The concept of critical rotor speed was explained by using the electrical torque versus rotor speed curve of an induction generator. In order to obtain a mathematical relationship between electrical torque and rotor speed, the steady-state equivalent circuit of an induction generator shown in Figure 2.22 was used and the expression for electrical torque similar to Equation 2.94 was obtained.

When induction machine operates as a generator, the mechanical torque is negative. Therefore, electrical-mechanical equilibrium equation of an induction generator can be written as

$$\frac{d\omega_r}{dt} = \frac{1}{2H}\left(T_e - T_M\right) \tag{2.104}$$

Whereby H is the inertia constant.

To facilitate visualisation, Equation 2.104 was multiplied by minus one (-1) and the magnitude of electrical torque versus induction generator rotor speed curve was plotted as shown in Figure 2.35.

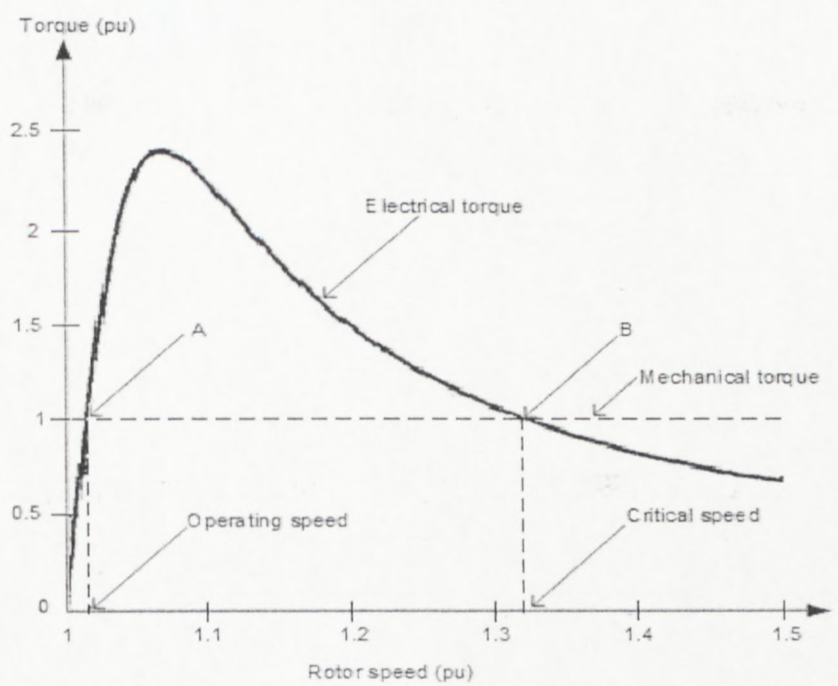


Figure 2.35: Induction Generator Electrical Torque/Rotor Speed Characteristics

From (2.104), two equilibrium points, where the electrical torque is equal to the mechanical torque were found. Point A represents stable equilibrium while point B is representing unstable equilibrium. The rotor speed at point A is the steady-state speed ω_0 in which the generator normally operates. The rotor speed at point B is which Grilo, et al (2007:1861-1869) called critical speed $\omega_{crit.}$. For elaboration of this Figure 2.36 and Figure 2.37 below are used.

In Figure 2.35, before fault, the generator is operating at a stable steady state point A with rotor speed ω_0. As the fault occurs the electrical torque abruptly drops to zero and generator operating point moves to point F. As a result, the rotor starts to accelerate according to Equation 2.104. At instant t_c, the fault is cleared and the generator operating point moves to point C where net torque $(T_e - T_M)$ is negative hence the rotor starts to decelerate and eventually return to operating point A.

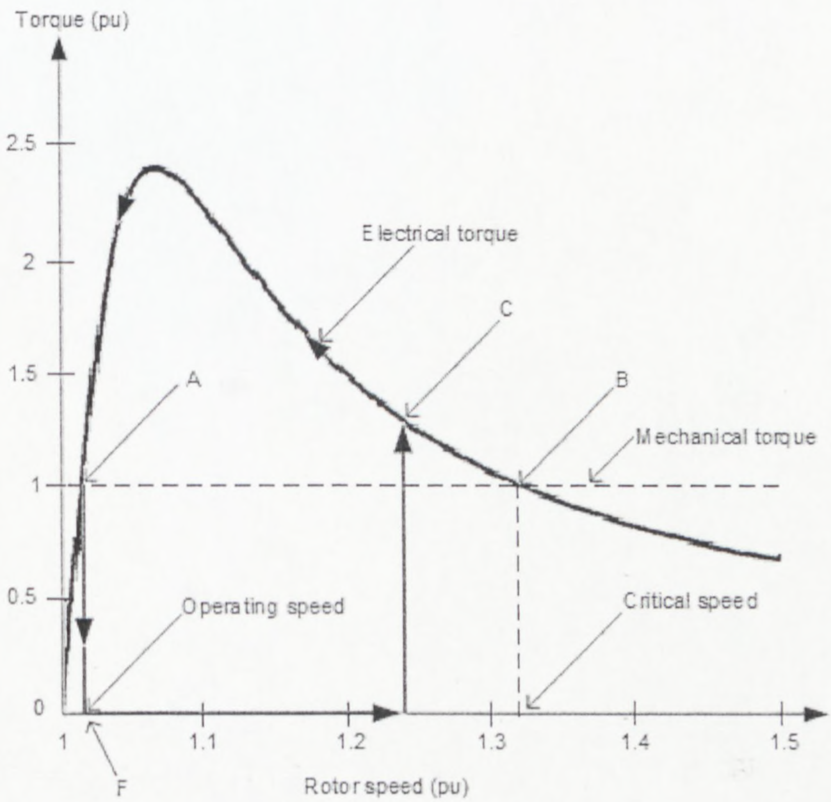


Figure 2.36: Behaviour of Induction Generator in Pre-Critical Speed Fault Clearance

On the other hand, in Figure2.37, the pre-fault operating is at point A. Like in the first case, as the fault occurs the electrical torque abruptly decreases to zero and the generator operating point moves to point F. The rotor of the generator starts to accelerate as per

Equation 2.104. When the fault is cleared at instant t_c, the generator operating point changes to point C the net torque $(T_e - T_M)$ remains positive. In this case the generator becomes unstable. With the above analysis, it can be verified that when the fault nearby induction generator is cleared before rotor of the generator reaches the critical speed, the generator response is stable. Otherwise, when the fault is cleared after the generator rotor has reached the critical speed, the generator response is unstable.

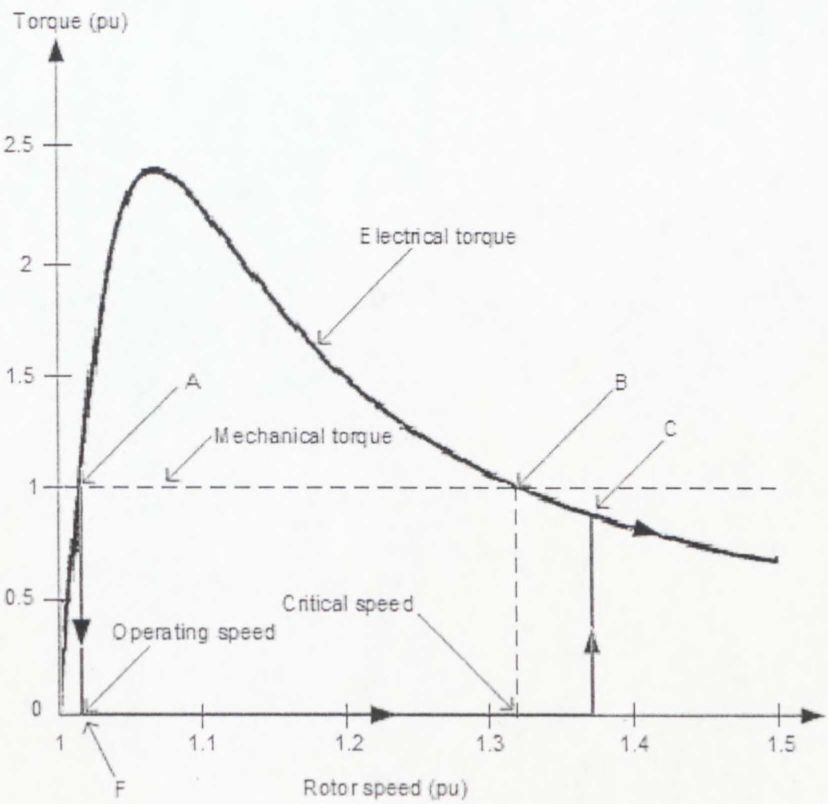


Figure 2.37: Behaviour of Induction Generator in Post-Critical Speed Fault Clearance

Therefore, Grilo, et al. (2007:1861-1869) have successfully showed, that it is possible to determine the critical fault clearing time analytically by solving Equation 2.94 and Equation 2.104.

2.6 Conclusions

Small hydro is the most clean and reliable among renewable energy sources that has not fully exploited due to economic reasons when compared with large hydro schemes and fossil fuel powered power plants but continuous rise in fossil fuel cost and environmental concerns make small hydro to again an attractive source of energy. In addition, modern hydraulic turbines are capable of converting hydro energy into mechanical energy with efficiency as high as 90% which makes hydroelectric power generation to be most efficient way of generating electricity.

Developments in technologies in civil engineering works, machines and fields which are involved in implementation of SHPs give an opportunity for enhancing not only the competitiveness of new SHPs in terms of cost of electricity unit generated but also acceptability due to both energy provision and preservation of environment.

Cost of electro-mechanical equipment constitute of a substantial proportion of total up-front investment of SHP in the range of 30 to 40 percent depending on specific site conditions. Since fuel cost for running an SHP do not exist, the running costs of the plant includes only maintenance of civil engineering works and electro-mechanical equipment. On the other hand, civil engineering works are robust with working lifetime of a century or more with minimum maintenance. This means maintenance costs of an SHP mainly consists of costs of maintaining electro-mechanical equipment. Therefore, selection of type of electro-mechanical employed has an impact on investment and running costs and eventually economic viability of an SHP.

Instrumentation, controls and monitoring systems in hydropower plants have no dependency on size and when conventional governor is used in an SHP, electricity unit cost become higher as compared with large schemes. Efforts of avoiding conventional governors in SHP have given positive results for micro-hydropower plants. In micro-hydro schemes electronic load controllers have successfully replaced conventional governors but the same has not happened in SHPs of higher capacities due to limitations in active power absorption of electronic load controllers and methods for dissipating excess energy. Use of conventional governors in SHPs is sighted as a reason of small hydro potential not to be fully exploited.

Synchronous generators and their respective control systems are principal converters of mechanical power into electrical power in SHPs. If the power balance between active power demanded by load connected to a synchronous generator and the power supplied the prime mover is maintained, a synchronous generator generates AC electric power with a constant frequency. Excitation system of the generator facilitates regulation of its terminal voltage and reactive power output of the machine. Within certain capacity range synchronous generators are found to be expensive as compared to induction generators of the equivalent capacity.

In spite of being cheap rugged in construction hence low maintenance cost, induction generators are less common in SHPs. This situation is due to the facts, that induction generators cannot regulate their terminal voltages and also it is difficult to control their generation frequency. Furthermore, induction generators require reactive power supply for excitation. However, an induction generator connected to an AC system with constant voltage, supplied with sufficient reactive power for its excitation generates active power of exactly the same frequency as that of the system it is connected to.

Attributes of synchronous generators and induction generators of capacities which can be used in SHPs are summarised in table 2.1 bellow.

Table 2.2: Summarised Attributes of Synchronous and Induction Generators

Synchronous generator	**Induction generator**
Efficient.	Moderately efficient.
Expensive.	Less expensive.
Requires maintenance.	Rugged and robust, little maintenance required.
Reactive power flow can be controlled through excitation.	Absorbs reactive power.
Fixed speed hence very stiff.	Small change in speed with torque, hence more compliant.
Responds in an oscillatory manner to sudden changes in torque.	Responds to sudden inputs in no oscillatory way.
Suitable for connection to weak networks. Can be used in autonomous systems.	Suitable for weak networks only with power electronics.
Requires special synchronisation equipment to connect to mains/ other generator for parallel operation.	Can be simply synchronised to the mains.

An electric servomotor is a precision electric motor that is used to control position or velocity mechanical systems. The most common are dc servomotors which have constant field excitation and control is achieved by varying voltage applied to armature windings. In market there are electric servomotors which have adequate capacity for industrial applications.

Regulation of a hydraulic turbine power output is done by adjusting gate/valve opening in the case of reaction turbine and needle position in impulse turbine. In both cases the process is position control. Therefore, an electric servomotor which is as powerful as the conventional governor that would have been required can successfully be used as a governor in an SHP of any capacity and replace the conventional governor. In addition, electric servomotors of sufficient capacity are readily available in market.

Static Var Compensators (SVCs) are capable of providing continuously variable var generation or absorption for dynamic system compensation which enables maintenance of voltage at its terminals. SVCs have been used in conventional power systems where continuous and fast control of reactive power is required. Since successful operation of induction generators require supply of reactive power, SVCs are seen as invaluable sources of reactive power that can be used for excitation of induction generators and operation of inductive load connected to the generator.

Phenomenon related to induction generator and its dynamic behaviour during faults differs from that shown by synchronous generator. The existing power system stability concepts used in power system analysis do not put into consideration the dynamic behaviour of induction machine operated as a generator. However, it is now known, that when faults occurs on a power system which include synchronous and induction generators, rotors of both generator types will accelerate and whether the machines will be stable or unstable after the fault has been cleared depends on fault clearing time.

For stability of a power plant employing synchronous and induction generators, critical fault clearing time for each generator should be determined and coordinate their protection systems.

CHAPTER THREE

Proposed Small Hydropower Plant

3.1 Introduction

Motivation behind the proposal of a new approach in implementation of small hydropower plant came about after identification of possibilities of cutting down both upfront investment cost and maintenance cost of small hydropower plant.

First input was the technical viability of generating reactive power by using newly developed power electronics devices which opened the opportunity for making use of the possibility of induction machines to be operated as generators and generate active power while they are supplied with reactive power and driven by prime movers. The other impulse was the advent of range of electric servomotors which can replace the expensive and more complex conventional governor used for regulation of hydraulic turbines and therefore enhanced the idea of implementing low cost small hydropower plants.

The economic benefits that can be realised in terms of savings in up-front investment cost due to application of cheap electro-mechanical equipment and low maintenance cost emanating from simplicity of control and ruggedness of the equipment were the foundation of the proposed small hydropower plant.

3.2 Main Components of the Proposed Hydropower Plant

The proposed new small hydropower plant used a combination of synchronous and induction generators for the conversion of mechanical power to electrical power. Both generators were driven by hydraulic turbines each regulated by electric servomotor as a governor for the synchronous generator and power output regulator for the induction generator. The generation frequency and voltage of the plant were 50 Hz and 400V respectively. Governing systems of the hydraulic turbine coupled to synchronous generator provided means of controlling turbine's power output and speed and consequently the frequency of generation.

The governing systems of the turbine driving synchronous generator included tacho-generator as a speed transducer, potentiometer and operational amplifier in the servomotor control, servomotor and servo operated valve or gate for water flow regulation as shown on Figure 3.1.

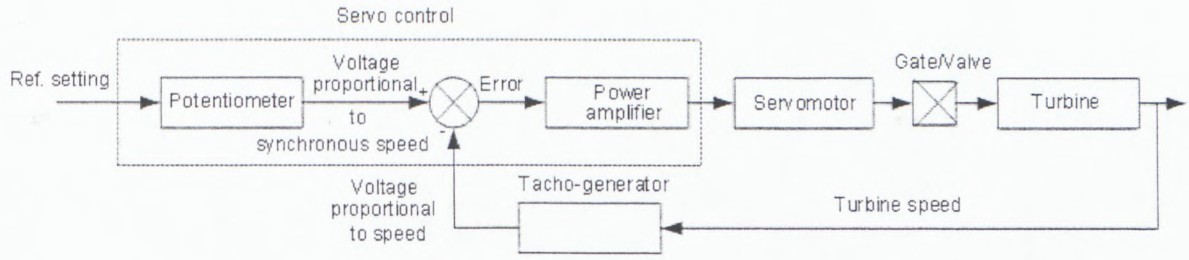


Figure 3.1: Governing System of Hydraulic Turbine Coupled to Synchronous Generator

Control of the turbine driving induction generator was implemented through the application of power relay, the servomotor control system, servomotor, and servo operated valve/gate as indicated on Figure 3.2.

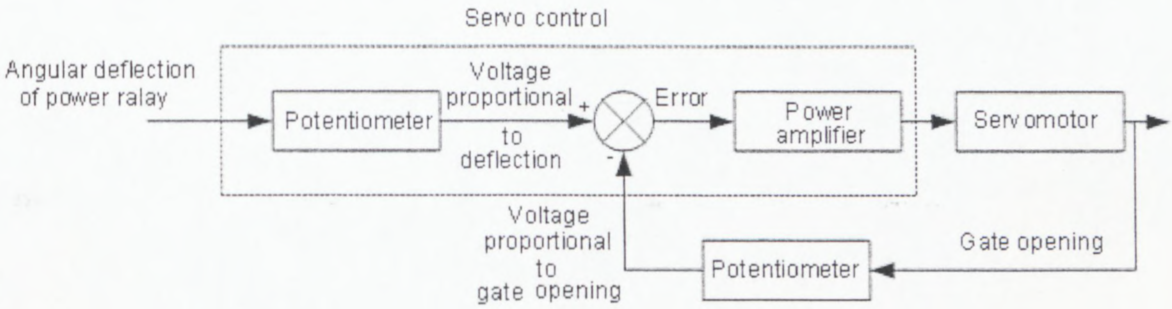


Figure 3.2: Governing System of Hydraulic Turbine Coupled to Induction Generator

The fundamental difference in control strategy of the two turbines is, that while governing system of turbine driving synchronous generator regulates power output and speed of the turbine which determines frequency of power generated, the control system of turbine driving induction generator regulates only the power output of the turbine to which it is interfaced.

The functional block diagram of basic elements associated with power generation, frequency control, and voltage regulation for the proposed power plant is shown in Figure 3.3. In this system, the tacho-generator convert mechanical rotation of the turbine into d.c voltage with low ripple content at linear proportionality to the speed. Power relay on the other hand monitors the power output of the plant. Depending on amount of active power drawn from the plant, the power relay instruct servo system to adjust the opening of the gate/valve regulating water flow to the turbine driving induction generator hence regulating its mechanical power output.

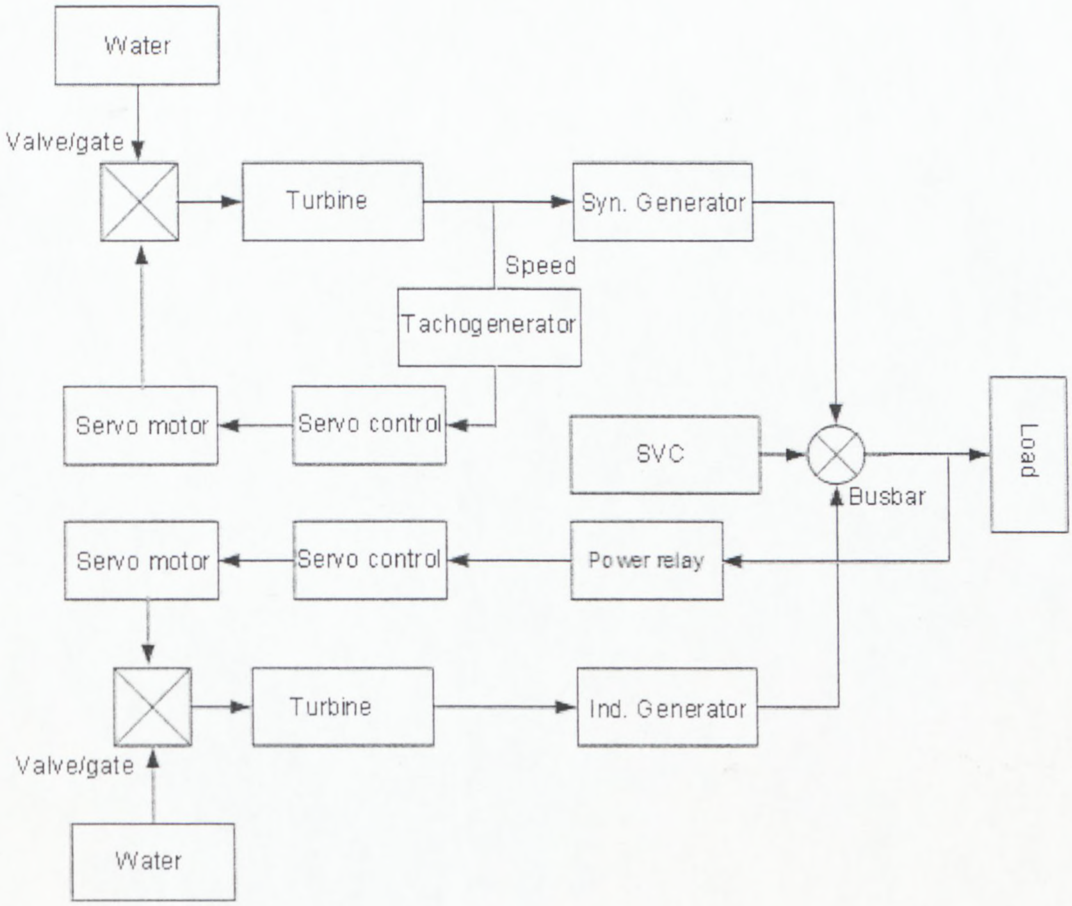


Figure 3.3: Functional Block Diagram of the Proposed Small Hydropower Plant

Voltage regulation at generator bus is performed by an inbuilt automatic voltage regulator (AVR) within excitation system of the synchronous generator and a static var compensator (SVC) connected to the generator bus as shown in Figure 3.4, by supplying to or absorbing from the generator bus reactive power. The SVC is composed of fixed capacitor and thyristor controlled reactor (FC-TCR) and its selection was based on cost and the facts that FC-TCR offer smooth and continuous control without transients. Elimination of harmonics from this equipment is easily achieved by tuning the FC as filter. The design of SVC is compact (Kodsi et al. 2006) which simplify its location. The selected SVC had sufficient reactive power generation capacity to meet reactive power requirements of the induction generator and facilitate maintenance of the required voltage and power factor at the generator bus when reactive power generation capacity of the synchronous generator was saturated.

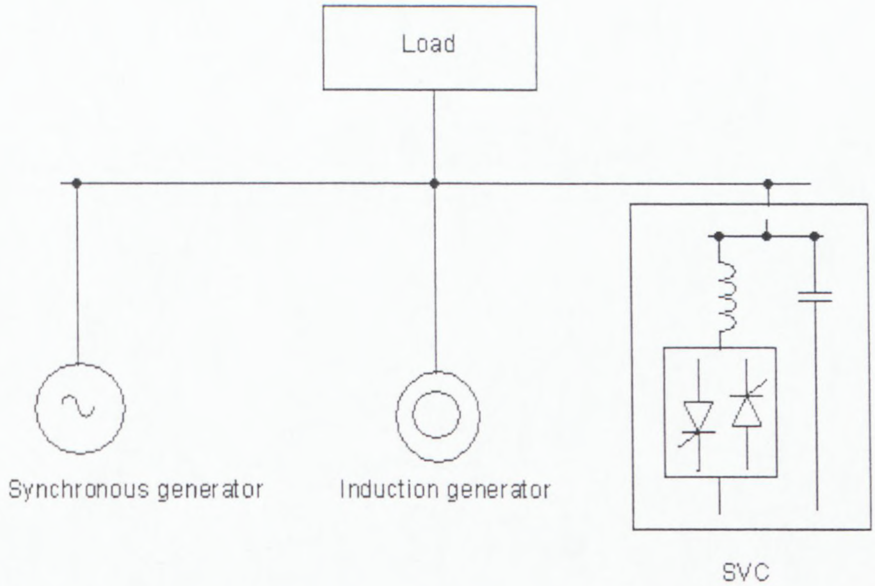


Figure 3.4: Schematic Diagram of the Proposed Small Hydropower Plant

3.3 Operation of the Proposed Plant

Successful operation of the proposed plant depended on observation of the recommended sequence for starting and loading of the machines.

The heart of the power plant is the synchronous generator which establishes voltage and frequency of generation at the generator bus. Therefore the plant must to be started by running turbine-synchronous generator unit until steady state voltage and frequency are established at the generator bus, only then load could be connected.

As loading of the plant causes change in speed of the synchronous generator thus the frequency of generation, servomotor and the associated control systems as load-frequency controller regulates the opening of the gate of turbine coupled to the synchronous generator and adjust water flow into the turbine thus regulating its mechanical power output which is supplied to the generator in order to maintain the steady state frequency. Parallel to the actions of servomotor, AVR and SVC react to maintain the generator bus voltage at a constant value despite of load changes.

For parallel operation of the two generating units in the plant, the unit with induction generator is connected to the power system after the synchronous generator has reached a required steady state condition. For successful connection the unit with induction generator should first be run above the synchronous speed, and then connected to the system. This is the most important operation in order first to avoid motoring effect of the induction machine and second to operate the machine as a generator. The voltage dip at the generator bus is minimised by action of the SVC connected prior to the connection of induction generator to the generator bus.

When the induction generator run above synchronous speed and then connected to a power system, its speed drops and thereafter start to follow the synchronous generator with negative slip proportional to its power output (Tamrakar et.al. 2007: 743-750). The power output of the induction generator depends on the power supplied by the turbine to which it is coupled, therefore with mechanism to adjust operating points of the power relay to activate the opening or closure of the gate of the turbine driving induction generator, water flow to the turbines can be regulated, hence the operator can manipulate distribution of load between generators without interfering with neither voltage nor frequency of generation.

Variations of power plant load are to be responded by the synchronous generator in accordance to instructions of the automatic load-frequency control systems incorporated to it. However, power relay set to instruct the opening or closing of the gate to the turbine driving induction generator when the amount of active power supplied to connected load from the plant reaches a pre-set quantity to enable adjustment of the output power of induction generator. The change in induction generator power output changes the amount of power drawn by the load from the synchronous generator. By increasing the output of induction generator, reduces the loading of the synchronous generator, hence giving room for its response in case of any further increase in power demanded from the plant.

In the event of synchronous generator outage, the induction generator cannot operate on its own in self- excited regime. Switching operations of the plant are facilitated by circuit breakers as depicted by the proposed plant's main electrical connection on Figure 3.5 below.

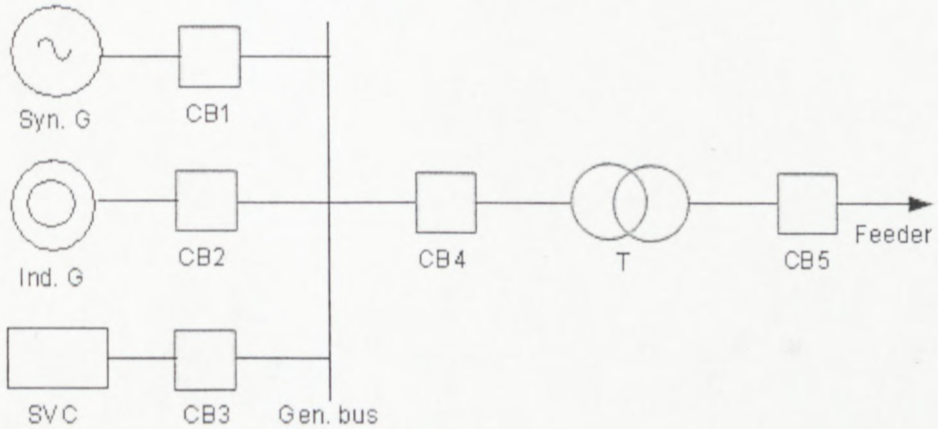


Figure 3.5: Main Electrical Connection in the Proposed Power Plant

3.4 Modeling of Main Components of the Plant

Main components of the proposed SHP include a synchronous and induction generator for electric power generation and hydraulic turbines as prime movers. The load-frequency control systems employ tacho-generator, servomotor driven gates/valves, servomotors and servomotor controllers. An SVC is also used for supply of reactive power and generator bus voltage regulation.

For clarification of performance of the proposed SHP, mathematical models of the main components of the plant are presented.

Modeling and analyses of synchronous machine was worked on intensely in the 1920s and 1930s and has been the subject of recent investigations. As for the induction generator, there are numerous models available in various publications. Therefore this study adopted mathematical models of both synchronous and induction generators and their block representations which are available in SimPowerSystems software which is a modern design tool that allows scientists and engineers to rapidly and easily build models that simulate power systems. The software uses the Simulink environment incorporated in MATLAB and SIMULINK software version 7.1.

SimPowerSystems software belongs to the Physical Modeling product family and uses blocks and connection line interface. SimPowerSystems libraries contain models of typical power equipment which are proven and their validity is based on the experience of the power Power Systems Testing and Simulation Laboratory of Hydro-Quebec, and also on the experience of Ecole de Technologie Superieure and Universite Laval. The models are presented hereunder for clarifications.

In MATLAB and SIMULINK software, a block representation of nonlinear hydraulic turbine similar to that developed by Kundur (1994) with servomotor and servo controlled gate/valve mechanisms is implemented. However, the mathematical models of turbines as derived by Kundur (1994) are separately presented in the study.

Although mathematical model of tacho-generator as speed transducer is shown, its implementation is incorporated within the synchronous generator block since speed is among measurements available from the block representing synchronous generator.

In this study, mathematical representation of Static Var Compensator was not elucidated, however, the block representing SVC in MATLAB and SIMULINK software was used in physical modelling of the proposed SHP.

3.4.1 Model of Synchronous Generator

The synchronous generator model presented takes into consideration dynamics of stator, field, and damper windings. The equivalent circuit of the model is represented in dq frame with all rotor parameters and quantities referred to the stator; they are identified by primed variables except for rotor speed represented as ω_r, while those of stator are attached with subscript's'. Other subscripts are defined as follows:

- d, q: d and q axis quantity
- l, m: Leakage and magnetising inductance
- f, k: Field and damper winding quantity

The electrical model of the machine is represented by flux linkage and voltage equations.

3.4.1.1 Flux Linkage Equations

The flux linkage in dq frame at any instant is given by

$$\begin{aligned} \psi_d &= L_d i_d + L_{md}\left(i'_{fd} + i'_{kd}\right) \\ \psi_q &= L_q i_q + L_{mq} i'_{kq} \end{aligned} \tag{3.1}$$

$$\psi'_{fd} = L'_{fd}\, i'_{fd} + L_{md}\left(i_d + i'_{kd}\right) \tag{3.2}$$

$$\begin{aligned} \psi'_{kd} &= L'_{kd}\, i'_{kd} + L_{md}\left(i_d + i'_{fd}\right) \\ \psi'_{kq1} &= L'_{kq1}\, i'_{kq1} + L_{mq} i_q \\ \psi'_{kq2} &= L'_{kq2}\, i'_{kq2} + L_{mq} i_q \end{aligned} \tag{3.3}$$

3.4.1.2 Voltages Equations in dq Frame

The respective voltages in dq frame are represented by

$$\begin{aligned} V_d &= R_s i_d + \frac{d}{dt}\psi_d - \omega_r \psi_q \\ V_q &= R_s i_q + \frac{d}{dt}\psi_q + \omega_r \psi_d \end{aligned} \tag{3.4}$$

$$V'_{fd} = R'_{fd}\, i'_{fd} + \frac{d}{dt}\psi'_{fd} \tag{3.5}$$

$$V'_{kd} = R'_{kd}\, i'_{kd} + \frac{d}{dt}\psi'_{kd}$$

$$V'_{kq1} = R'_{kq1}\, i'_{kq1} + \frac{d}{dt}\psi'_{kq1} \quad (3.6)$$

$$V'_{kq2} = R'_{kq2}\, i'_{kq2} + \frac{d}{dt}\psi'_{kq2}$$

3.4.1.3 Mechanical Characteristics

The synchronous generator block implements the mechanical system described by the following equations

$$\Delta\omega(t) = \frac{1}{2H}\int_0^t (T_m - T_e)dt - K_d\Delta\omega(t) \quad (3.7)$$

And

$$\omega(t) = \Delta\omega(t) + \omega_0 \quad (3.8)$$

Where

$\Delta\omega$ = Speed variation with respect to speed of operation (synchronous speed)

H = Constant of inertia

T_m = Mechanical torque

T_e = Electromagnetic torque

K_d = Damping factor representing the effect of damper winding

$\omega(t)$ = Mechanical speed of the rotor

ω_0 = Speed of operation (synchronous speed)

3.4.2 Model of Induction Generator

The model of induction generator is representing electrical and mechanical parts. The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. The electrical variables and parameters for the rotor are referred to the stator indicated by the prime signs in the machine equations. All stator and rotor quantities are in dq reference frame. Definition of the machine parameters are in table 3.1 under leaf.

3.4.2.1 Electrical System

In the model, flux linkages are represented through the following equations:

$$\begin{aligned} \psi_{qs} &= L_s i_{qs} + L_m i'_{qr} \\ \psi_{ds} &= L_s i_{ds} + L_m i'_{dr} \end{aligned} \tag{3.9}$$

$$\begin{aligned} \psi'_{qr} &= L'_r i'_{qr} + L_m i_{qs} \\ \psi'_{dr} &= L'_r i'_{dr} + L_m i_{ds} \end{aligned} \tag{3.10}$$

$$\begin{aligned} L_s &= L_{ls} + L_m \\ L'_r &= L'_{ls} + L_m \end{aligned} \tag{3.11}$$

Voltage and torque equations are formulated as:

$$\begin{aligned} V_{qs} &= R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega\psi_{ds} \\ V_{ds} &= R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega\psi_{qs} \end{aligned} \tag{3.12}$$

$$\begin{aligned} V'_{qr} &= R'_r i'_{qr} + \frac{d}{dt}\psi'_{qr} + (\omega - \omega_r)\psi'_{dr} \\ V'_{dr} &= R'_r i'_{dr} + \frac{d}{dt}\psi'_{dr} - (\omega - \omega_r)\psi_{qr} \end{aligned} \tag{3.13}$$

$$T_e = 1.5P(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \tag{3.14}$$

3.4.2.2 Mechanical System

The mechanical system is modelled by the following equations:

$$\begin{aligned} \frac{d}{dt}\omega_m &= \frac{1}{2H}(T_e - F\omega_m - T_m) \\ \frac{d}{dt}\theta_m &= \omega_m \end{aligned} \tag{3.15}$$

Table 3.1: Definition of Induction Generator Parameters in the Model.

Parameter	Definition
R_s, L_{ls}	Stator resistance and leakage inductance
R'_r, L'_{lr}	Rotor resistance and leakage inductance
L_m	Magnetising inductance
L_s, L'_r	Total stator and rotor inductances
V_{qs}, i_{qs}	q axis stator voltage and current
V'_{qr}, i'_{qr}	q axis rotor voltage and current
V_{ds}, i_{ds}	d axis stator voltage and current
V'_{dr}, i'_{dr}	d axis rotor voltage and current
Ψ_{qs}, ψ_{ds}	Stator q and d axis fluxes
Ψ'_{qr}, ψ'_{dr}	Rotor q and d axis fluxes
ω_m	Angular velocity of the rotor
θ_m	Rotor angular position
P	Number of pole pairs
ω_r	Electrical angular velocity($\omega_m \times P$)
θ_r	Electrical rotor angle position ($\theta_m \times P$)
T_e	Electromagnetic torque
T_m	Shaft mechanical torque
J	Rotor moment of inertia coefficient
H	Rotor inertia constant
F	Rotor viscous friction coefficient

3.4.3 Models of Hydraulic Turbine

The performance of a hydraulic turbine depends on the characteristics of the water column feeding the turbine namely the effects of water inertia, water compressibility and pipe wall elasticity in the penstock. Therefore, precise modelling of hydraulic turbine requires inclusion of travelling waves effects which occur in the elastic walled pipe carrying compressible fluid. However, the typical speed of the waves is about 1200 m/s which make the possible to be ignored when penstocks are short as is the case under consideration.

The models of hydraulic turbine adopted in this project were developed by Kundur (1994:378-391) based on the assumptions that

- Hydraulic resistance is negligible

- The penstock pipe is inelastic and the water is incompressible
- The velocity of the water varies directly with the gate opening and with the square root of the net head
- The turbine output power is proportional to the product of head and volume flow.

The turbine and penstock characteristics are determined by three basic equations relating to:

a. Velocity of water in the penstock
b. Turbine mechanical power
c. Acceleration of water column.

3.4.3.1 Linear Turbine Model

The velocity of the water in the penstock is given by

$$U = K_w G\sqrt{H} \tag{3.16}$$

Where

U = water velocity

G = gate/valve position

H = hydraulic head at the gate and

K_w = a constant of proportionality.

For small displacement about an operating point

$$\Delta U = \frac{\partial U}{\partial G}\Delta G \tag{3.17}$$

Substituting the appropriate expressions for the partial derivatives and dividing by $U_0 = K_w G_0\sqrt{H_0}$ yields

$$\frac{\Delta U}{U_0} = \frac{\Delta H}{2H_0} + \frac{\Delta G}{G_0}$$

Or

$$\Delta\overline{U} = \frac{1}{2}\Delta\overline{H} + \Delta\overline{G} \tag{3.18}$$

The subscript "0" denotes initial steady-state values and the prefix "Δ" denotes small deviations and the super bar "_" indicates normalised values based on steady-state operating values.

The turbine mechanical power is proportional to the product of pressure and flow, hence

$$P_m = K_p HU \tag{3.19}$$

Linearising Equation 3.19 by considering small displacement, and normalising by dividing both sides by $P_{m0} = K_p H_0 U_0$, we have

$$\frac{\Delta P_m}{P_{m0}} = \frac{\Delta H}{H_0} + \frac{\Delta U}{U_0}$$

Or

$$\Delta\overline{P}_m = \Delta\overline{H} + \Delta\overline{U} \tag{3.20}$$

Substituting for $\Delta\overline{U}$ from Equation 3.18 gives

$$\Delta\overline{P}_m = 1.5\Delta\overline{H} + \Delta\overline{G} \tag{3.21A}$$

Alternatively, by substituting for $\Delta\overline{H}$ from Equation 3.18 we may write

$$\Delta\overline{P}_m = 3\Delta\overline{U} - 2\Delta\overline{G} \tag{3.21B}$$

The acceleration of water column due to change in head at the turbine, characterised by Newton's second law of motion may be expressed as

$$(\rho LA)\frac{d\Delta U}{dt} = -A(\rho a_g)\Delta H \tag{3.22}$$

Where

L = length of conduit (penstock)

A = pipe area

ρ = mass density

a_g = acceleration due to gravity

ρLA = mass of water in the conduit

$\rho a_g \Delta H$ = incremental change in pressure at turbine gate

t = time in seconds

By dividing both sides by $A\rho a_g H_0 U_0$, the acceleration equation in normalised form becomes

$$\frac{LU_0}{a_g H_0}\frac{d}{dt}\left(\frac{\Delta U}{U_0}\right) = -\frac{\Delta H}{H_0}$$

Or

$$T_w \frac{d\Delta \overline{U}}{dt} = -\Delta \overline{H} \tag{3.23}$$

Where by definition

$$T_w = \frac{LU_0}{a_g H_0} \tag{3.24}$$

T_w is referred to as the water starting time. It represents the time required for head H_0 to accelerate the water in the penstock from standstill to velocity U_0. Typically, its value at full load lies between 0.5s and 4.0s.

From Equation 3.18 and 3.23, we can express the relationship between change in velocity and change in gate position as

$$T_w \frac{d\Delta \overline{U}}{dt} = 2\left(\Delta \overline{G} - \Delta \overline{U}\right) \tag{3.25}$$

Replacing $\frac{d}{dt}$ with Laplace operator s we may write

$$T_w s \Delta \overline{U} = 2\left(\Delta \overline{G} - \Delta \overline{U}\right)$$

$$\Delta\overline{U} = \frac{1}{1+\frac{1}{2}T_w s}\Delta\overline{G} \qquad (3.26)$$

Substituting for $\Delta\overline{U}$ from Equation 3.21B and rearranging, we obtain

$$\frac{\Delta\overline{P}_m}{\Delta\overline{G}} = \frac{1-T_w s}{1+\frac{1}{2}T_w s} \qquad (3.27)$$

Equation 3.27 represents the 'classical' transfer function of a hydraulic turbine. It shows how the turbine power output change in response to a change in gate opening for an ideal lossless turbine. However, such a model is inadequate for studies involving large variations in power output and frequency. The more appropriate model for such studies is a nonlinear model.

3.4.3.2 Nonlinear Turbine Model

A hydraulic system considered in this model is of simple configuration with unrestricted head and tailrace.

Assuming a rigid conduit and incompressible fluid, the basic hydrodynamic equations are:

$$U = K_w G\sqrt{H} \qquad (3.28)$$

$$P = K_p HU \qquad (3.29)$$

$$\frac{dU}{dt} = -\frac{a_g}{L}(H - H_0)$$
(3.30)

$$Q = AU \qquad (3.31)$$

Where

U = water velocity

G = ideal gate opening

H, H_0 = hydraulic head at the gate and its initial steady-state value respectively

Q = water flow rate

a_g = acceleration due to gravity

t = time in seconds

Our interest is in large signal performance, thus we normalise Equations 3.28 and 3.29 based on rated values.

Equations 3.28 and 3.29 in normalised form become

$$\frac{U}{U_r} = \frac{G}{G_r}\left(\frac{H}{H_r}\right)^{1/2} \tag{3.32}$$

$$\frac{P}{P_r} = \frac{U}{U_r}\frac{H}{H_r} \tag{3.33}$$

The subscript "r" denotes rated values. In per unit notation, Equations 3.32 and 3.33 may be written as

$$\overline{U} = \overline{G}\left(\overline{H}\right)^{1/2} \tag{3.34}$$

$$\overline{P} = \overline{U}\;\overline{H} \tag{3.35}$$

From Equation 3.34

$$\overline{H} = \left(\frac{\overline{U}}{\overline{G}}\right)^2 \tag{3.35}$$

Similarly, the per unit form of Equation 3.30 is

$$\frac{d}{dt}\left(\frac{U}{U_r}\right) = -\frac{a_g}{L}\frac{H_r}{U_r}\left(\frac{H}{H_r} - \frac{H_0}{H_r}\right)$$

Or

$$\frac{d}{dt}\overline{U} = -\frac{1}{T_w}\left(\overline{H} - \overline{H}_0\right) \tag{3.36A}$$

Or in Laplace notation

$$\frac{\overline{U}}{\overline{H}-\overline{H}_0}=-\frac{1}{T_w s} \tag{3.36B}$$

In Equation 3.36, T_w is the water starting time at rated load which assumes a constant value for a given turbine-penstock unit. Its value is given by

$$T_w=\frac{LU_r}{a_g H_r}=\frac{LQ}{a_g A H_r} \tag{3.37}$$

The mechanical power output of the turbine P_m is determined after considering fixed power loss of the turbine as

$$P_m=P-P_L \tag{3.38}$$

Value of the fixed power loss of the turbine P_L is given by

$$P_L=U_{NL}H \tag{3.39}$$

The quantity U_{NL} represents the no-load water velocity.

In normalised form, Equation 3.39 become

$$\frac{P_m}{P_r}=\frac{P}{P_r}-\frac{P_L}{P_r}=\left(\frac{U}{U_r}-\frac{U_{NL}}{U_r}\right)\frac{H}{H_r}$$

Or

$$\overline{P}_m=\left(\overline{U}-\overline{U}_{NL}\right)\overline{H} \tag{3.40}$$

Equation 3.40 gives the per unit value of the turbine power output on a base equal to the turbine MW rating. In power system studies, it is convenient to express power output and mechanical torque of a turbine on a base of either generator MVA rating or a common MVA base. Hence

$$\overline{T}_m=\left(\frac{\omega_0}{\omega}\right)\overline{P}_m\left(\frac{P_r}{MVA_{base}}\right)=\frac{1}{\overline{\omega}}\left(\overline{U}-\overline{U}_{NL}\right)\overline{H}\ \overline{P}_r \tag{3.41}$$

In Equation 3.4, $\overline{\omega}$ represents per unit speed and $\overline{P_r}$ is per unit turbine rating. The gate opening is taken to be ideal meaning the change from no load to full load being equal to 1 per unit. This is related to the real gate opening g as shown in Figure 3.6. The real gate opening is based on the change from the fully closed to fully open position being equal to 1per unit.

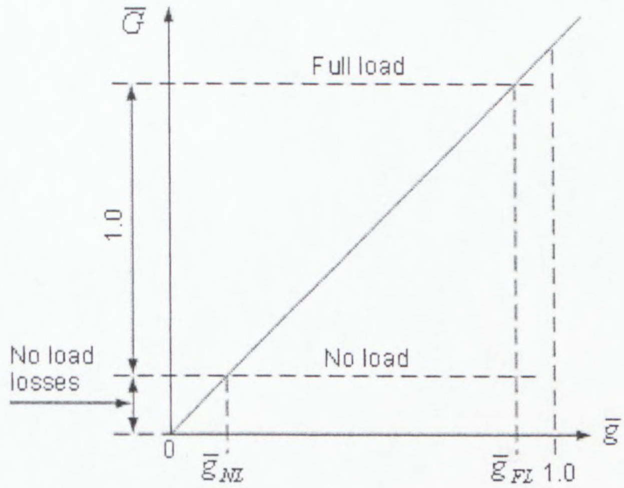


Figure 3.6: Relationship between Ideal and Real Gate Openings

The ideal gate opening is related to real gate opening as follows

$$\overline{G} = A_t \overline{g} \tag{3.42}$$

The constant A_t is the turbine gain given by

$$A_t = \frac{1}{\overline{g}_{FL} - \overline{g}_{NL}} \tag{3.43}$$

Equations 3.34 to 3.37 and 3.41 to 3.43 completely describe the water column and turbine characteristics.

3.4.4 Models of Gate and Servomotor

In the proposed plant, positions of both gates/valves regulating the flow of water into respective turbines are determined by characteristics of their driving servomotors. For both turbines, dc servomotors with constant field excitation are used. The gate opening position which corresponds to angular position of armature shaft is changed by varying the voltage supplied to the armature winding through the servo control system.

The servomotor and the coupled gate/valve are characterised by the armature winding of resistance R_a and inductance L_a, inertia moment J representing total inertia moment of the armature and the gate/valve, and viscous damping coefficient B is schematically represented in Figure 3.7.

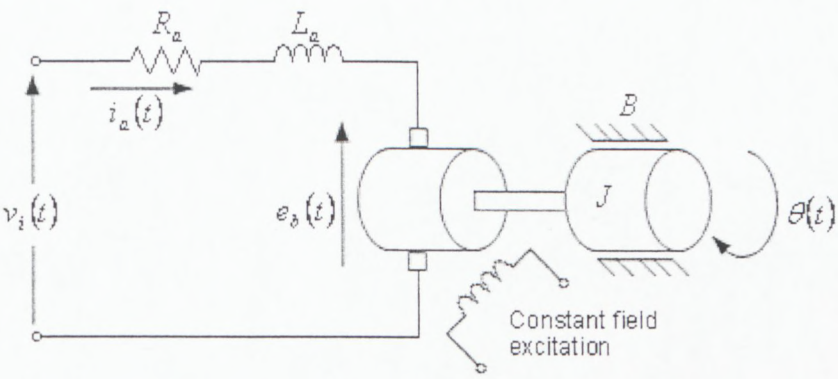


Figure 3.7: Schematic Diagram of dc Servomotor Coupled to Load

Kirchhoff's voltage law for the armature circuit gives

$$v_i(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_b(t) \tag{3.44}$$

The back e.m.f $e_b(t)$ for constant flux is proportional to speed

$$e_b(t) = K_b \frac{d\theta(t)}{dt} \tag{3.45}$$

The developed torque for constant flux is proportional to armature current

$$T(t) = K_t i_a(t) \tag{3.46}$$

And according to Newton's second law, the movement generated by this torque is determined from the following expression

$$T(t) - B\frac{d\theta(t)}{dt} = J\frac{d^2\theta(t)}{dt^2} \tag{3.47}$$

Eliminating $e_b(t)$ and $T(t)$, and Laplace transforming, gives

$V_i(s) = R_a I_a(s) + L_a s I_a(s) + K_b s\theta(s)$. And $K_t I_a(s) - Bs\theta(s) = Js^2\theta(s)$.

Eliminating $I_a(s)$

$$V_i(s) = \frac{(R_a + L_a s)(Bs + Js^2)\theta(s)}{K_t} + K_b s\theta(s)$$

Therefore

$$\frac{\theta(s)}{V_i(s)} = \frac{K_t}{s\left(JL_a s^2 + (BL_a + JR_a)s + (BR_a + K_b K_t)\right)} \qquad (3.48)$$

Since the inductance is usually negligible, the transfer function in Equation 3.48 reduces to

$$\frac{\theta(s)}{V_i} = \frac{K_t}{s(JR_a s + BR_a + K_b K_t)} = \frac{K_t / BR_a + K_b K_t}{s\left(1 + \frac{JR_a}{BR_a + K_b K_t} s\right)}$$

Or

$$\frac{\theta(s)}{V_i(s)} = \frac{K_m}{s(1 + \tau_m s)} \qquad (3.49)$$

The gain K_m and time constant τ_m depends on the parameter values in the servomotor-gate system. In block diagram form the system model is represented as in Figure 3.8

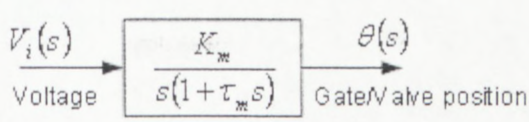


Figure 3.8: Block Diagram of Servomotor-Gate System

3.4.5 Models of Servomotor Controller and Tacho-Generator

The servomotor controller compares the signal (voltage)from the tacho-generator which is proportional to the speed of the turbine-synchronous generator unit with the reference signal which reflect the set operating speed, determines the deviation, and produces a control signal that will reduce the speed deviation to zero or to a smaller value. The tacho-generator in this case is a speed sensor or measuring element. For controlling purposes, electronic PI controller using operational amplifiers is employed.

3.4.5.1 Model of Servomotor Controller

The servomotor control unit incorporate operational amplifier implemented as PID controller and a power amplifier of gain K_A in tandem. The PID controller applies proportional control, integral control, and derivative control actions.

The properties attributed to PID controller shows, that while the control signal can be amplified with an adjustable gain due to the proportional properties, integral control action eliminates the steady-state error while the derivative control action makes the output of the controller to change at a rate proportional to the rate of change of control signal.

With $u(t)$ being the controller output and $e(t)$ the control signal, the control action of a PI controller is defined by

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t)dt + K_p T_d \frac{d}{dt}e(t)$$

The transfer function of the PID controller is

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i s} + T_d s\right)$$

The proportional constant K_p, integral time T_i and derivative time T_d depend on parameters of the controller.

When a PID is expressed as

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s$$

The constant K_p is called the proportional gain, K_i is called the integral gain, and K_d is called the derivative gain. Therefore the servomotor control unit is modelled as shown in Figure 3.9 bellow.

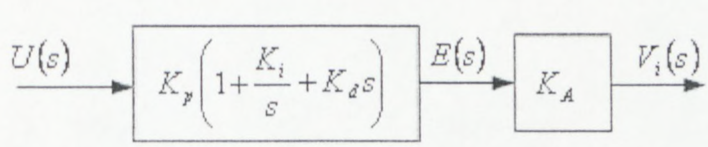


Figure 3.9: Model of Servomotor Control Unit

However, for the purpose of simulation, the block of PID controller model as implemented in the used MATLAB/SIMULINK was employed.

3.4.5.2 Model of Tacho-Generator

Tacho-generator is principally a voltage generator that gives a voltage output with value which is strictly linear proportional to the input rotational speed expressed by

$$v_o(t) = K_h \omega(t)$$

The transfer function is represented as

$$\frac{V_o(s)}{\omega(s)} = K_h$$

The constant K_h is a parameter of a tacho-generator. The block representing tacho-generator is as shown in Figure 3.10

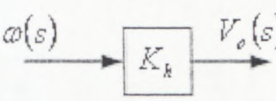


Figure 3.10: Tacho-Generator Model

3.4.6 Model of Static Var Compensator

Likewise the models of synchronous and induction generators, the block of phasor model of a three-phase SVC available in MATLAB/SIMULINK 7.1 is used in this project. The SVC regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer.

Detailed representation of power electronics, measurement, and synchronisation systems are not included in the model. These systems are approximated by simple transfer functions that yield their correct representations at the system's fundamental frequency.

3.4.7 Model of Power Relay

Power relay is operated as a switch whose operation takes place when the monitored power reaches preset values. MATLAB/SIMULINK software provides a model of a relay which is adopted for a power relay model.

3.5 Conclusions

Electricity generation by means of small hydropower is a reliable and proved technology which attracts attention of energy sector developers. Major concern in employing small hydropower has been the costs involved which at the end makes the unit generation cost to be comparatively higher and consequently render the small hydropower plants uncompetitive. Measures for reduction of costs in different sections of small hydropower plant have been introduced in several studies.

This study proposes use of combination of synchronous generator and induction generator in a small hydropower plant whose operation require two generating units to be installed. Difference in construction and principles of operation between synchronous and induction generators can be used to the advantage of efforts to implement low cost small hydropower plant. Flexibility in terminal voltage regulation and load-frequency control of synchronous generator makes the power generated to meet quality demands of power supply and ruggedness and simplicity of induction generator reduces investment and maintenance costs of the power plant in which it is installed.

The balance between power delivered power plant and power demand of connected load is achieved by the action governors regulating the hydraulic turbines. Conventional governors are expensive and complex however, they are replaceable and in the study electric servomotors have replaced conventional governors.

Control strategy for turbine driving synchronous generator is to regulate both mechanical power output and speed rotor of the turbine which determines power frequency of the system. Introduction of tacho-generator as speed transducer has served the purpose. In the case of the turbine driving induction generator, control strategy is to regulate mechanical power output of the turbine only. For this purpose power relay that monitors power supplied to the connected load from the plant is used. The relay signal is used to regulate the mechanical power output of the turbine hence the contribution of induction generator in power supplied to the load.

In normal operation conditions, load to power plant is inductive therefore requires reactive power supply. And for its operation, induction generator absorbs reactive power to deliver active power. In the proposed small hydropower plant, Static Var Compensator complements synchronous generator in supplying the reactive power required by the induction generator and the connected load.

Models of main components of the proposed plant have their block representation in MATLAB/Simulink software which facilitates physical modeling of the plant and its simulation.

CHAPTER FOUR

Model and Simulation of Proposed Small Hydropower Plant

4.1 Introduction

Simulation model of the proposed small hydropower plant was implemented by applying physical modelling approach using Simulink blocks available in MATLAB/SIMULINK software. Blocks used included that of hydraulic turbine, synchronous generator pu standard, asynchronous machine pu standard and static var compensator phasor type in SimPowerSystems tool box. Also blocks for circuit breaker, load, and relay. Measuring and displaying devices were also employed.

The capacity of modelled plant was intended to be above that of micro-hydropower plant and employ large induction generator. However, in order to avoid operational characteristics that might be caused by wrongly recorded parameters of generators, the readily available synchronous and induction machines' models with proved parameters found in the machine library were used. The induction generator model found was limited to 160kW capacity which was used in combination with 670kVA synchronous generator.

4.2 Features of the Modeled Plant

The small hydropower plant investigated in the study was run of river type at a site whose water flow rate which reflects its generation capacity varied with season. Hydrological and techno-economical surveys and studies had confirmed viability of constructing a small hydro electric generation plant on the site. Environmental impact assessments were properly done and measures for mitigation of the foreseen degradation and their effects were put into operation.

Because of the flow variations at sites employing run of rive SHPs, it had been observed that, for effectively utilisation of generation capacity of the site two generating units should be used. The modelling was not based on a particular or specific identified site therefore all machines and equipment selected was assumed to have general characteristics that allowed the use of blocks in MATLAB and SIMULINK software for physical modelling.

4.2.1 Turbine and Turbine Control

Prime movers in both electric power generating units of the plant were hydraulic turbines whose capacity matched with active power output of respective coupled generator and water intake structures suits the requirements for efficient performance of the turbines. Type of the turbines employed was that dictated by site conditions, namely flow rate and effective head of the site. Methodology of turbine selection which entails type and capacity of turbine required was not in the scope of this study. However their proper performance was essential for effective operation of the plant.

Mismatch between power delivered by the turbine to generator and that taken from the generator by load cause acceleration or deceleration of rotor of the synchronous generator depending on nature of the mismatch. If the power received by the generator is more than that demanded by the load from it due mismatch of the mechanical and electromagnetic torques acting on the rotor, hence the generator's rotor accelerate but if it is the opposite, rotor of the generator decelerate according to Equation 2.2. Among effects of such imbalance, is variation of frequency of the generated power leading to uncalled for consequences to the system as a whole. Therefore, monitoring and keeping the power balance technically known as load frequency control is important activity in electric power generation.

In this study, load frequency control equipment installed for the synchronous generator was electric servomotors whose operation objective was to maintain frequency of the system within the specified limits by taking care of changes in load demand. The servomotor was reacting to change in rotor speed which is direct reflection change in load demand by opening or closing respective valve/gate of the turbine regulating flow consequently the power output of the turbine. In this way the synchronous generator could practically keep the frequency of the generated power within predetermined limits.

4.2.2 Synchronous Generator and Excitation System

Synchronous generator in the innovated small hydropower plant under study was key generator determining main quality parameters of power generated by the system namely, frequency and generation voltages at plant bus. As mentioned in the preceding sections, synchronous generator's rotor speed is the determinant factor on generation frequency; in this respect its control had a paramount importance for the whole plant. Thus servomotor and associated controls were put in place to ensure it was maintained within acceptable limits if not constant.

Importance of excitation system need not to be over emphasised, as shown in Section 2.2.4, level of excitation of rotor magnetic field and its speed of rotation determines generated e.m.f inside the machine and therefore its terminal voltage. When rotor speed is maintained constant, automatic voltage regulator (AVR) in excitation system controls voltage magnitude at the terminals and reactive power output of the machine since the later has influence on the former. In the study excitation system employed match with the synchronous generator in operation for terminal voltage and reactive power regulation as well as stability of the system. Strategy of operation and control of synchronous generator as applied to the plant is depicted in Figure 4.1 below.

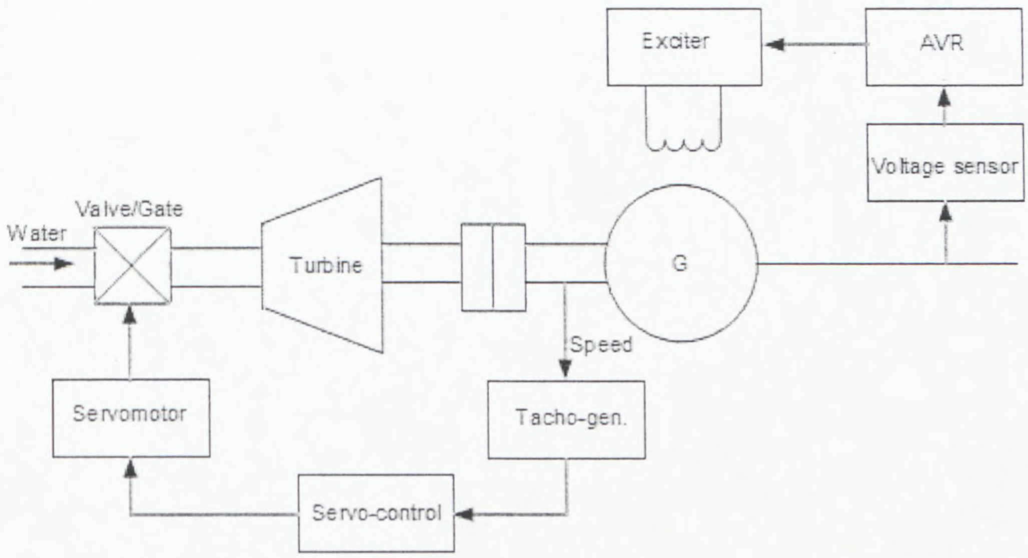


Figure 4.1 Schematic Diagram of LFC for Turbine-Synchronous Generator Unit with AVR

4.2.3 Induction Generator

Cheap and robust induction generator was used to generate active power in the plant nevertheless it had to be supplied with reactive power from the system for its excitation. Control of the generator was simple because it was enough to regulate water flow into the turbine as the generator's power output was proportional to driving torque supplied by the hydraulic turbine to which it was coupled.

Mechanical power output which is also referred to as mechanical torque of the turbine delivered to the induction generator was regulated based on decision made on amount of active power the induction generator has to contribute to the power output of the power plant by opening the respective turbine gate to the corresponding level depending on signal received from power relay that activate servomotor operation. In order to maintain power balance in the system hence frequency, synchronous generator controls respond to change of induction generator power output by adjusting that of synchronous generator accordingly. The operation and control techniques applied to the induction generator have been illustrated in Figure 4.2.

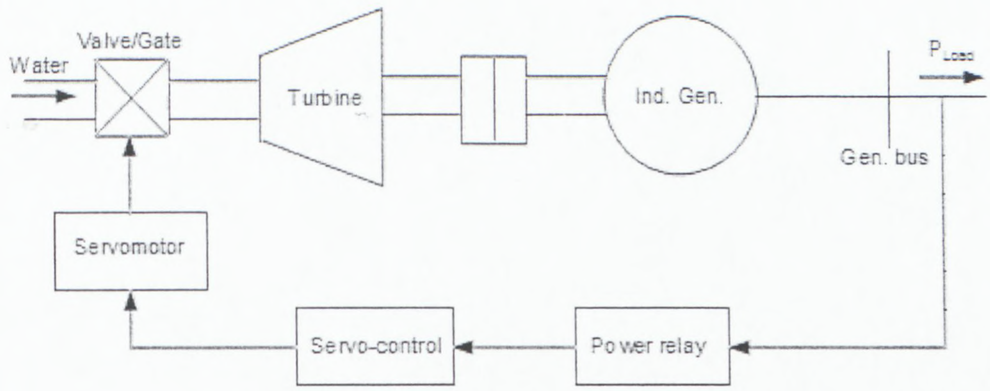


Figure 4.2 Schematic Diagram of Turbine-Induction Generator Unit Control

4.2.4 Static Var Compensator

Static var compensator connected to generator bus of the plant had variable reactance that enabled it either to generate or absorb reactive power in order to regulate the voltage magnitude at the bus. In so doing it could meet reactive power requirement for induction generator excitation and supplement the synchronous generator in supplying reactive power to the load connected to the power plant. It was assumed higher harmonics filters had been successfully tuned to eliminate possible negative effects that could be caused nonlinear elements that make the SVC.

4.2.5 Load and Load Connection

Load of general characteristics with lagging power factor was being supplied by the proposed isolated small hydropower plant. Characteristics of distribution networks were neglected or assumed to have negligible influence to the performance of the plant. However, the connection of load to the plant was effected through circuit breakers assumed to have been properly selected.

4.2.6 Description of Simulation Model

Simulation model of the proposed SHP was implemented on MATLAB/SIMULINK environment by physical modelling. Machines and all circuit elements are represented by their respective model blocks available in the software. Complete model of the proposed SHP made of model blocks of machines, SVC, loads, switchgears, and measuring and displaying devices is depicted on Figure 4.3.

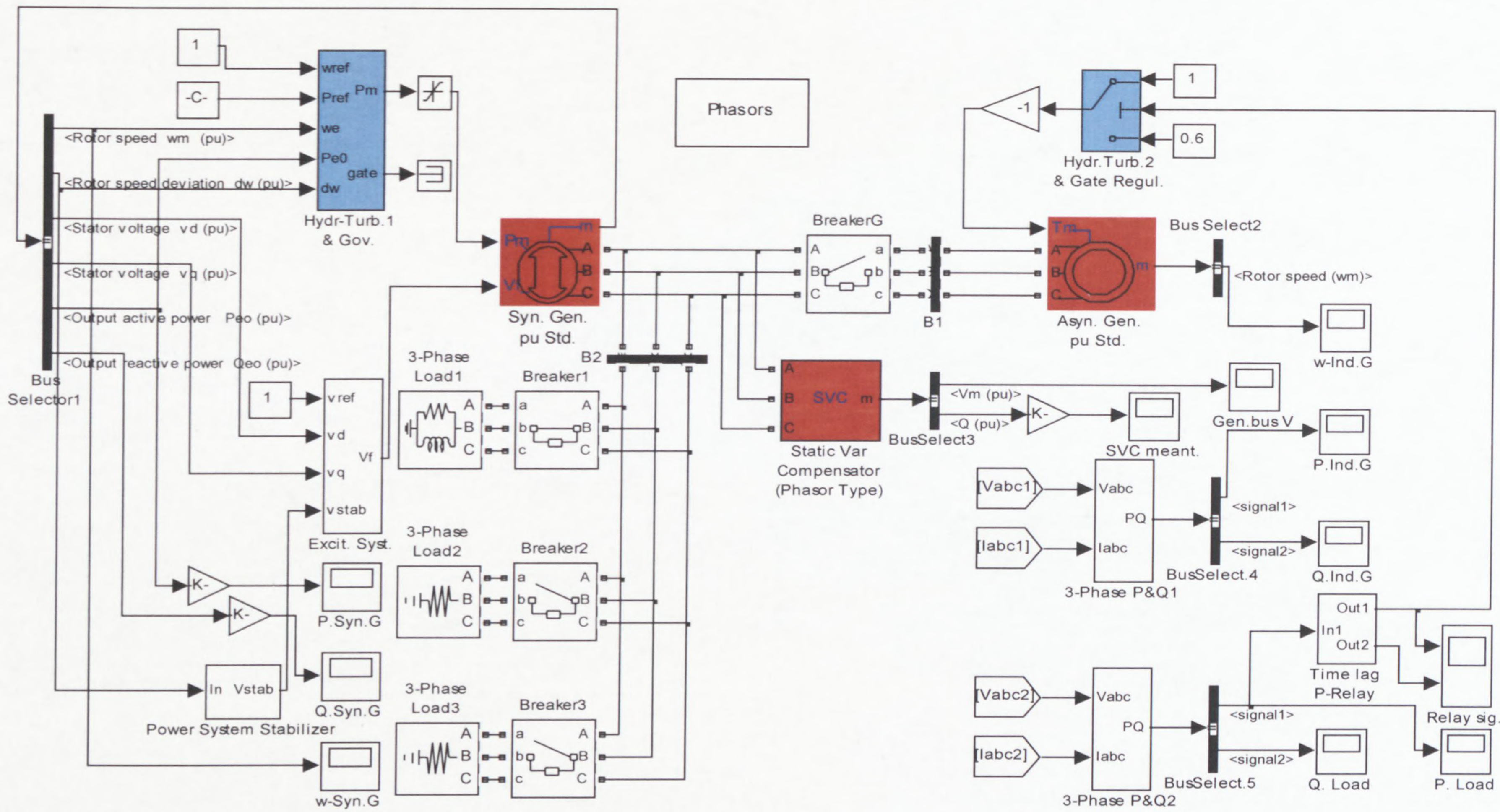


Figure 4.3: Simulation Model of the Proposed Small Hydropower Plant

4.2.6.1 Hydraulic Turbines and Their Control Strategies

In the model there are two hydraulic turbines labelled Hydr-Turb1 and Hydr-Turb2 driving synchronous generator and induction generator respectively.

Hydr-Turb1 incorporates servomotor and servomotor controller as speed governor; the speed is regulated by using speed signal from the coupled synchronous generator as feedback signal which is compared with reference signal Wref. Any change in generator load, causes change in speed of the generator rotor which is also coupled to the rotor of the driving turbine; the resultant speed is then compared with the reference speed Wref. The signal error obtained from the comparison is used by the servomotor controller to instruct the servomotor to make corresponding adjustment of the turbine gate/valve opening hence adjusting mechanical power output of the turbine Pm supplied to the synchronous generator. In this way, the speed of synchronous generator is adjusted and maintained at its steady state value.

A Hydr-Turb2 drives the induction generator, unlike the power output of Hydr-Turb1which is continuously adjusted; the power output of this turbine is adjusted step-wise by the turbine regulator.

Turbine regulator attached to Hydr-Turb2 is made of a servomotor, servomotor controller and a power relay. The actuating signal for the regulator is coming from the power relay which monitors the active power delivered by the plant to the connected load. At different level of the power output of the plant, the power relay instruct step-wise opening adjustment of gate/valve of Hydr-Turb2. This regulates the mechanical power output of the turbine and consequently the driving torque to the induction generator.

The step-wise change in gate/valve opening is simulated by a switching mechanism that switches the power output of the turbine from 0.6 pu to 1.0 pu which represent a change from 60% to full load capacity of the induction generator.

4.2.6.2 Synchronous Generator

In the model of the SHP, the synchronous generator and its excitation system are represented by respective model blocks in which both electrical and mechanical characteristics were considered.

In the synchronous generator block, the electrical characteristics are presented in dq components. The dq components of the generator terminal voltage are used as feedback signal to the excitation system of the generator. The exciter model block translate the dq component into generator terminal voltage and then compare it with the reference voltage Vref. The error signal causes corresponding adjustment in excitation of the generator field to take place. In this way the amount of reactive power supplied by the generator and voltage at the generator terminals are regulated.

Excitation system of synchronous generator in addition to reactive power output and voltage regulation, also participate in ensuring stable operation of the synchronous generator.

4.2.6.3 Induction Generator

Like synchronous generator in the model of the plant induction or asynchronous generator is represented by a model block in which electrical and characteristics are included.

Supply of reactive power for excitation of the generator and the terminal voltage regulation are the responsibilities of power system to which the generator is connected.

4.2.6.4 Static Var Compensator

Static var compensator model block used in the modelling the proposed SHP implements a phasor model of a three-phase static var compensator.

SVC is a shunt device of the FACTS family using power electronics to control power flow. It regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system in the effort of regulating the voltage of the bus to which it is connected.

4.2.6.5 Power Relay

Power relay in the model is represented by a relay and time-delaying blocks.

4.2.6.6 Loads and Switchgears

Loads connected to the power plant are of general inductive characteristics as it is normally the case in power systems. The connections are effected through circuit breakers represented by their respective blocks which represent switchgears.

4.2.6.7 Measurement and Displaying Devices

Measurements of active and reactive power supplied by the plant to consumers are taken at B2 and contribution of induction generator is measured at B1. Voltage at the generator bus is measured by an inbuilt voltage measuring device in the SVC block.

Synchronous generator rotor speeds, as well as its active and reactive power output values are derived from internally modelled measuring devices in the generator model block. Similarly, speed of the induction generator is measured by a device modelled within the induction generator model block.

Measured quantities are displayed on scope blocks.

4.3 Simulation of the Proposed SHP Performance

Operation of the proposed SHP was simulated using the model of the plant shown in Figure 4.3 which was developed earlier. The model was programmed to simulate the operation starting form the moment when the power plant is operating under a steady state condition with only the synchronous generator which is running at synchronous speed and its terminal voltage also referred to as the generator bus voltage is 400 V. The power plant is supplying Load1 of rated power demand of (500+j300) kVA which is connected to the generator bus through Beaker1. In order to start simulation of the model at a steady state initial condition, procedure for the steady state initialisation of power system model had to be followed.

The steady state initialisation of the plant model was done by using the load flow and machine initialisation option of the powergui block which solves the load flow in the power system and updates voltages and currents phasors of the system. For this purpose, synchronous generator was identified in the powergui block as a swing generator hence its terminal voltage and the active power that it had to generate was specified. In the process of initialising the synchronous generator, the powergui initialised the hydraulic turbine coupled to the generator as well and also updated the corresponding field excitation required by the generator according to the values calculated in load flow solution. On the other hand, initial conditions of the induction generator during simulations were specified in the induction machine's block in which the slip was set to negative value to reflect the machine running above the synchronous speed. The basic slip for simulations was arbitrary adopted as -0.001 pu.

In the model, mechanical power output of the hydraulic turbine coupled to synchronous generator was regulated to ensure, that the active power output of the synchronous generator was limited to 0.8 pu based on the synchronous generator's rating to enable the machine to supply the system with the required reactive power as well. At the beginning the simulation of the system the induction generator which was driven by the turbine Hydr.Turb2, was supplied with a driving torque equal to 0.6 of the induction generator's full load driving torque which was either maintained or increased to its full load value later depending on the operation condition under investigation. The load connected to the plant was also made to be constant or increased to simulate plant loading conditions under which the power demanded from the power plant was increased.

The connection of the induction generator into the system was delayed, the generator was brought into the system by closing Breaker G two cycles (0.04 s) after the start of simulation implying connection of the induction generator into the system after the steady state condition had been reached and both the terminal voltage and frequency of generation at the generator bus had reached their statutory values.

Static Var Compensator connected to the generator bus was expected to be of such a capacity capable of generating reactive power to meet the excitation requirement of the induction generator and supply reactive power to the load and support the synchronous generator in maintenance of the generator bus voltage at 400 V.

Simulations were conducted with SVCs of different reactive power output range and different initial slip of the induction generator in order to study their effects on performance of the proposed power plant. In all cases, when load to the power plant was to be increased it was done by connecting Load2 of 50 kW and Load3 of 40 kW through the operation of Breaker2 and Breaker3 respectively. With better option of SVC capacity which facilitated good small signal stability of the plant, transient stability of the plant was simulated to ascertain stability of the plant in case of fault and fault clearance or large disturbance to the plant.

Power relay switch settings allowed initialisation of the increase of induction generator's power output to its full load capacity when the power demanded by load from the plant reaches a specified level and facilitate the reduction of the output of the induction generator back to 0.6 of its full load capacity when the active power demanded by load falls to 500 kW. In order to minimise effects of switching transients and also to avoid intermittent change of induction generator power output due to transients, the power relay was equipped with time-lag mechanism that delay the relay operation for a specified period of time estimated to be sufficient for transients to subside.

4.3.1 Performance of the SHP under Constant Load and Different SVC Capacity

When conditions for operation of an induction machine connected to an AC system as a generator are fulfilled, namely the machine been driven above the synchronous speed and supplied with reactive power sufficient for its excitation, its active power output can be changed by varying the driving torque i.e. varying the mechanical power supplied to the induction generator by the prime mover coupled to it. In the proposed power plant, reactive supplied to the induction generator as well as the load connected to the power plant is generated by the synchronous generator and the SVC connected to the generator bus. The active power generated by the induction generator complements that generated by the synchronous generator in meeting active power requirements of the load connected to the plant.

In order to understand operational behaviour of the plat and determine appropriate SVC capacity for effective operation of the plant under consideration, simulations of the proposed SHP with SVCs of different reactive power output ranges connected to the generator bus one at a time were performed. At the same time the interaction between the synchronous generator and the parallel connected induction generator and the operation of the plant in general was assessed.

During simulation, for each SVC connected to the generator bus two operation conditions were simulated whereby the induction generator driven by a hydraulic turbine was connected into the system while its power output was 0.6 pu of its full load capacity or 96 kW was maintained in the first situation. The second situation simulated, was when the mechanical power supplied to the induction generator was initially as in the previous case, 0.6 pu at the moment the induction generator was connected into the system and the was later increased to match with full load torque and consequently the output power of the induction generator was increased from 96 kW to 160 kW or its full load capacity. In both situations, the load connected to the plant was maintained at (500 + j300) kVA.

Static Var Compensators connected to the system during the simulations had the reactance that could vary from being pure capacitive to pure inductive with reactive power generation capacity i.e. reactive power output range from capacitive implying ability to supply the system with reactive power to inductive or ability to absorb reactive power from the system. The SVCs used for simulations were of the following reactive power output ranges: (-j300 to +j300) kvar, (-j400 to +j400) kvar, (-j500 to +j500) kvar and (-j600 to j600) kvar. Simulation results for each simulated case are shown in graphs preceded by discussion of the respective simulation.

4.3.1.1 Induction Generator Power Output Maintained at 96 kW

Simulation of the proposed SHP operation supplying a constant load was performed for the purpose of studying interactions between the synchronous generator and induction generator in the plant. As the operation of the induction generator requires external supplied reactive power, SVC was included. However, the determination of appropriate capacity of SVC that can ensure smooth operation of the plant was to be done, therefore simulations with different

SVCs of different capacities starting with the one of lower capacity which had reactive power output range of (-j300 to j300) kvar connected to generator bus were conducted. The outcomes of the simulations are discussed bellow.

The simulation results of cases when SVC of different capacities are employed depicted in figure 4.4 to figure 4.11 shows, that initial power output of the power plant matched with the declared active and reactive power demand of the connected load namely (500 + J300) kVA. However, just before the induction generator was connected into the system, the power output started to fluctuate slightly. The connection of induction generator into the system caused active and reactive power surges on the output side of the plant and peak values of the surges were in the increase with increase in the capacity of SVC connected to the generator bus. When the plant reached a steady state condition from t = 0.5s, the active power output was about 480 kW while reactive power output settled at around 280 kvar which both are lower than the declared power demand of the connected load. Apart from the mentioned short fall in power output, the plant showed stable operation characteristics with both synchronous and induction generators in the system.

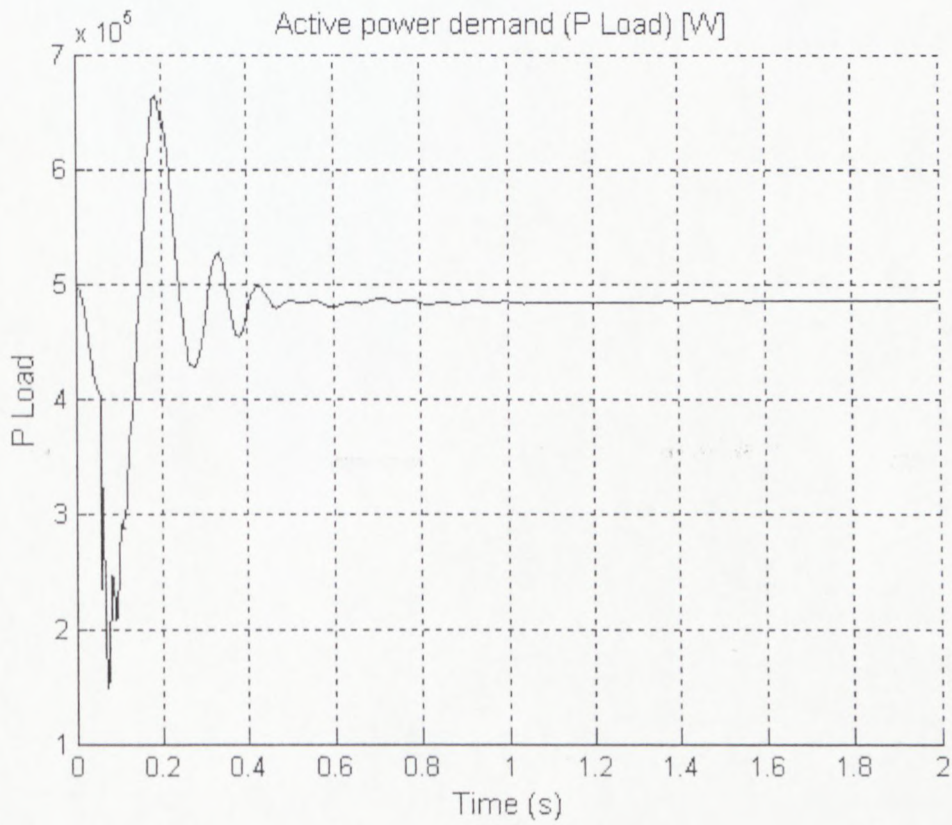


Figure 4.4: Active Power Output of the SHP When SVC Output Range is (-j300 to j300) kvar

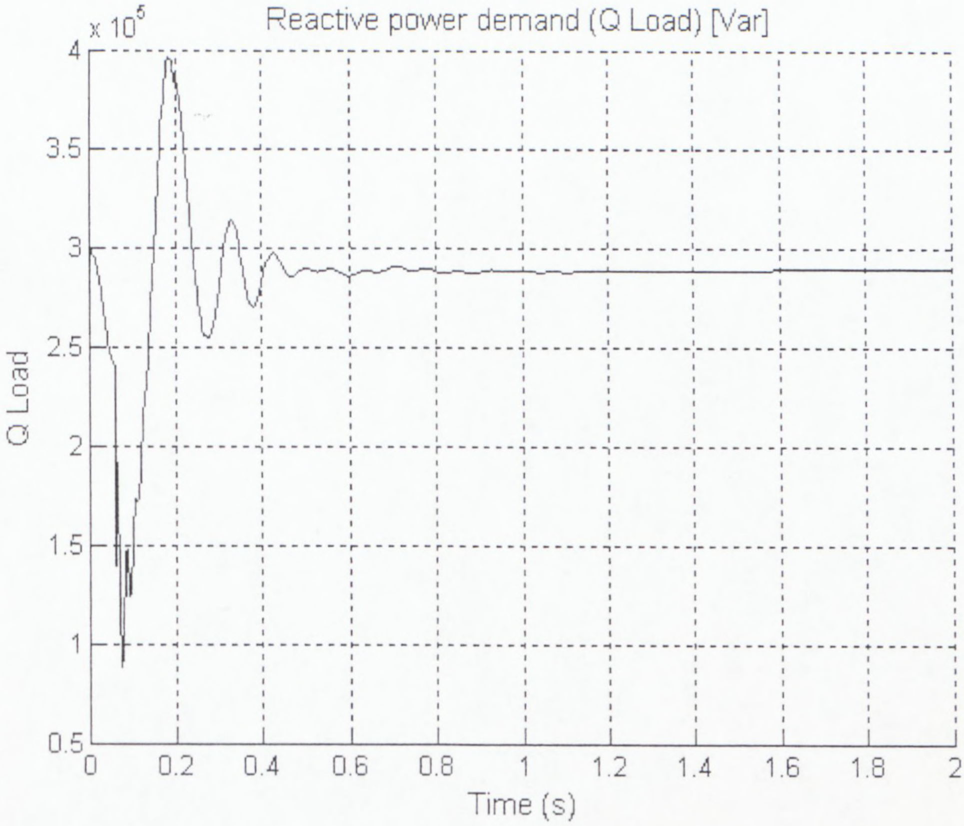


Figure 4.5: Reactive Power Output of the SHP When SVC Output Range is (-j300 to j300) kvar

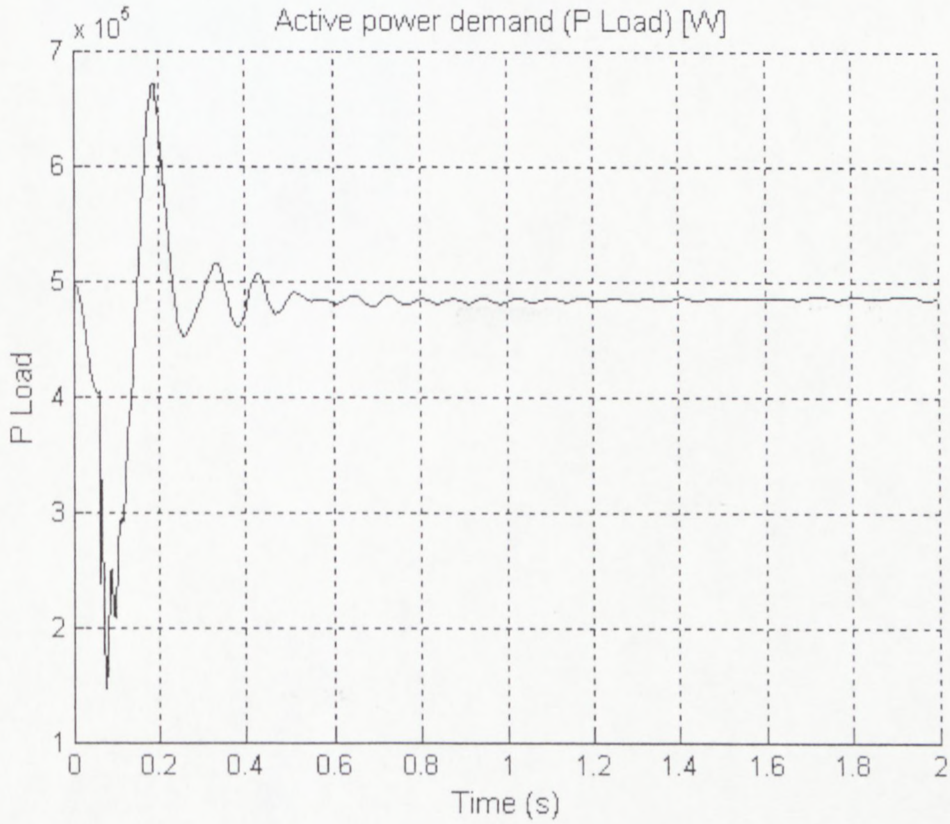


Figure 4.6: Active Power Output of the SHP When SVC Output Range is (-j400 to j400) kvar

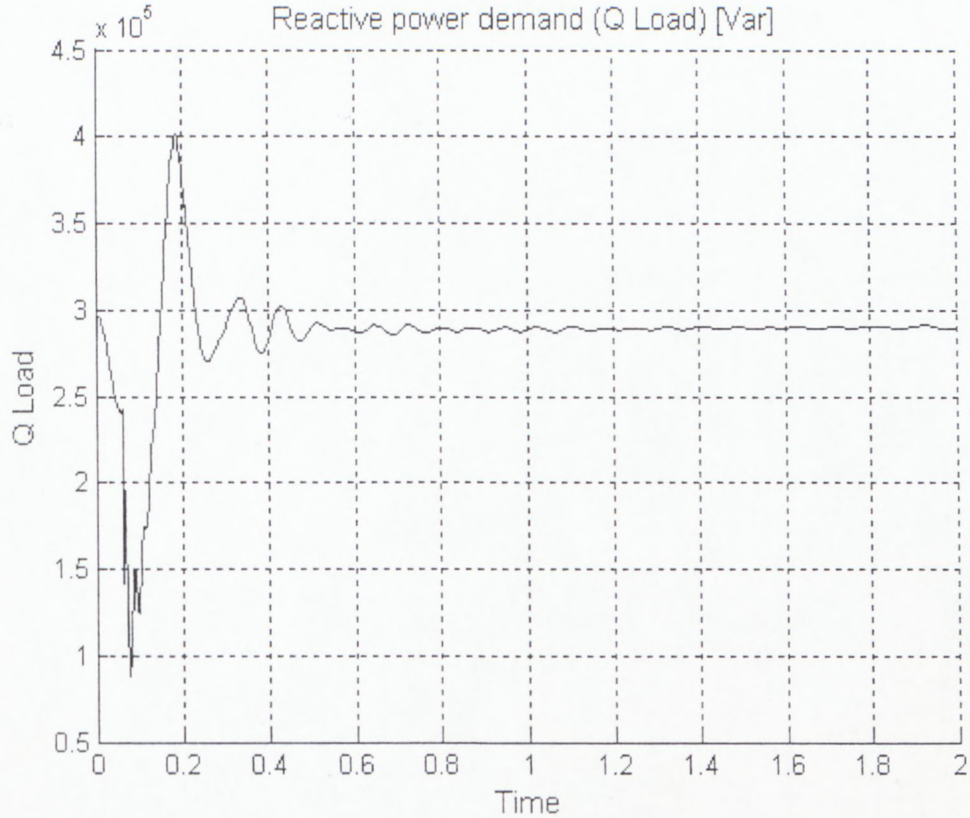


Figure 4.7: Reactive Power Output of the SHP When SVC Output Range is (-j400 to j400) kvar

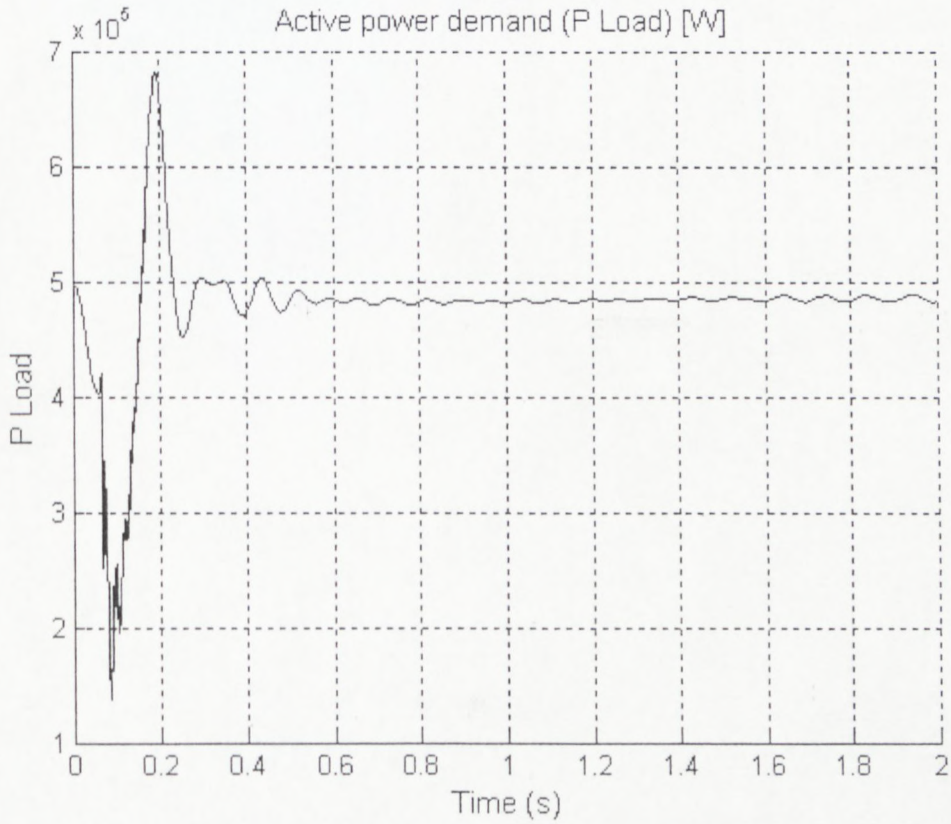


Figure 4.8: Active Power Output of the SHP When SVC Output Range is (-j500 to j500) kvar

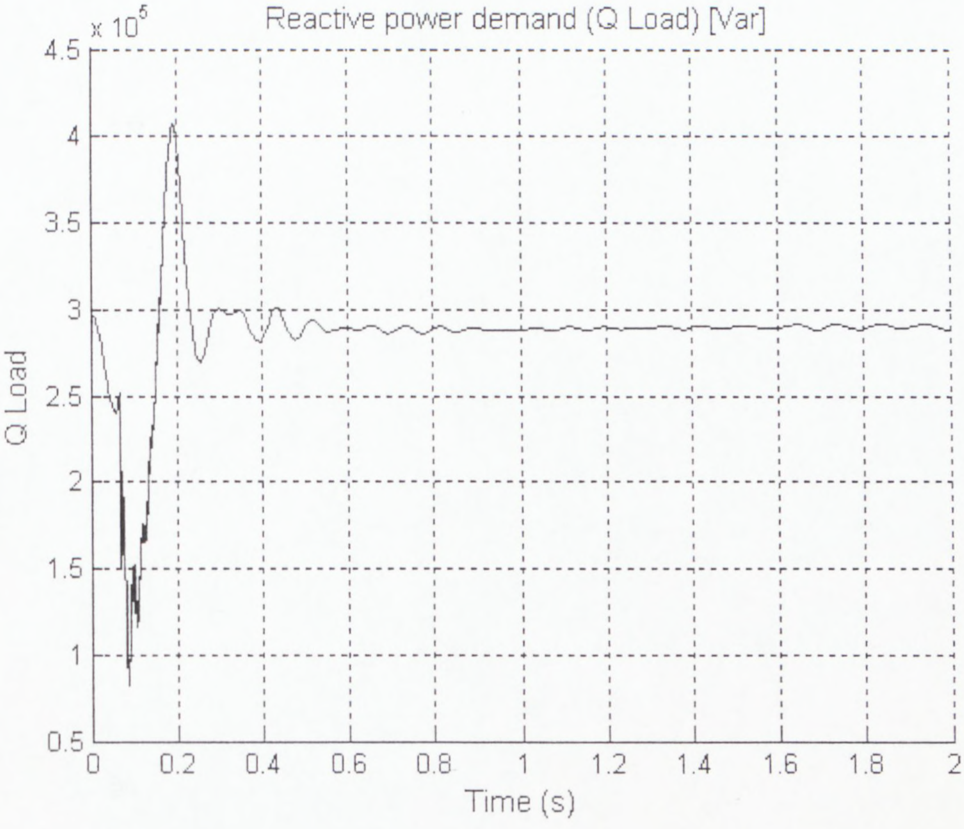


Figure 4.9: Reactive Power Output of the SHP When SVC Output Range is (-j500 to j500) kvar

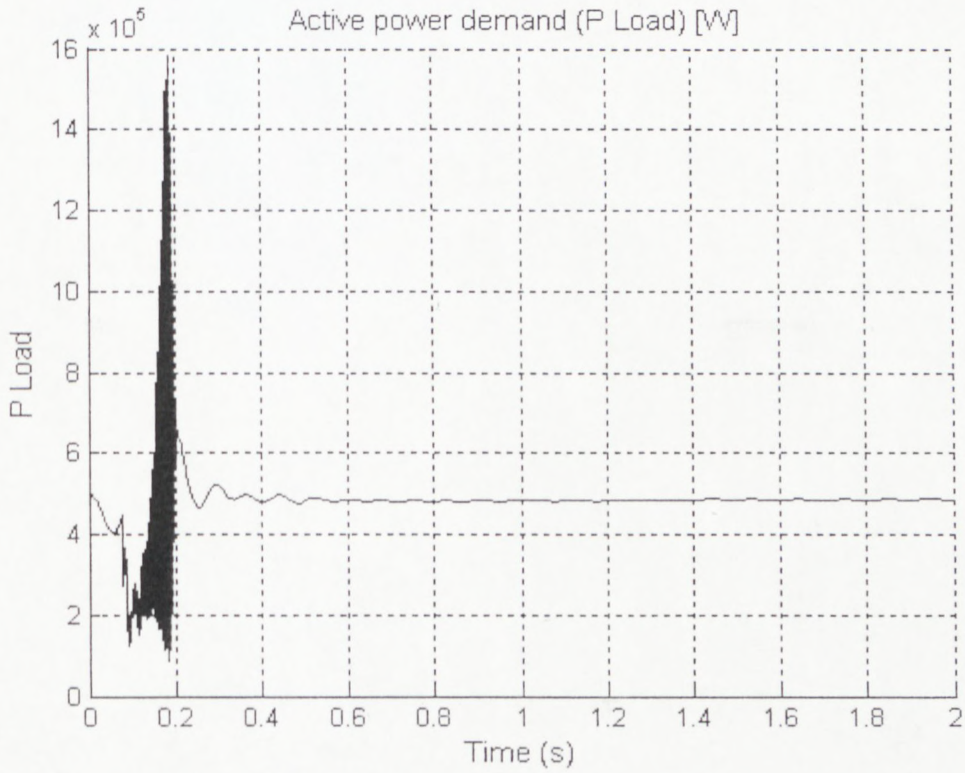


Figure 4.10: Active Power Output of the SHP When SVC Output Range is (-j600 to j600) kvar

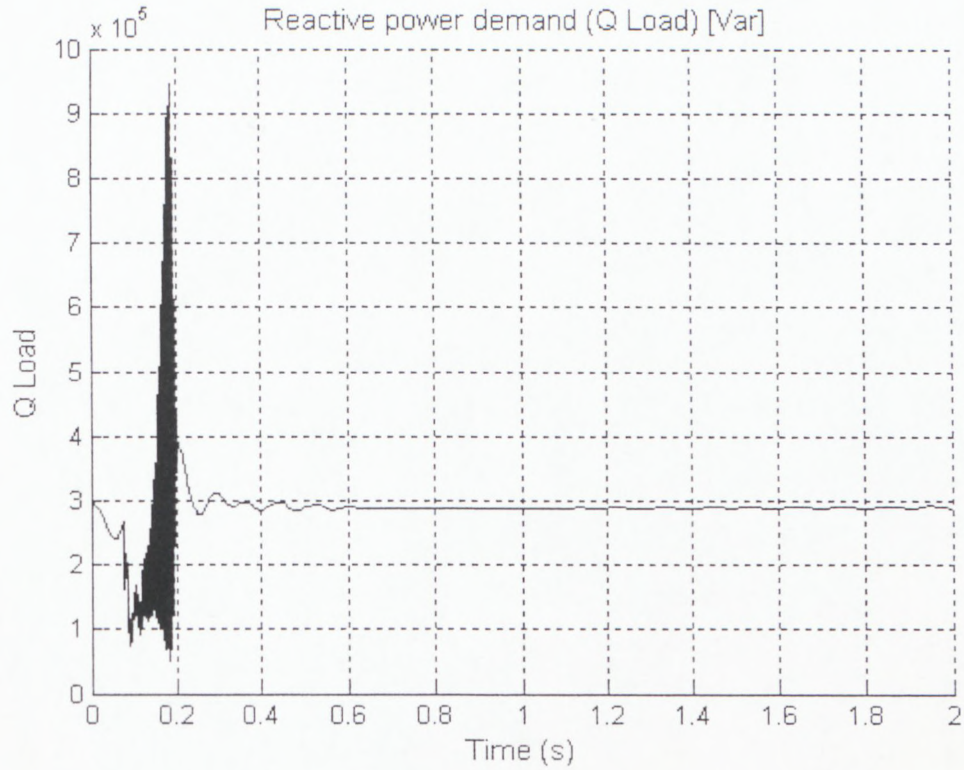


Figure 4.11: Reactive Power Output of the SHP When SVC Output Range is (-j600 to j600) kvar

After connecting the induction generator into the system and subsidence of the transients, both the active and reactive power output of the proposed plant settled at stable values slightly less than the initial power output. The smallest difference between initial power output and the output after transient period was achieved with the (-j600 to j600) kvar SVC connected to the generator bus as depicted in figure 4.10 and figure 4.11.

In response to incoming of the induction generator into the system, the power output of the synchronous generator varied with oscillations for some time. When the transient period which lasted about 0.35s elapsed, active power output of the synchronous dropped from initial 500 kW to approximately 400 kW. The same behaviour was demonstrated by the synchronous generator when the plant was simulated with SVC of different capacities connected to the generator bus results which are shown in Figure 4.12 to Figure 4.15.

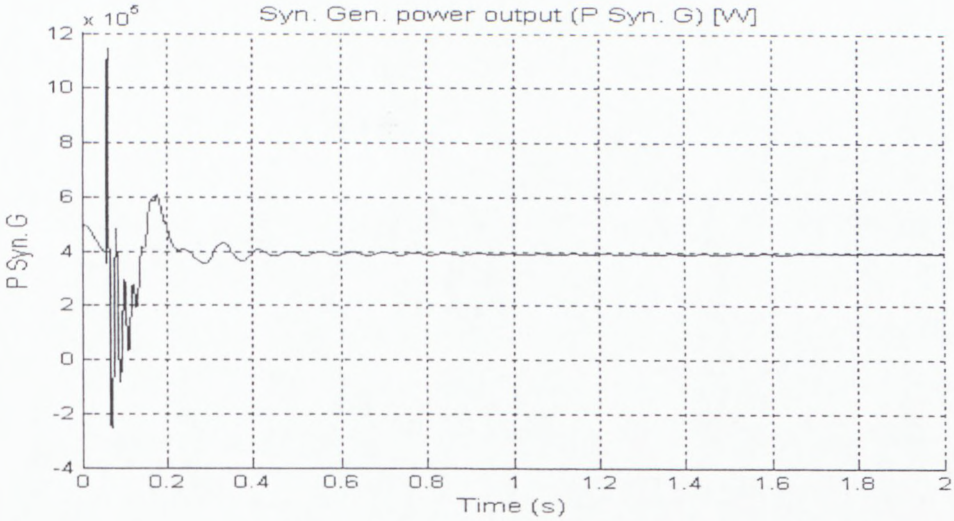


Figure 4.12: Synchronous Generator Power Output When SVC Output is (-j300 to j300) kvar

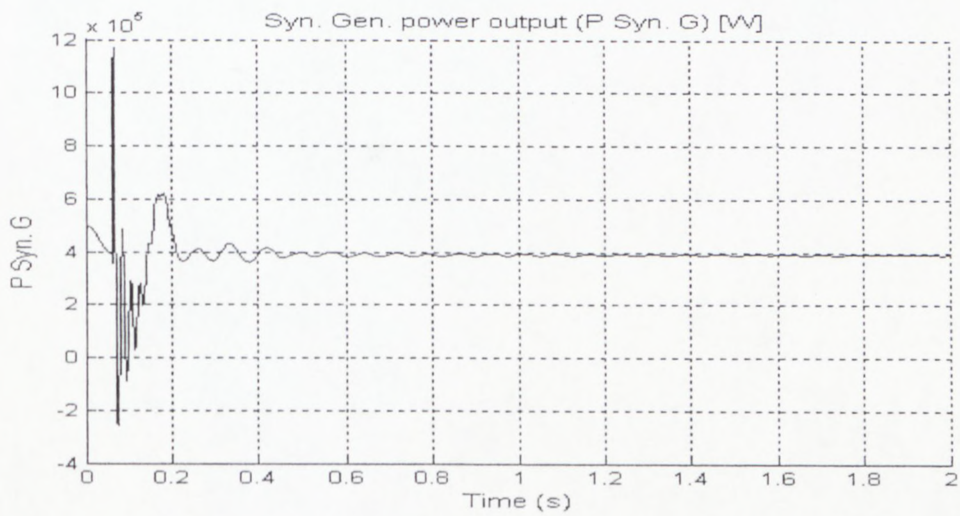


Figure 4.13: Synchronous Generator Power Output When SVC Output is (-j400 to j400) kvar

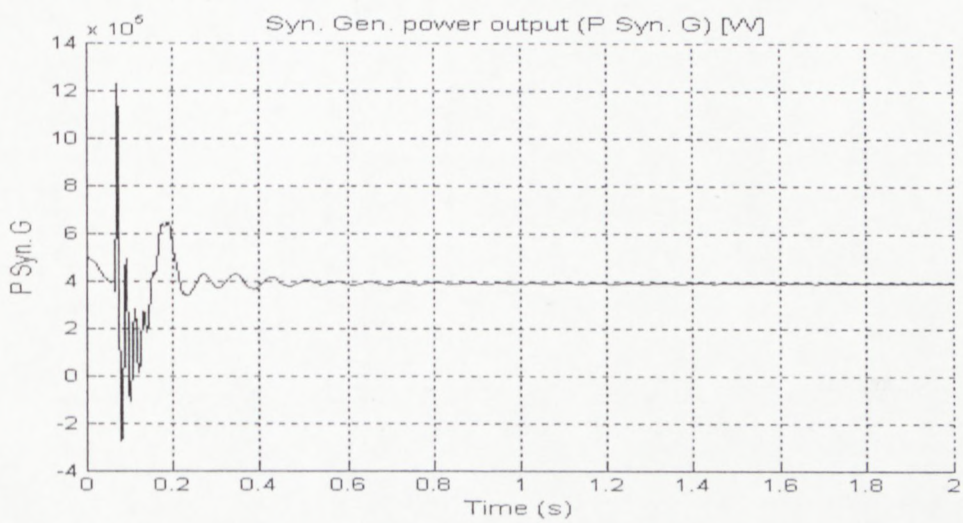


Figure 4.14: Synchronous Generator Power Output When SVC Output is (-j500 to j500) kvar

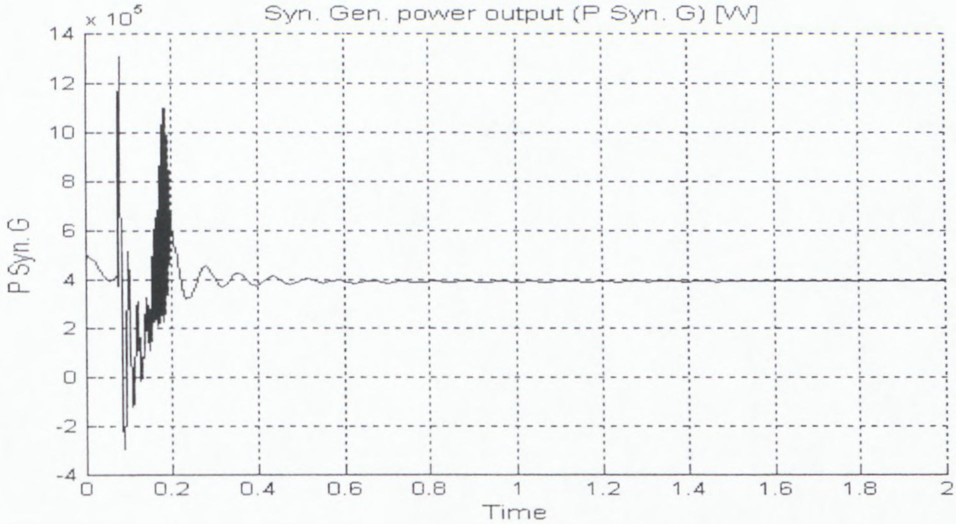


Figure 4.15: Synchronous Generator Power Output When SVC Output is (-j600 to j600) kvar

Induction generator active power output on the other hand rose after the transient period from zero at the beginning of each simulation to 96 kW or approximately 100 kW in steady state conditions as evidenced in Figure 4.16, Figure 4.18, Figure 4.20, and Figure 4.22. This indicates that induction generator took over part of the load from the synchronous generator.

Mechanical power or driving torque supplied by the turbine coupled to induction generator Turb2, remained constant at the value resulting to induction generator's active power output to be constant at 96 kW. For this purpose power relay was tuned not to send signal that could activate switching signal instructing Turb2 to increase the mechanical power supplied to induction generator. Figure 4.17, Figure 4.19, Figure 4.21 and Figure 4.23 shows Turb2 switching signal being at zero value throughout simulation period in all cases.

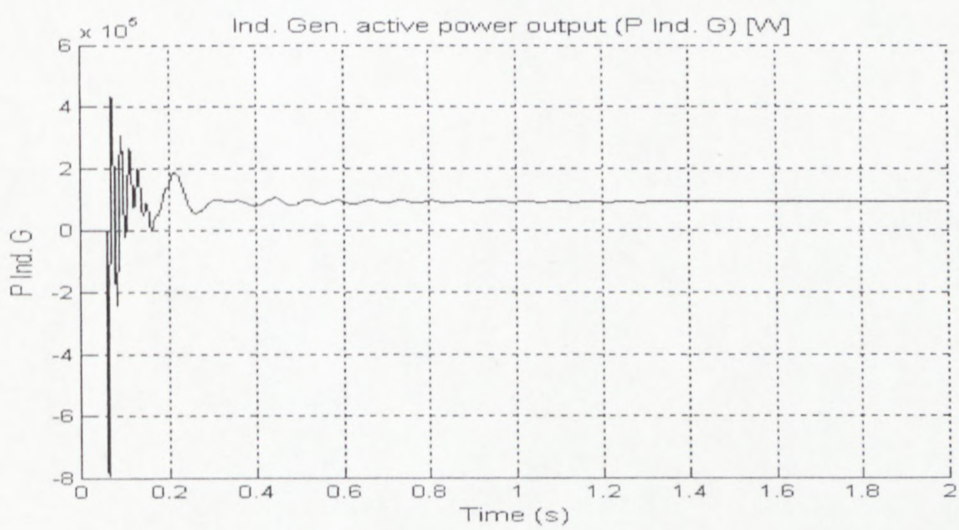


Figure 4.16: Induction Generator Power Output When SVC Output is (-j300 to j300) kvar

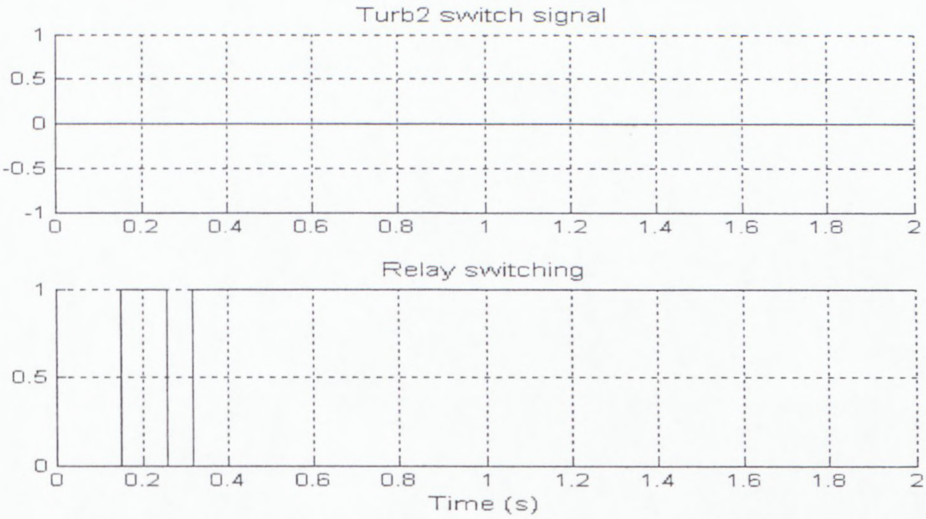


Figure 4.17: Power Relay Switching Signals When SVC Output is (-j300 to j300) kvar

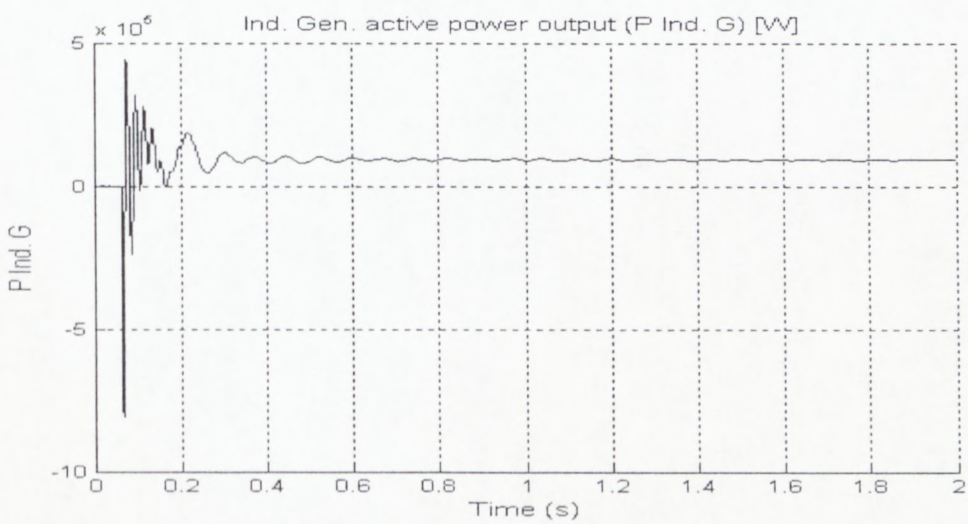


Figure 4.18: Induction Generator Active Power Output When SVC Output is (-j400 to j400) kvar

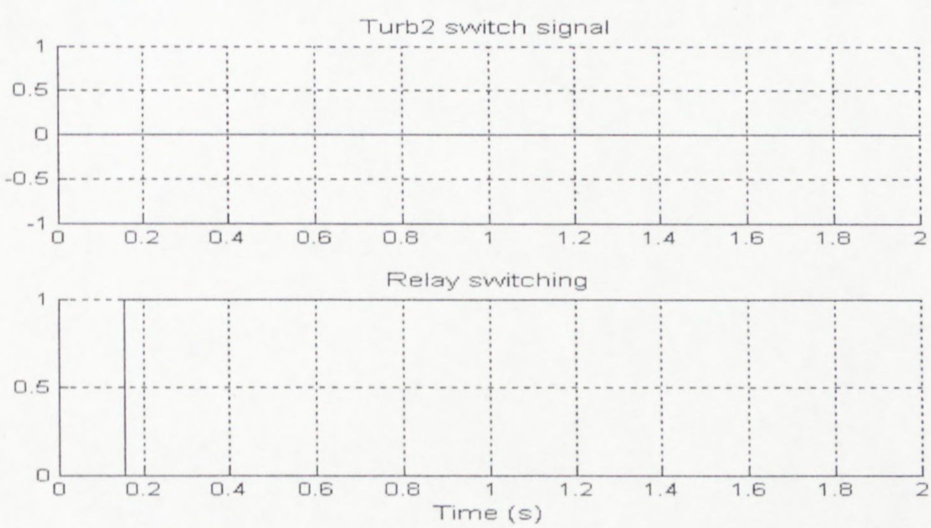


Figure 4.19: Power Relay Switching Signals When SVC Output is (-j400 to j400) kvar

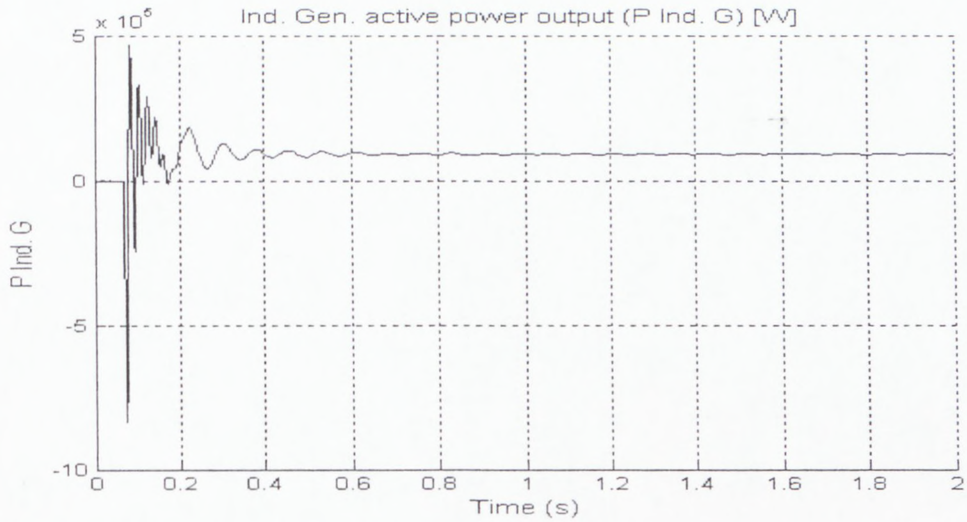


Figure 4.20: Induction Generator Active Power Output When SVC Output is (-j500 to j500) kvar

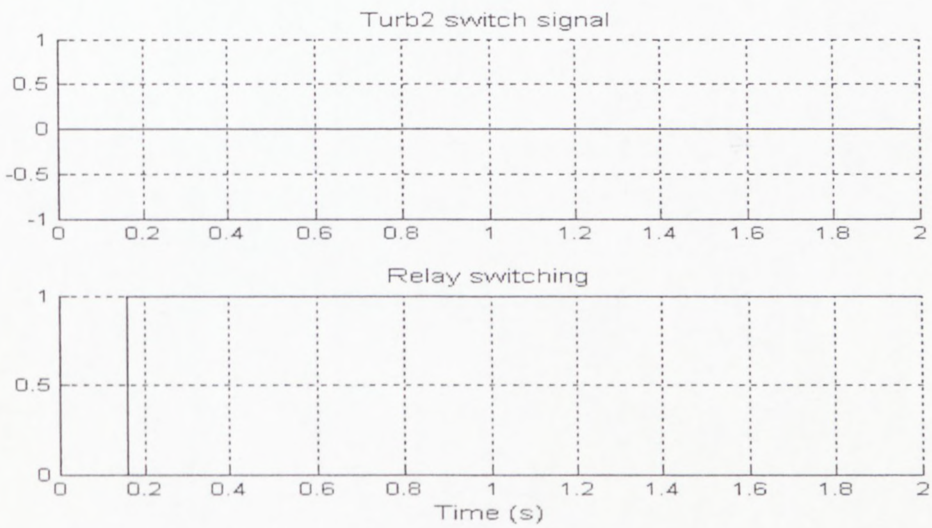


Figure 4.21: Power Relay Switching Signals When SVC Output is (-j500 to j500) kvar

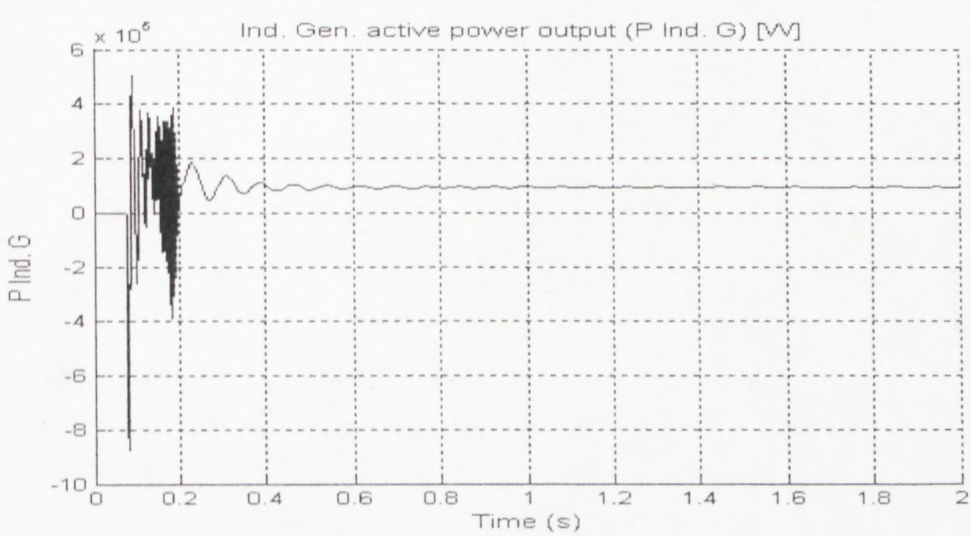


Figure 4.22: Induction Generator Active Power Output When SVC Output is (-j600 to j600) kvar

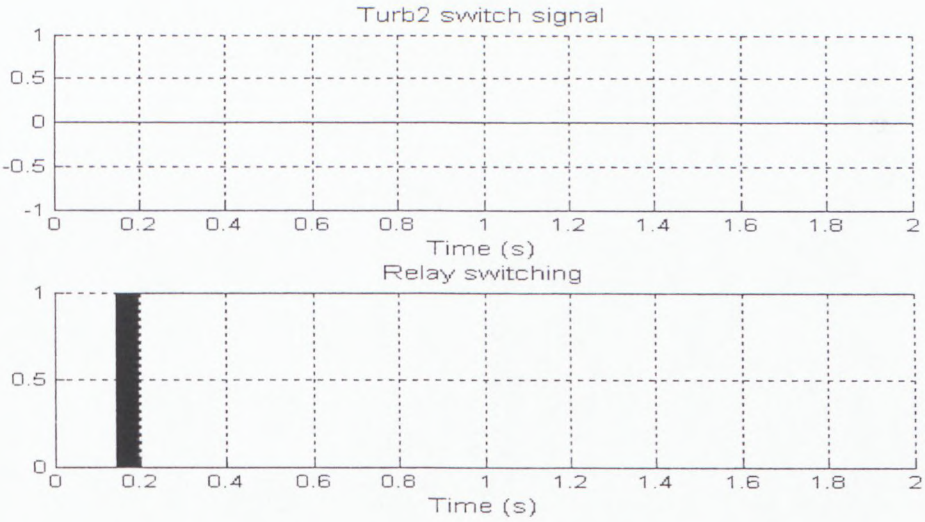


Figure 4.23: Power Relay Operation Signals When SVC Output is (-j600 to j600) kvar

Induction generator contributed to supply of active power to the load connected to the power plant but at the same time absorbed reactive power from the system as demonstrated in Figure 4.24, Figure 4.27, Figure 4.30 and Figure 4.33. In addition, rotor of the induction generator ran at a higher speed than that of the synchronous generator the fact exhibited when comparing induction generator speed with synchronous generator rotor speed which is also the system generation frequency in Figure 4.26 with Figure 4.25, Figure 4.29 with Figure 4.28, and Figure 4.32 with Figure 4.31 and Figure 4.35 with Figure 4.34. It is worth to note, that the speed synchronous generator's rotor after transient period, reached steady state value of approximately 0.999 pu.

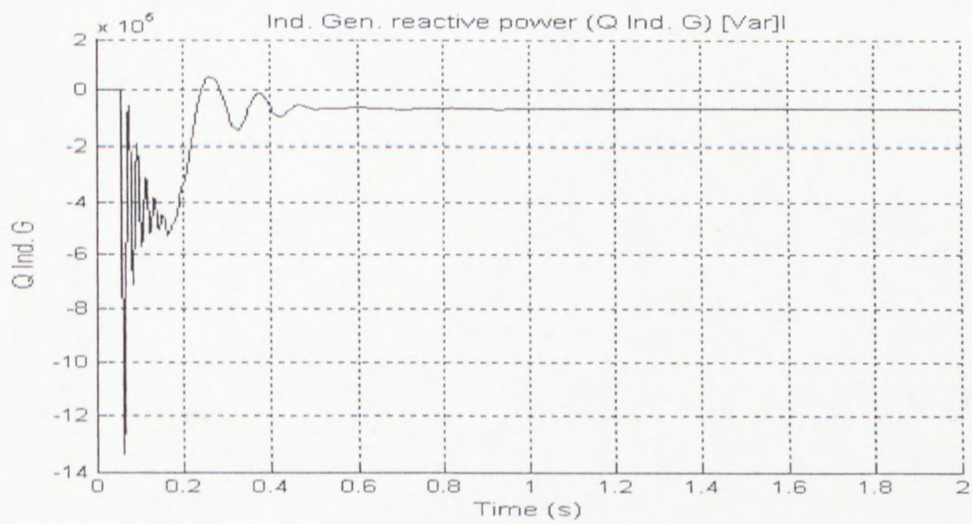


Figure 4.24: Induction Generator Reactive Power When SVC Output is (-j300 to j300) kvar

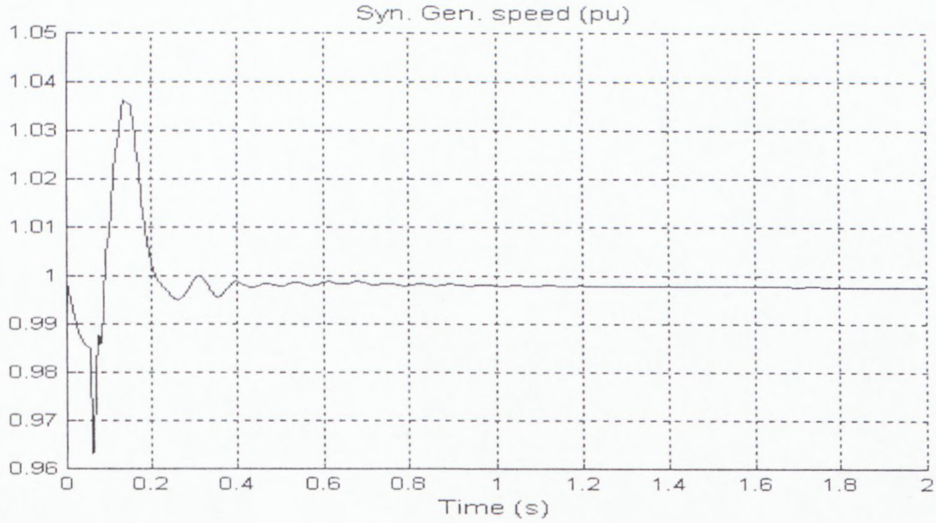


Figure 4.25: Synchronous Generator Speed When SVC Output is (-j300 to j300) kvar

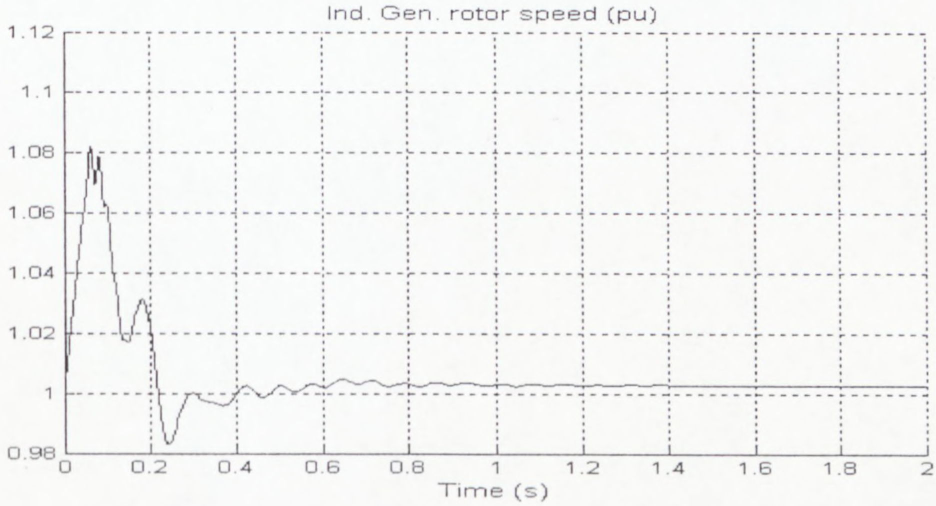


Figure 4.26: Induction Generator Rotor Speed When SVC Output is (-j300 to j300) kvar

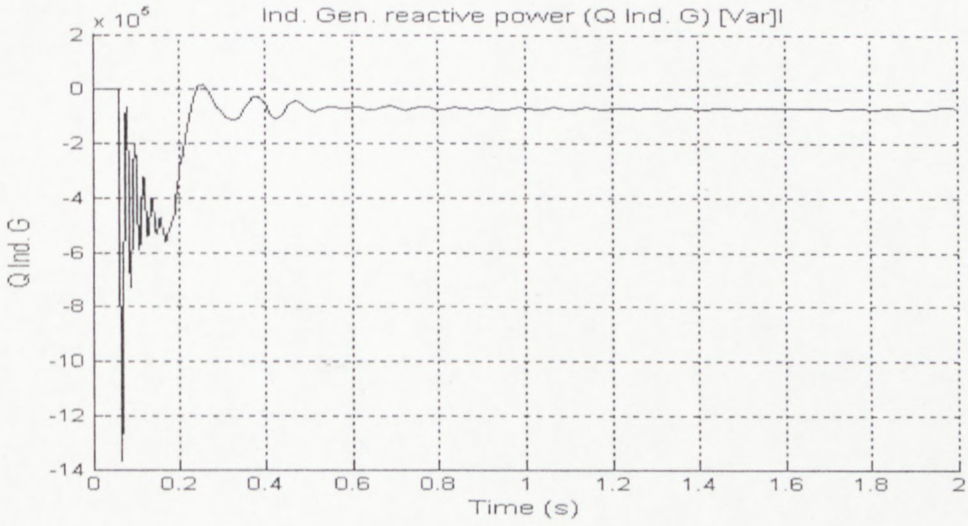


Figure 4.27: Induction Generator Reactive Power When SVC Output is (-j400 to j400) kvar

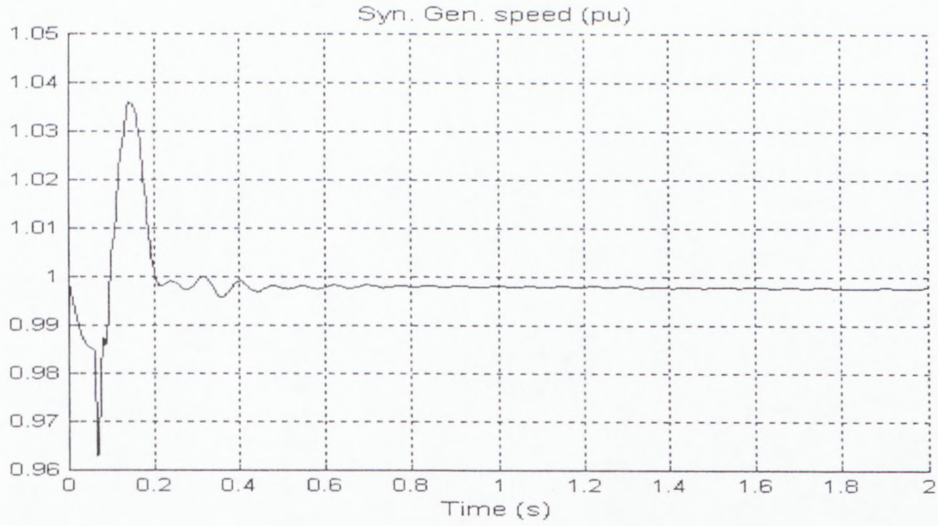


Figure 4.28: Synchronous Generator Speed When SVC Output is (-j400 to j400) kvar

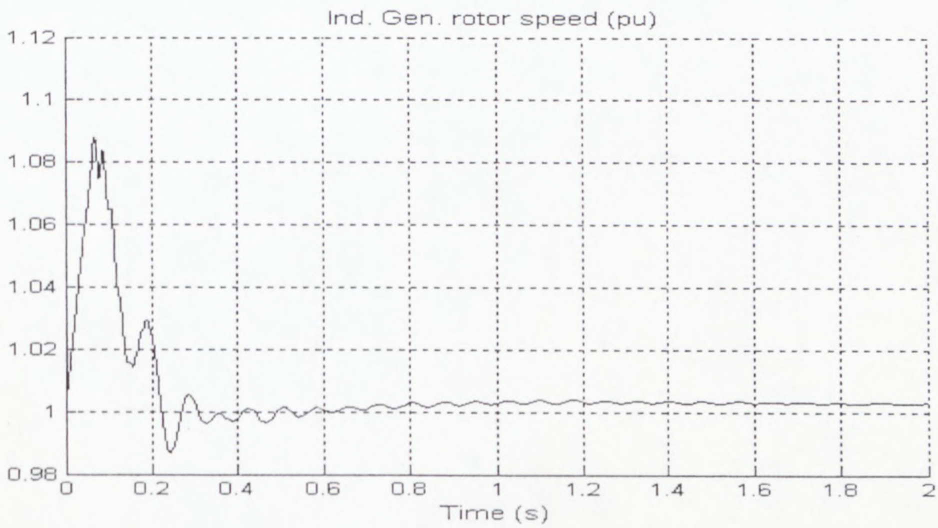


Figure 4.29: Induction Generator Rotor Speed When SVC Output is (-j400 to j400) kvar

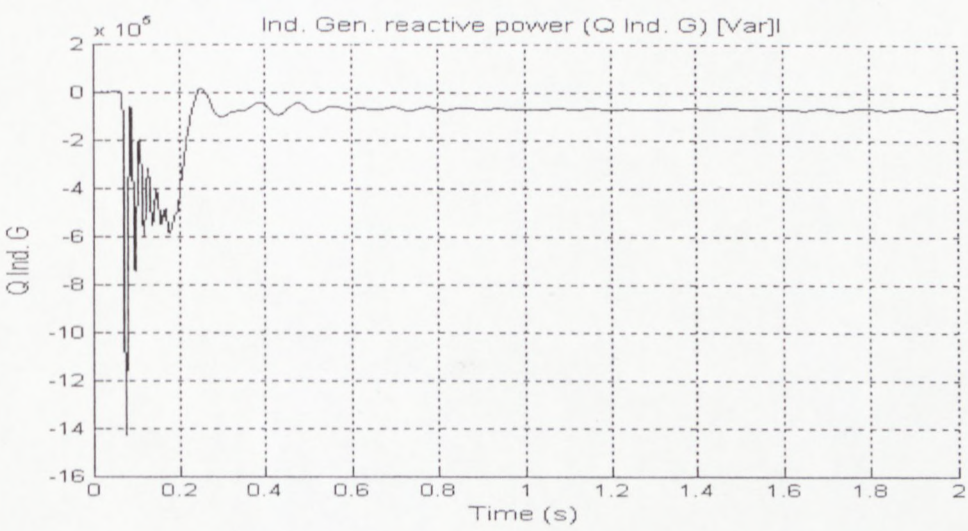


Figure 4.30: Induction Generator Reactive Power When SVC Output is (-j500 to j500) kvar

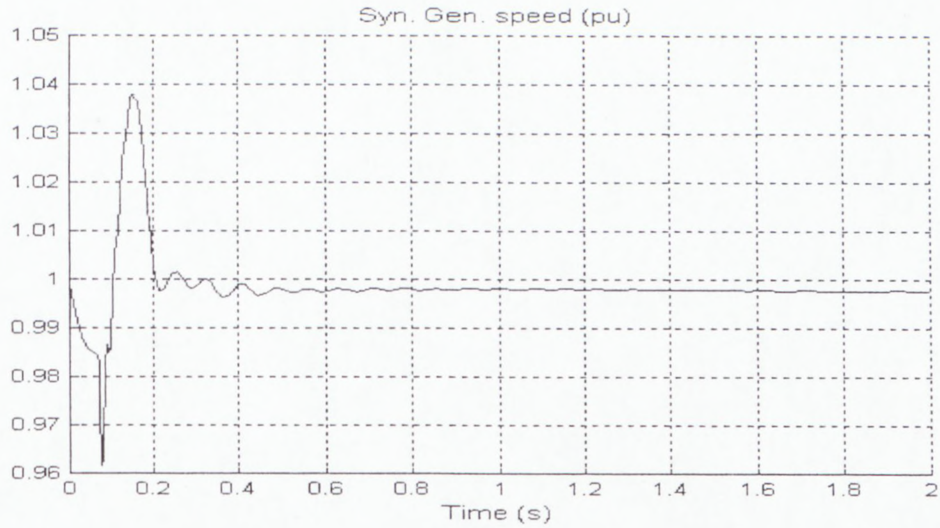


Figure 4.31: Synchronous Generator Speed When SVC Output is (-j500 to j500) kvar

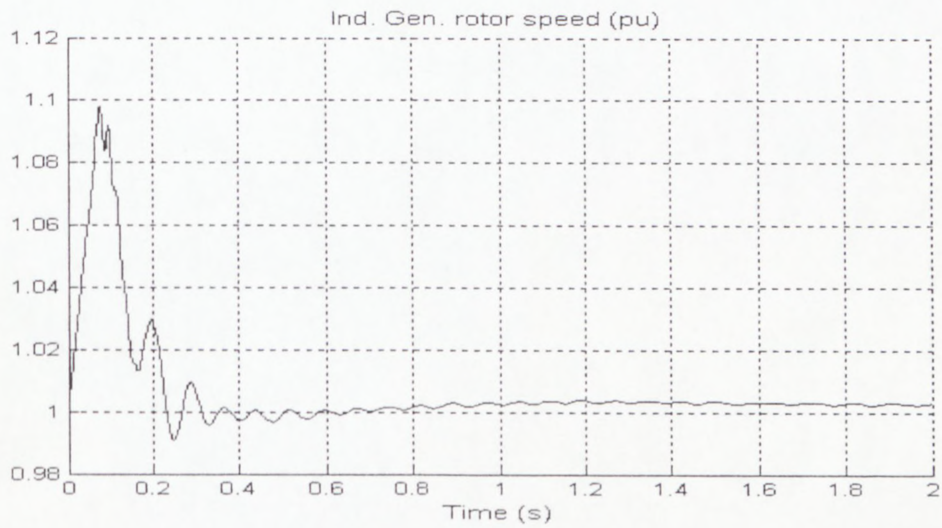


Figure 4.32: Induction Generator Rotor Speed When SVC Output is (-j500 to j500) kvar

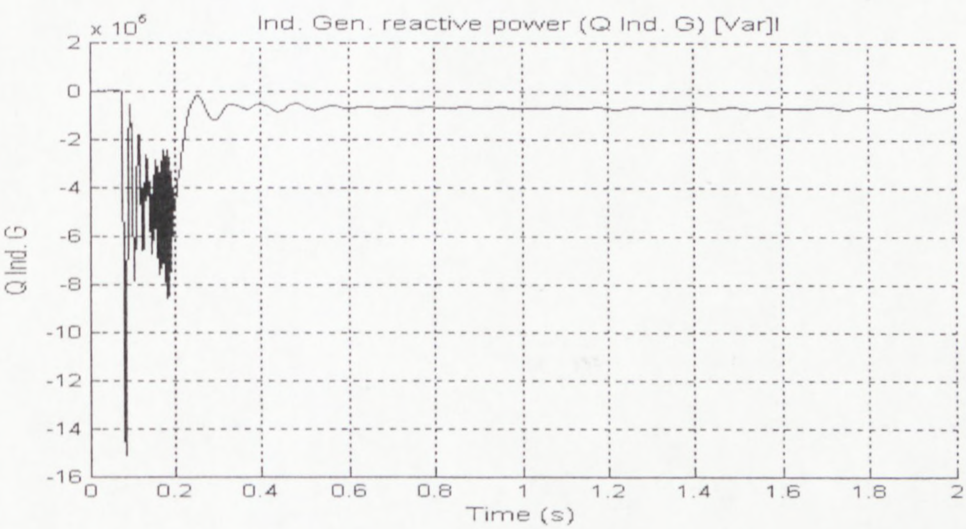


Figure 4.33: Induction Generator Reactive Power Output When SVC Output is (-j600 to j600) kvar

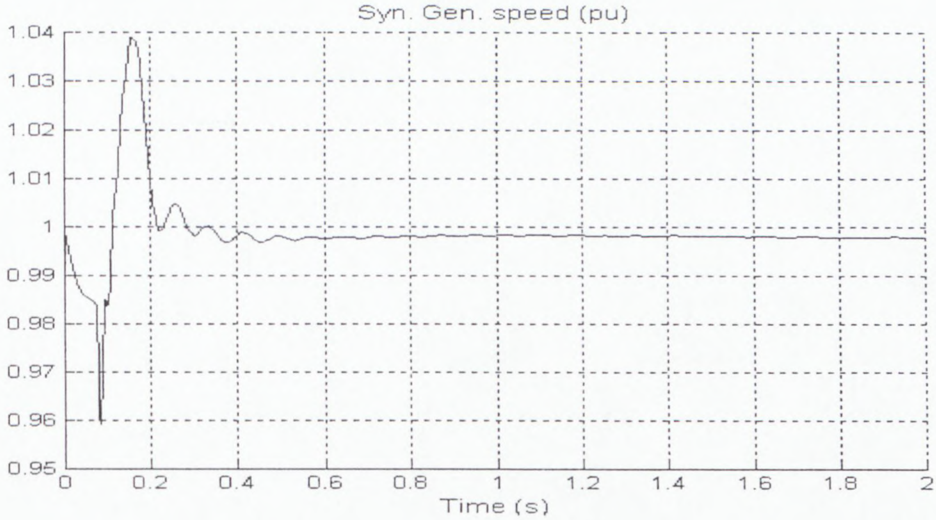


Figure 4.34: Synchronous Generator Speed When SVC Output is (-j600 to j600) kvar

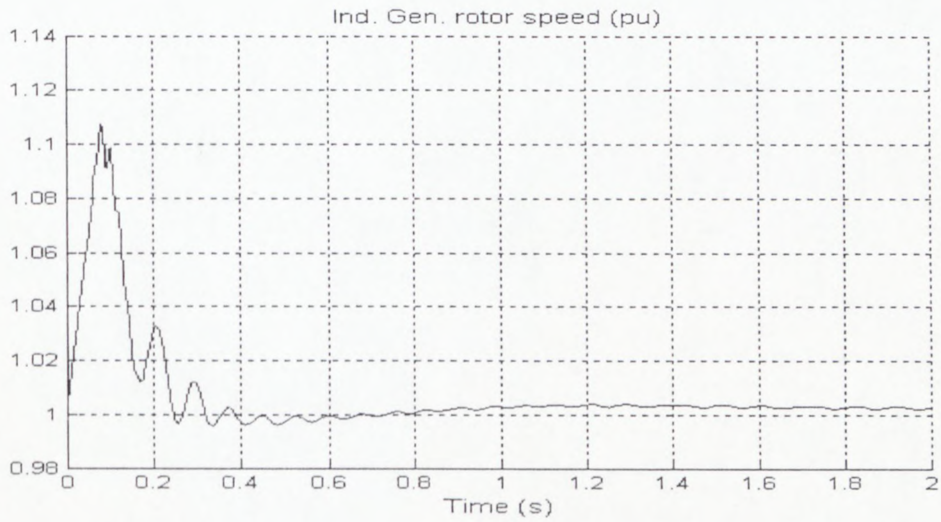


Figure 4.35: Induction Generator Rotor Speed When SVC Output is (-j600 to j600) kvar

In the proposed power plant synchronous generator is source of both active and reactive power. Simulation results with the constant load to the plant show reactive power output of the synchronous generator as reflected in Figure 4.36, Figure 4.39, Figure 4.42, and Figure 4.45 is influenced by SVC connected to the generator bus. The results indicate reactive power supplied by synchronous generator to the system assumed different characteristics with change in capacity of the SVC included into the system.

Static Var Compensator connected to the generator bus in all cases operated both in inductive mode absorbing excess reactive power delivered by the synchronous generator to the system and capacitive mode injecting reactive power into the system supplementing that supplied by the synchronous generator when required. The inductive behaviour of SVC was shown when reactive power of the SVC was positive implying reactive power flow was from the generator bus to SVC and opposite when in capacitive operation mode. Figures 4.37,

Figure 4.40, Figure 4.43 and Figure 4.46 show the operation characteristics of SVC of different capacities connected to the generator bus.

Simulation outcomes showed that simultaneous operation of synchronous generator and SVC in generation of reactive power to meet system requirements resulted to maintenance of voltage of generator bus at a steady value of approximately 0.99 pu as depicted in figure 4.38, Figure 4.41, Figure 4.44 and Figure 4.47.

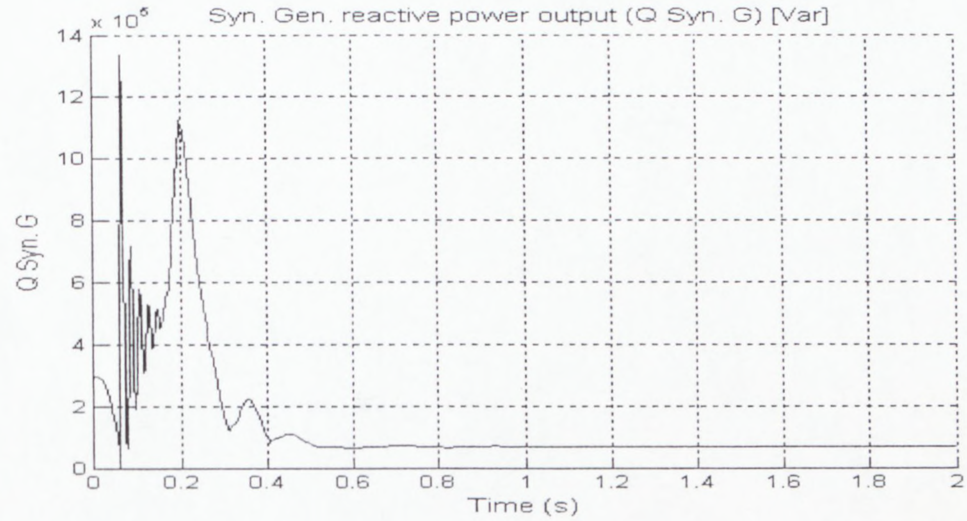


Figure 4.36: Synchronous Generator Reactive Power Output When SVC Output is (-j300 to j300) kvar

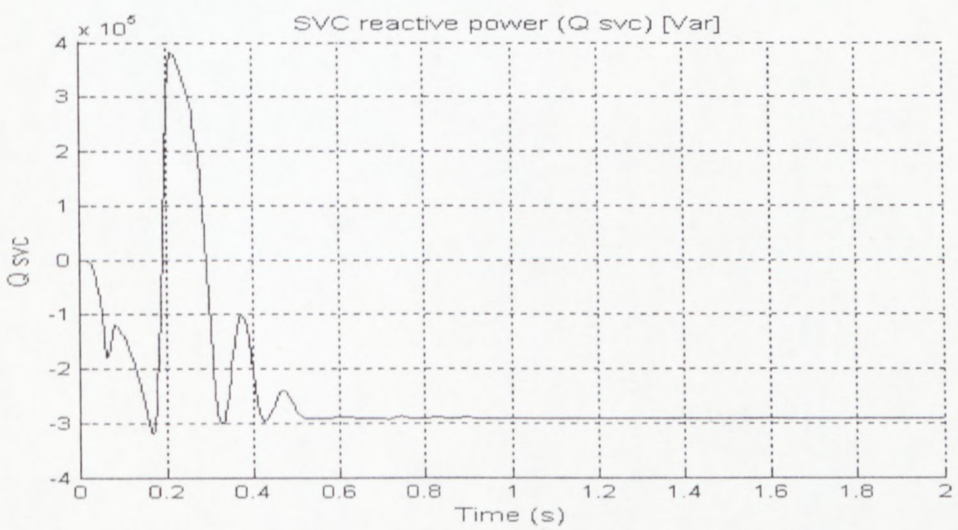


Figure 4.37: SVC Reactive Power Output When Output Range is (-j300 to j300) kvar

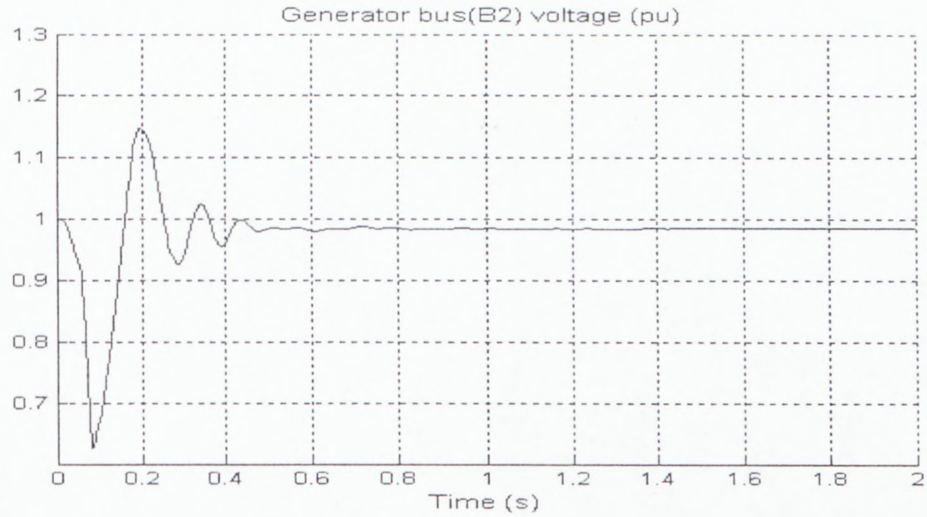


Figure 4.38: Generator Bus Voltage When SVC Output is (-j300 to j300) kvar

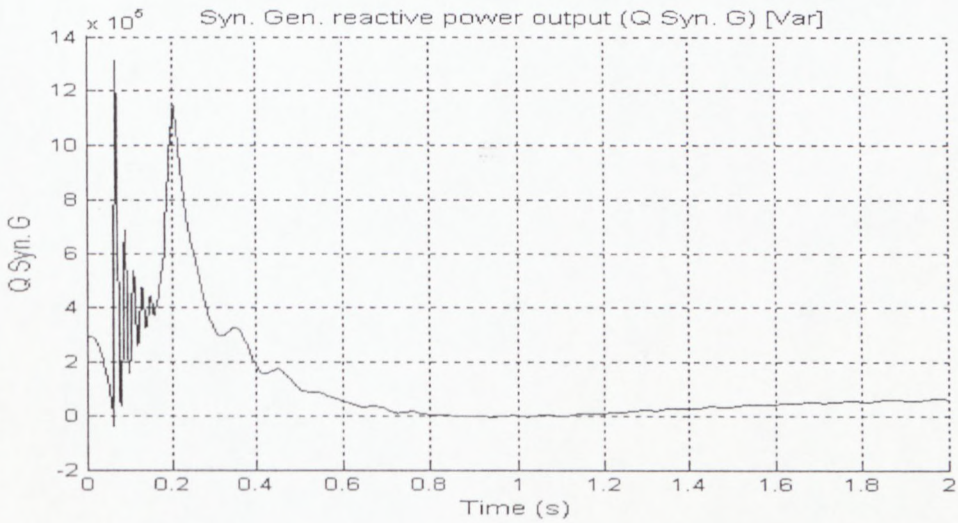


Figure 4.39: Synchronous Generator Reactive Power Output When SVC Output is (-j400 to j400) kvar

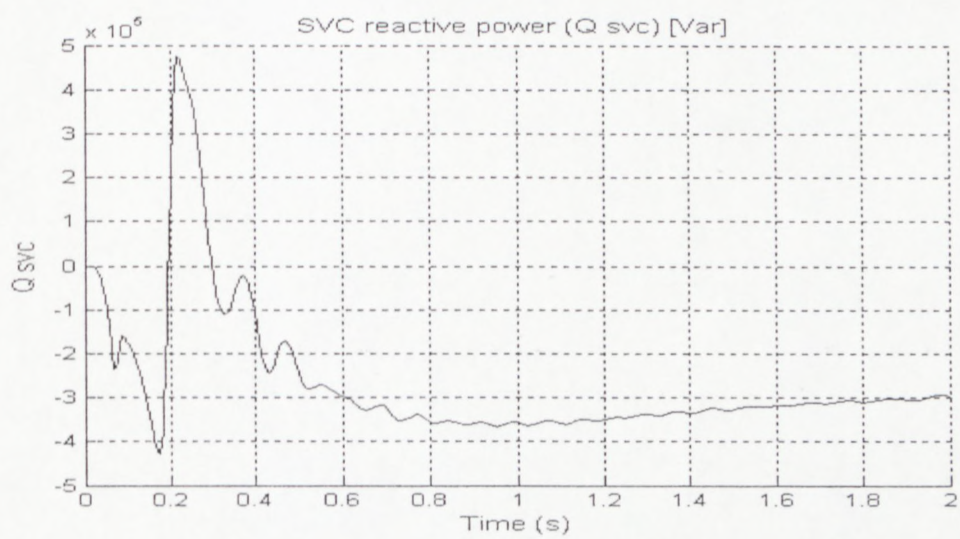


Figure 4.40: SVC Reactive Power When the Output Range is (-j400 to j400) kvar

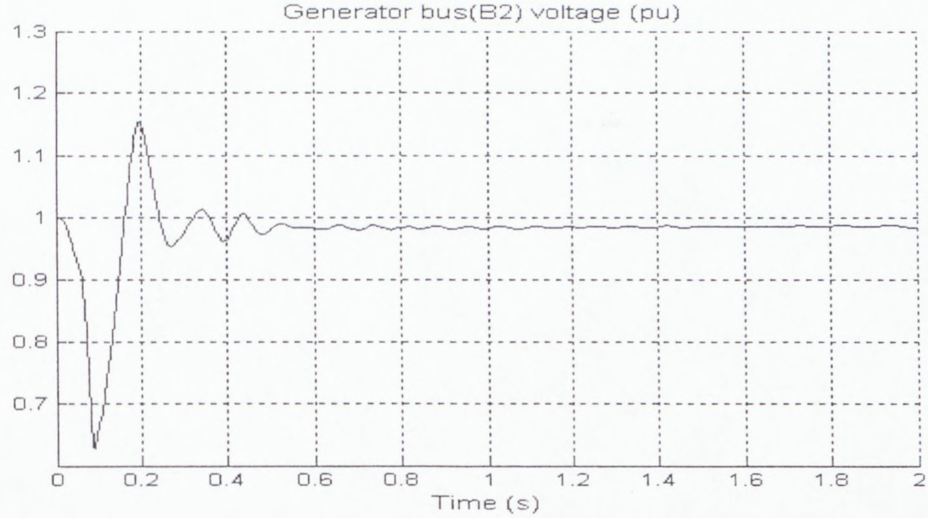


Figure 4.41: Generator Bus Voltage When SVC Output is (-j400 to j400) kvar

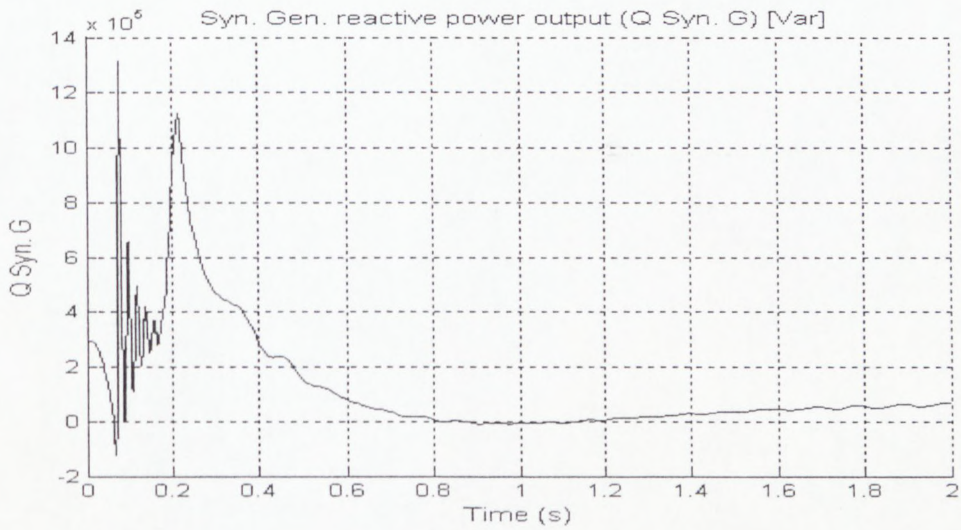


Figure 4.42: Synchronous Generator Reactive Power Output When SVC Output is (-j500 to j500) kvar

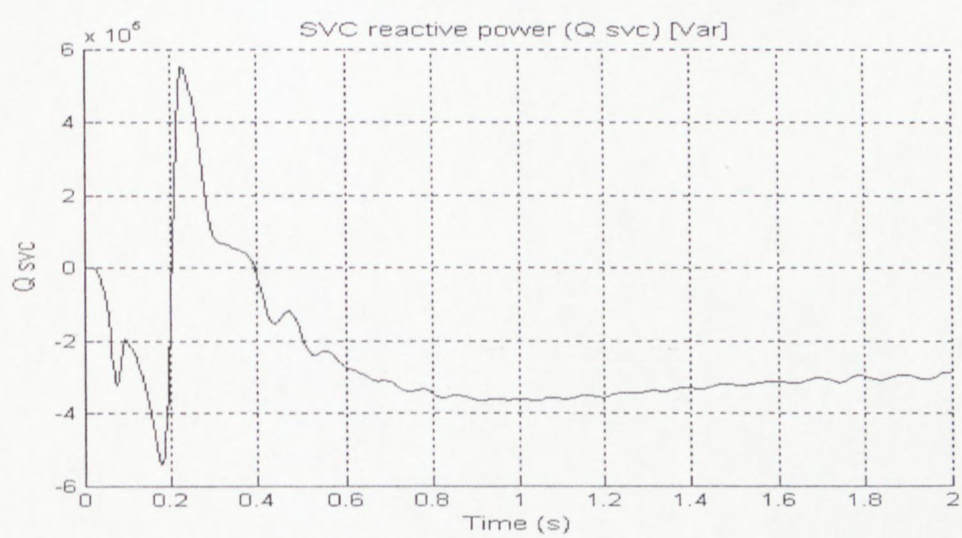


Figure 4.43: SVC Reactive Power When the Output Range is (-j500 to j500) kvar

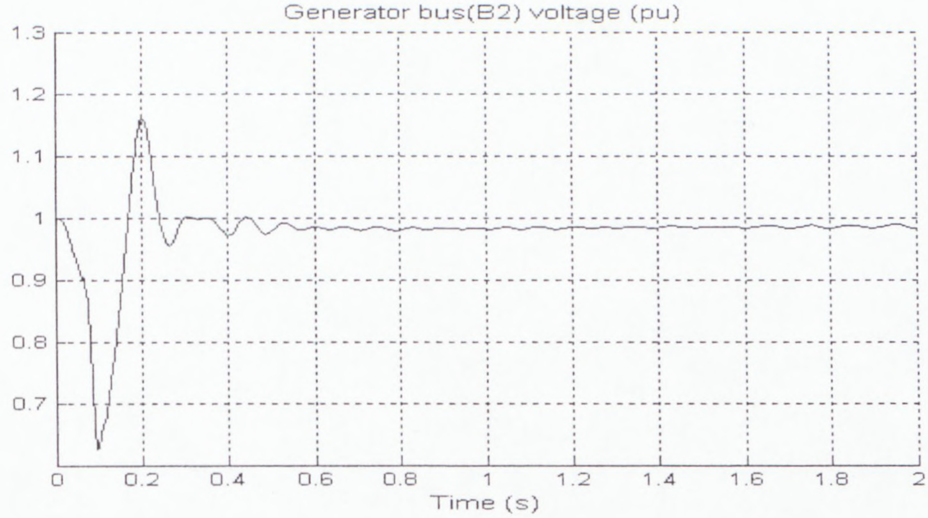


Figure 4.44: Generator Bus Voltage When SVC Output is (-j500 to j500) kvar

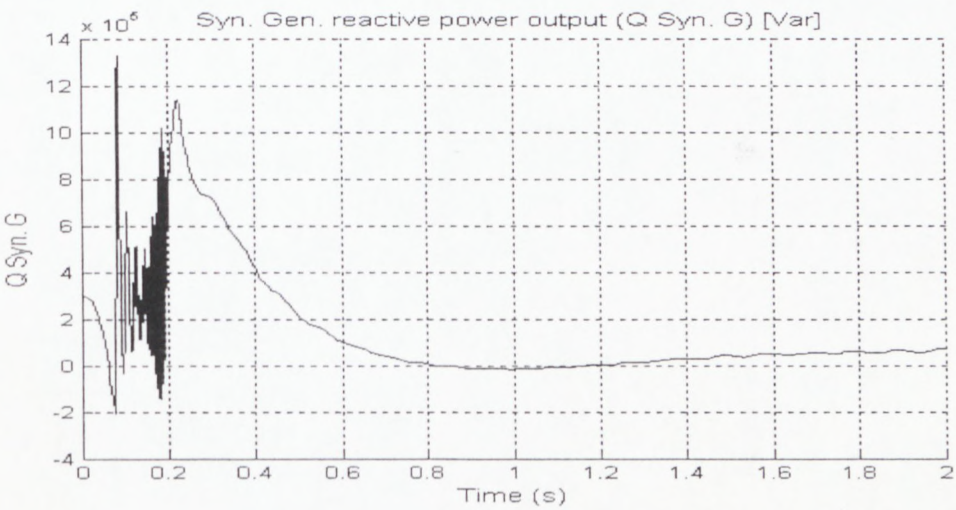


Figure 4.45: Synchronous Generator Reactive Power Output When SVC Output is (-j600 to j600) kvar

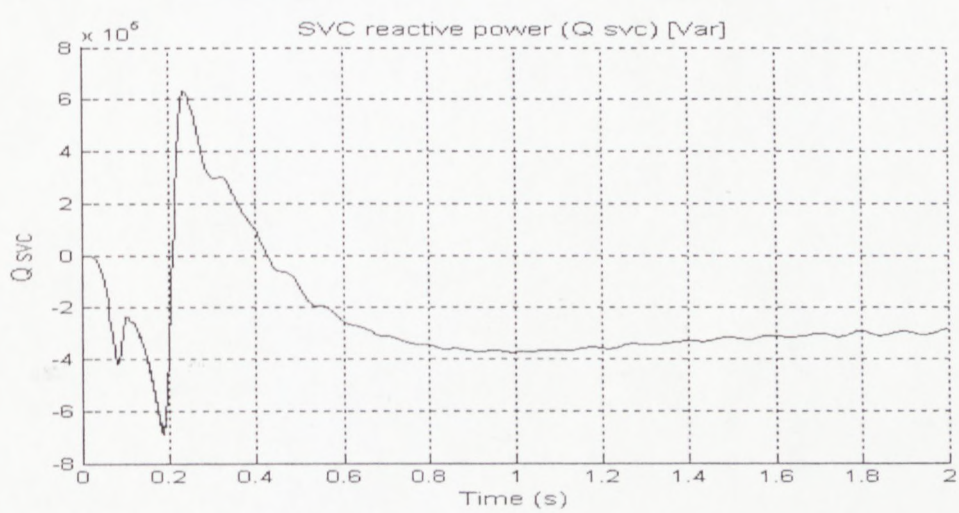


Figure 4.46: SVC Reactive Power Output When the Output Range is (-j600 to j600) kvar

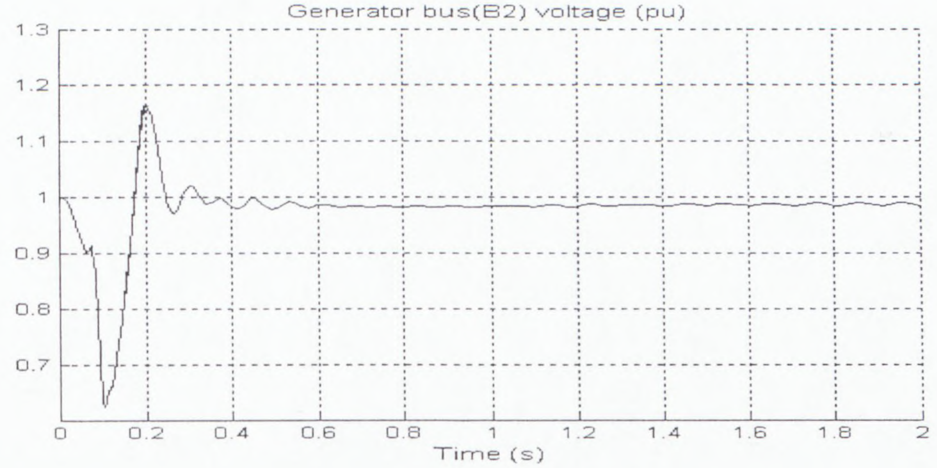


Figure 4.47: Generator Bus Voltage When SVC Output is (-j600 to j600) kvar

4.3.1.2 Induction Generator Power Output Increased to 160 kW

Simulation of the plant with increase of induction generator power output to its full load capacity of 160 kW while maintaining the load to the power plant at constant level was performed, in order to study the performance of the proposed power plant. Special interest was on interaction between synchronous generator and induction generator when active power output of induction generator change due to action of power relay instructing Turb2 to increase the power it supplies to induction generator.

Like in previous cases, the proposed SHP was simulated supplying a constant inductive load with 500 kW and 300 kvar. Even in this situation, the power supplied to the load was initially drawn from the synchronous generator alone as induction generator was yet to be connected. The induction generator was brought into the system two cycles later first driven by the hydraulic turbine whose power output provided a driving torque to the induction generator enough to make the generator produce 60% of its full load power output or 96 kW. At certain instant of time during simulation, power relay sent switching signal (turb2 switch signal assumes a unit value) activating increase of the torque driving induction generator to a value sufficient to facilitate full load active power output of the induction generator.

The moment turb2 switching signal was sent by the power relay as shown in Figure 4.50, Figure 4.53, Figure 4.56 and Figure 4.59, the induction generator active power output started to increase as shown in corresponding Figure 4.49, Figure 4.52, Figure 4.55 and Figure 4.58. In similar magnitude, power output of the corresponding synchronous generator with some oscillations dropped simultaneously as show in figure 4.48, Figure 4.51, Figure 4.54 and Figure 4.57. However, the oscillations were seen to diminish with time.

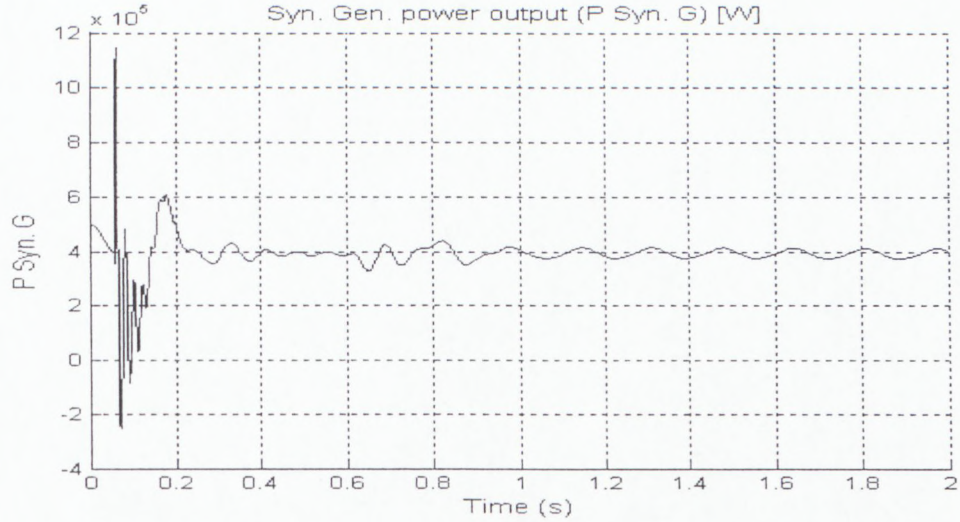


Figure 4.48: Synchronous Generator Power Output When SVC Output is (-j300 to j300) kvar

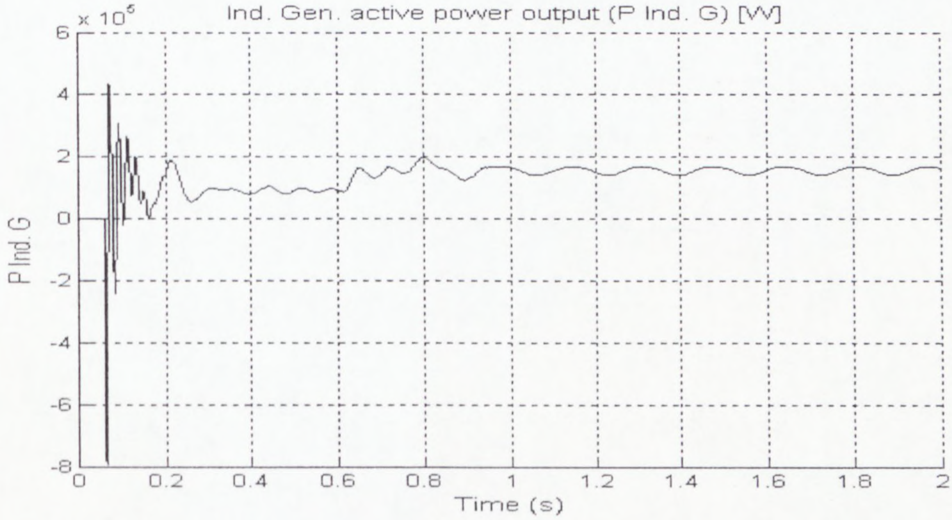


Figure 4.49: Induction Generator Active Power Output When SVC Output is (-j300 to j300) kvar

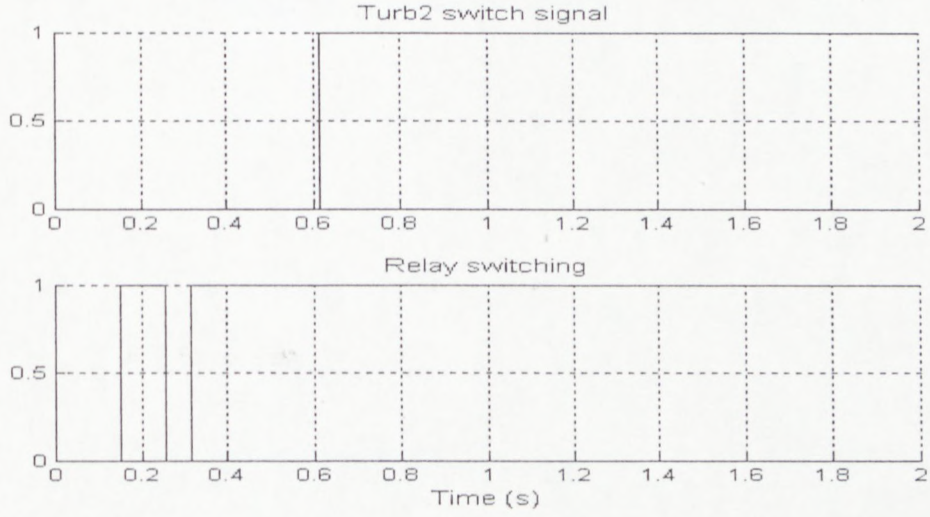


Figure 4.50: Power Relay Switching Signals When SVC Output is (-j300 to j300) kvar

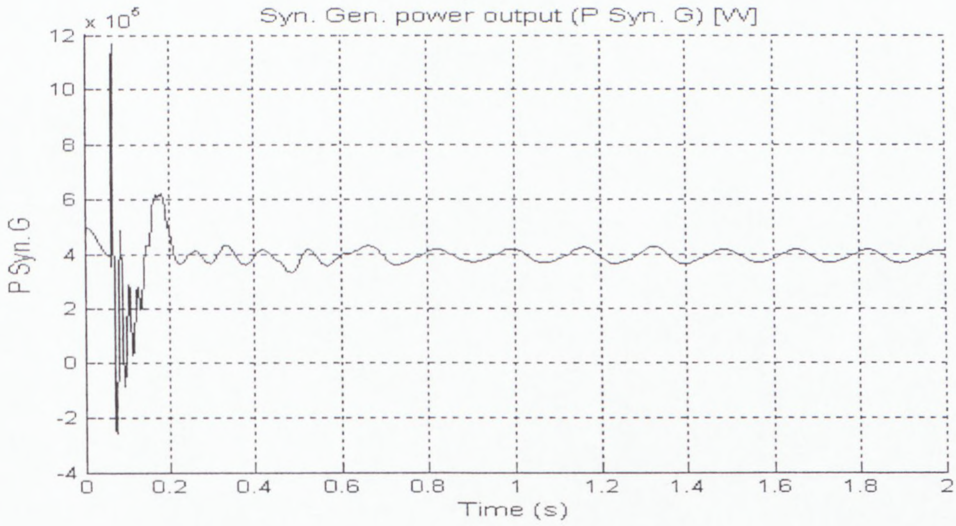


Figure 4.51: Synchronous Generator Power Output When SVC Output is (-j400 to j400) kvar

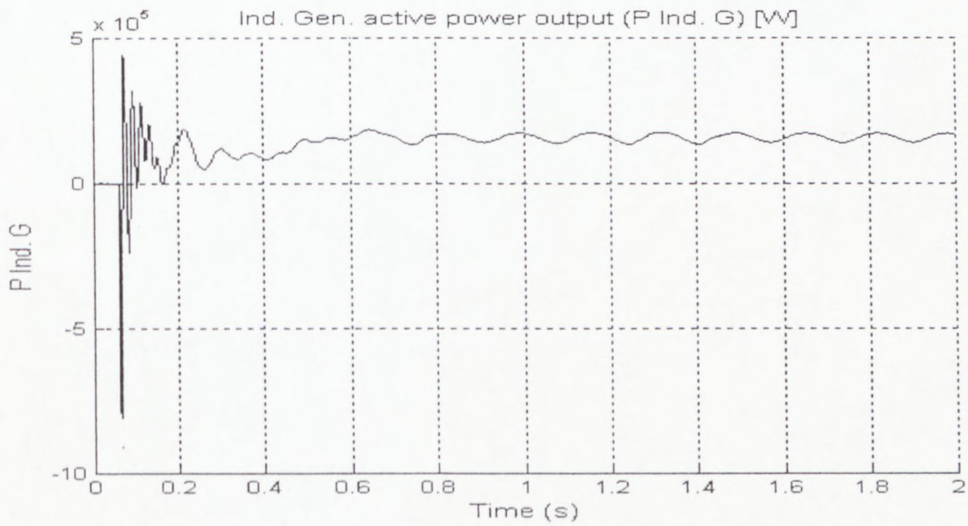


Figure 4.52: Induction Generator Active Power Output When SVC Output is (-j400 to j400) kvar

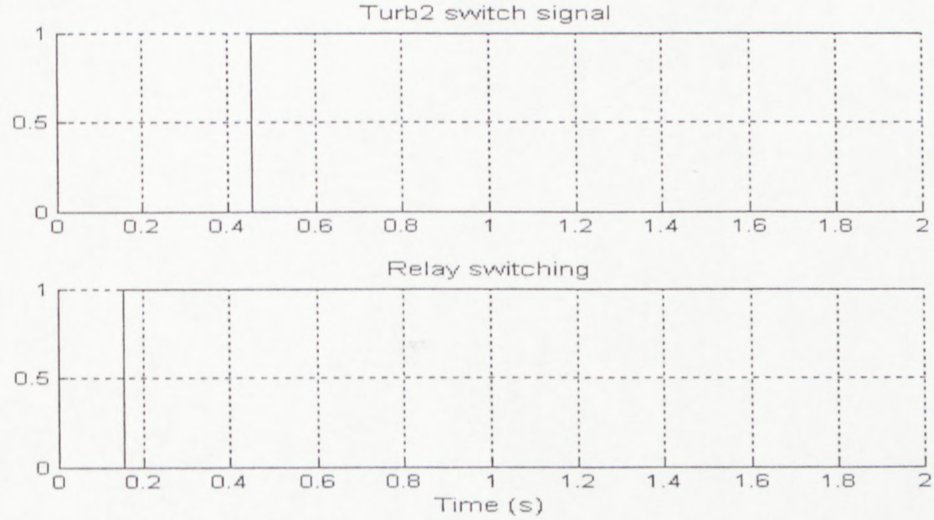


Figure 4.53: Power Relay Switching Signals When SVC Output is (-j400 to j400) kvar

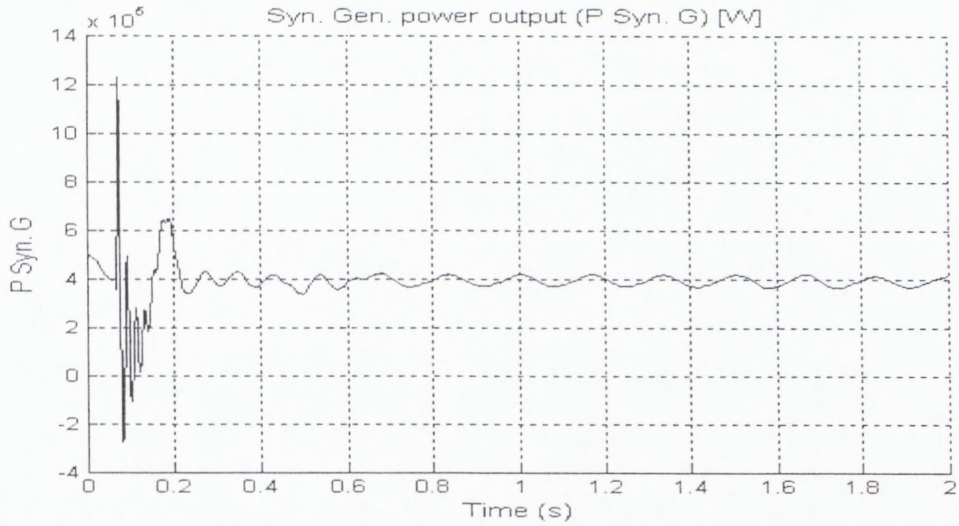


Figure 4.54: Synchronous Generator Power Output When SVC Output is (-j500 to j500) kvar

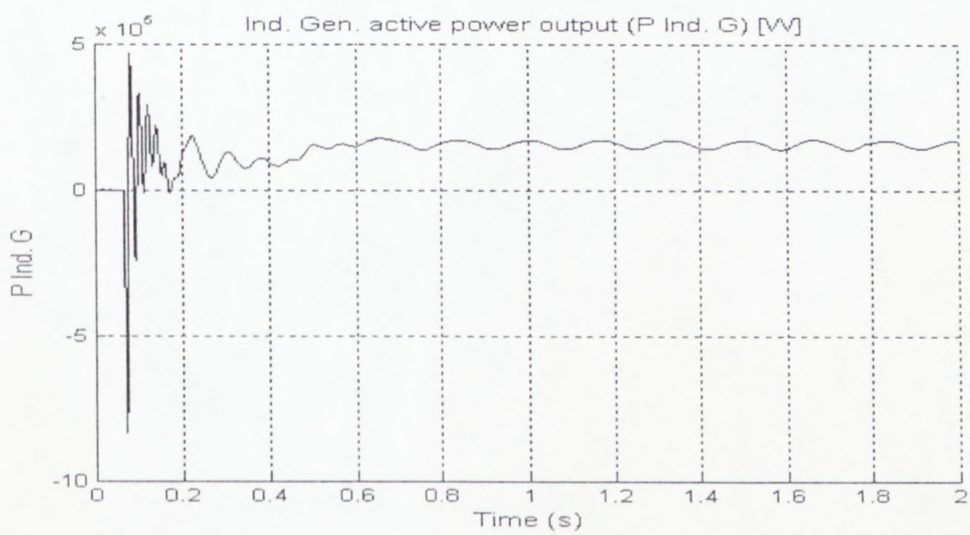


Figure 4.55: Induction Generator Active Power Output When SVC Output is (-j500 to j500) kvar

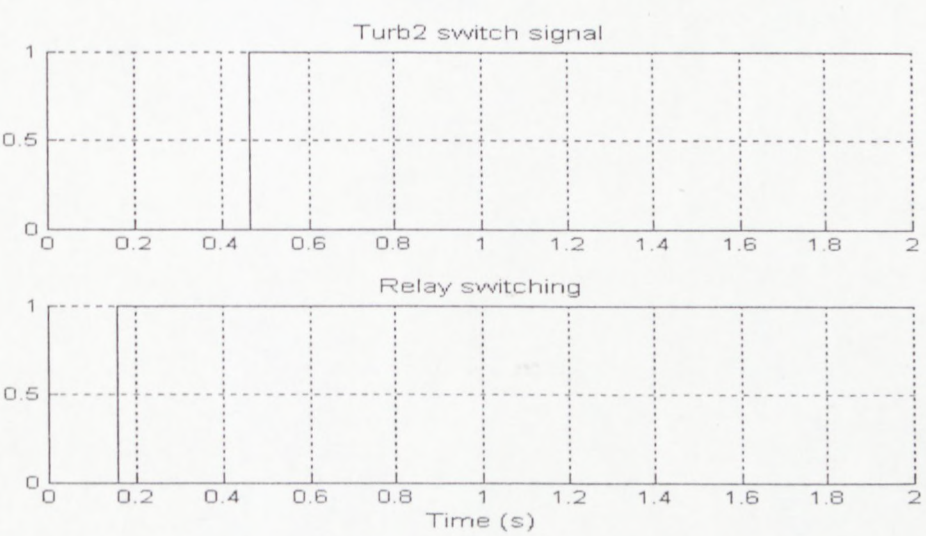


Figure 4.56: Power Relay Switching Signals When SVC Output is (-j500 to j500) kvar

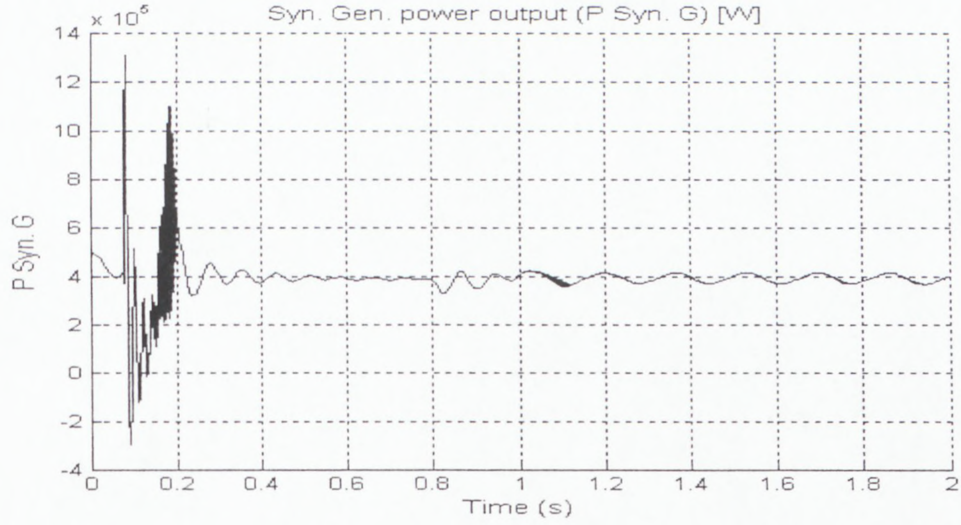


Figure 4.57: Synchronous Generator Power Output When SVC Output is (-j600 to j600) kvar

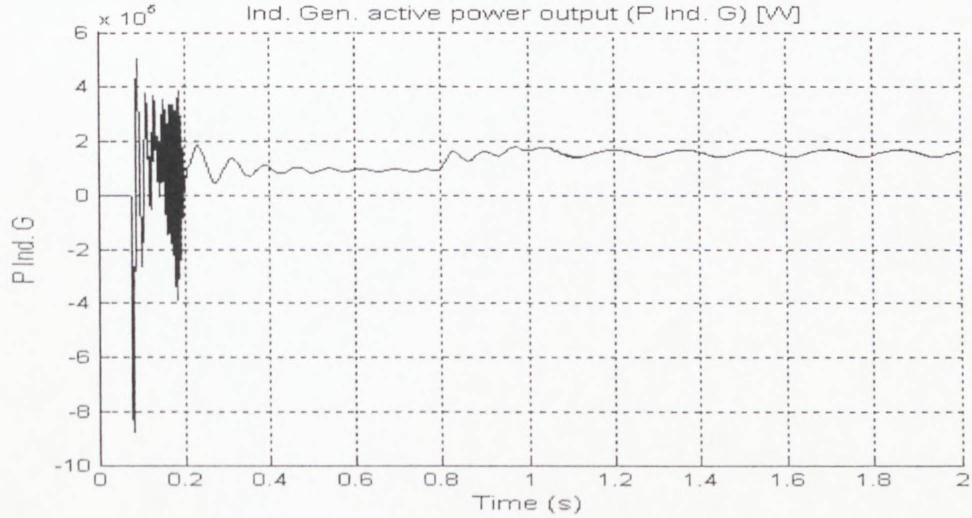


Figure 4.58: Induction Generator Power Output When SVC Output is (-j600 to j600) kvar

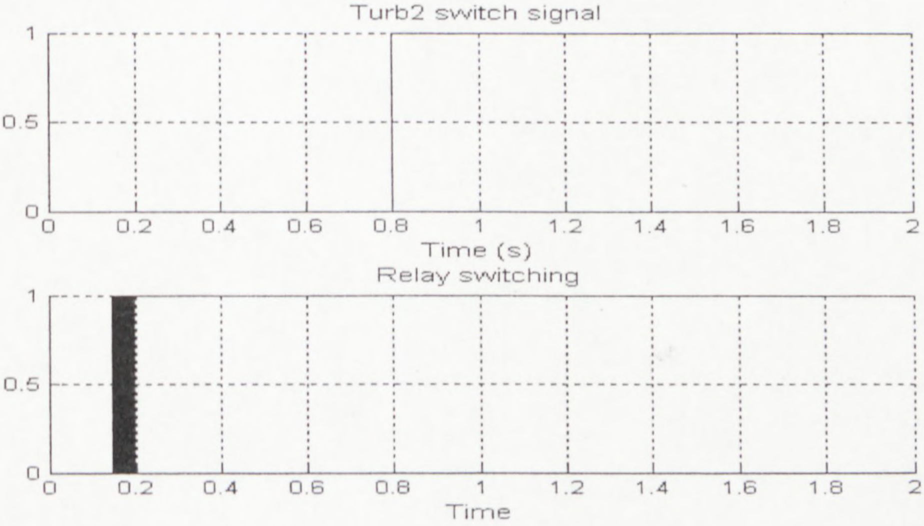


Figure 4.59: Power Relay Operation Signals When SVC Output is (-j600 to j600) kvar

The drop of active power output of synchronous generator was followed by increase of its rotor speed till it reached steady state value of approximately 1.005 pu as shown in Figure 4.60, Figure 4.63, Figure 4.66 and Figure 4.69. This change in speed of the synchronous generator or frequency of generation is due to two reasons:

- Reduction of the generator's power output resulted into mismatch between the mechanical torque supplied by the driving turbine and the electromagnetic torque acting on the machine's rotor and as a consequence the rotor accelerated according to Equation 2.2.
- Rise of a steady state speed/frequency to approximately 1.005 pu is attributed to droop characteristic of the governing system of the driving turbine as exhibited in Figure 2.9.

The induction machine continued to operate as a generator whereby its rotor followed that of synchronous generator with negative slip synchronous generator rotor speed being the reference as observed in Figure 4.61, Figure 4.64, Figure 4.67 and Figure 4.70. Also it absorbed reactive power from the system (negative reactive power) as shown in Figure 4.62, Figure 4.65, Figure 4.68 and Figure 4.71. In addition, it is also noted that with increase in active power output the induction generator there was an increase of reactive power absorbed as well.

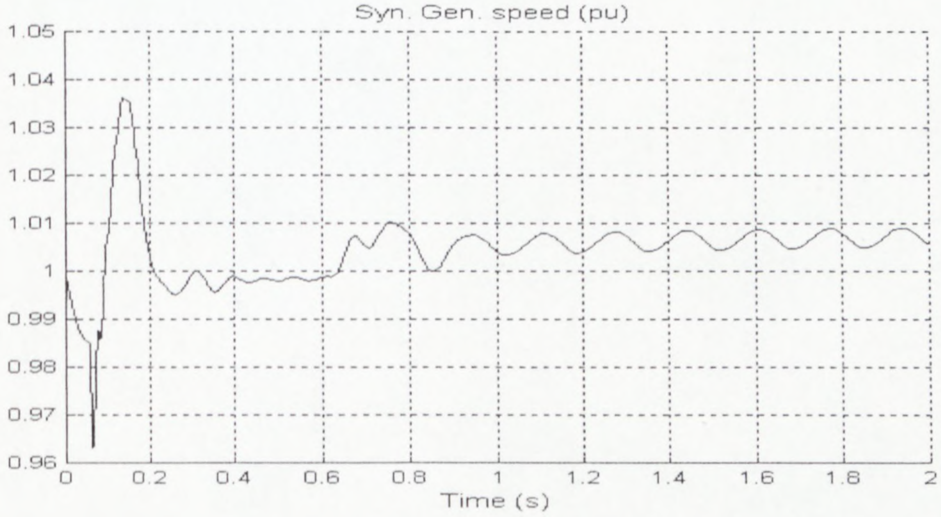


Figure 4.60: Synchronous Generator Speed When SVC Output is (-j300 to j300) kvar

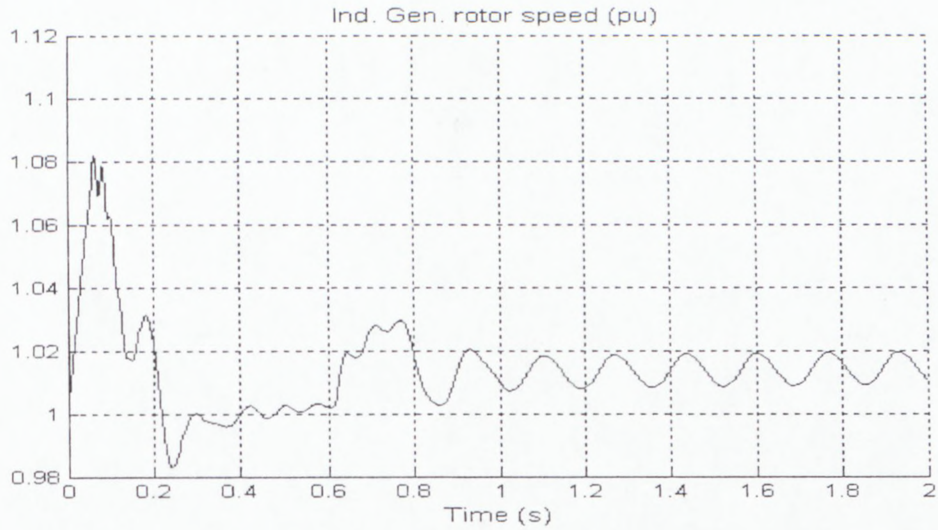


Figure 4.61: Induction Generator Rotor Speed When SVC Output is (-j300 to j300) kvar

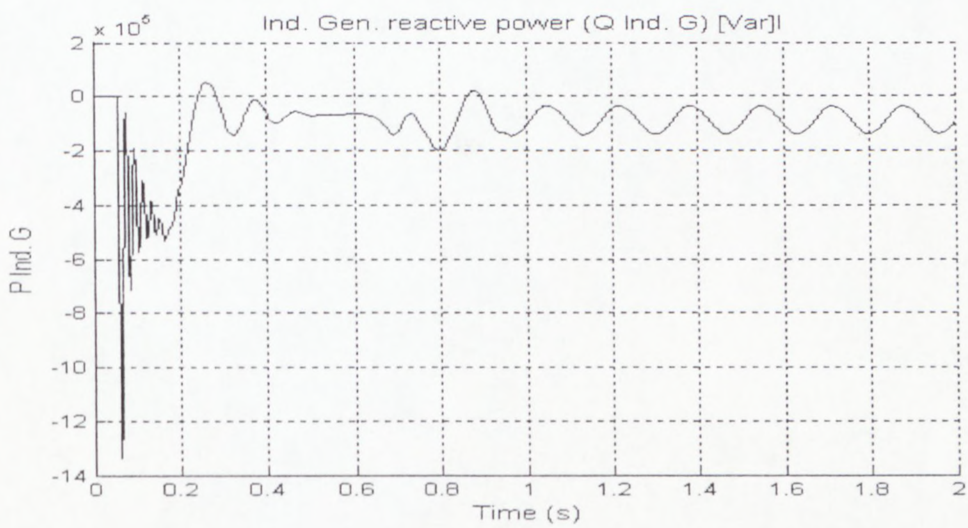


Figure 4.62: Induction Generator Reactive Power When SVC Output is (-j300 to j300) kvar

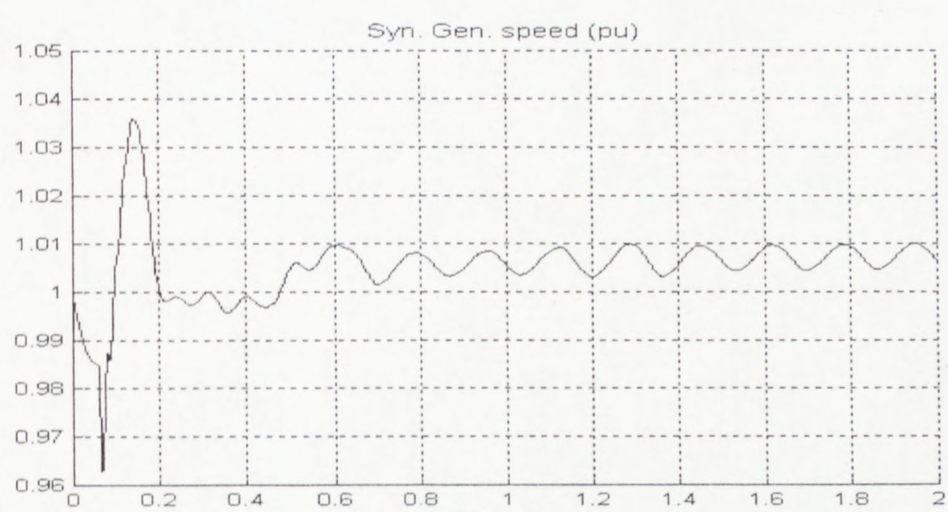


Figure 4.63: Synchronous Generator Rotor Speed When SVC Output is (-j400 to j400) kvar

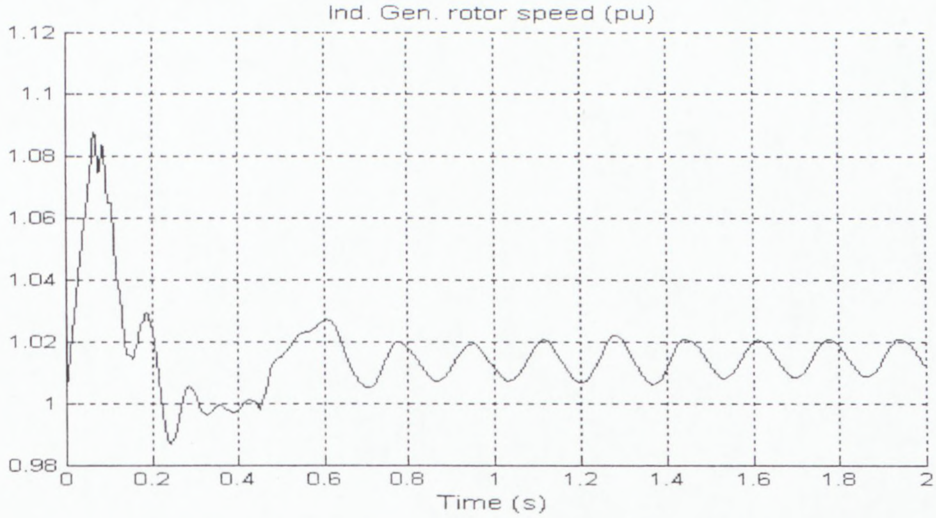


Figure 4.64: Induction Generator Rotor Speed When SVC Output is (-j400 to j400) kvar

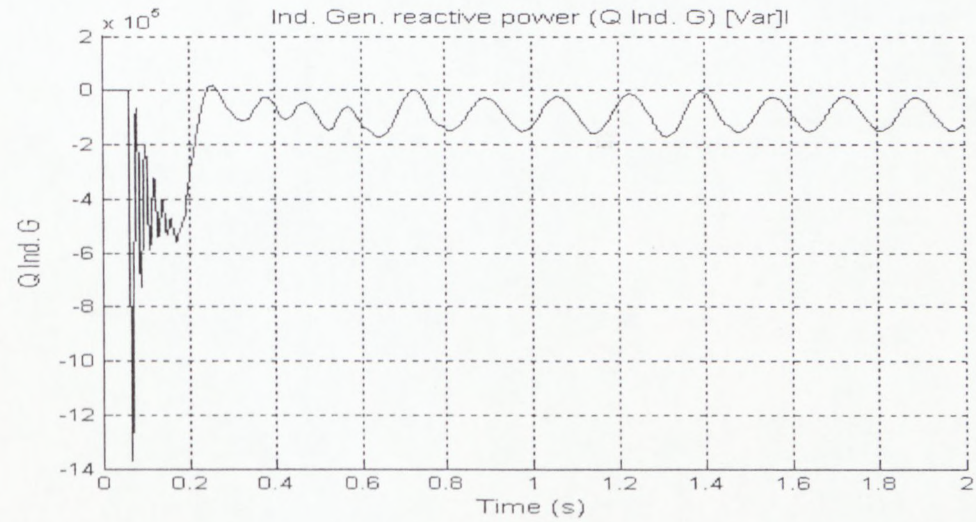


Figure 4.65: Induction Generator Reactive Power When SVC Output is (-j400 to j400) kvar

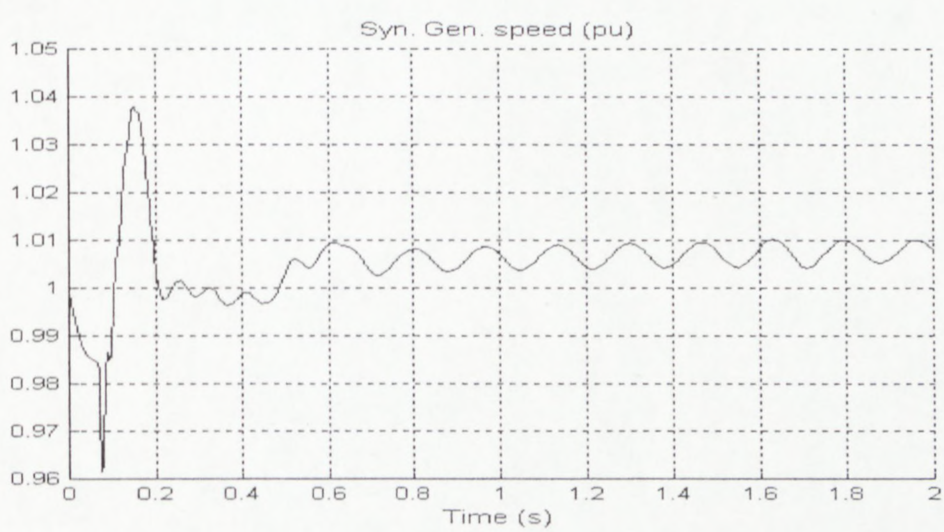


Figure 4.66: Synchronous Generator Rotor Speed When SVC Output is (-j500 to j500) kvar

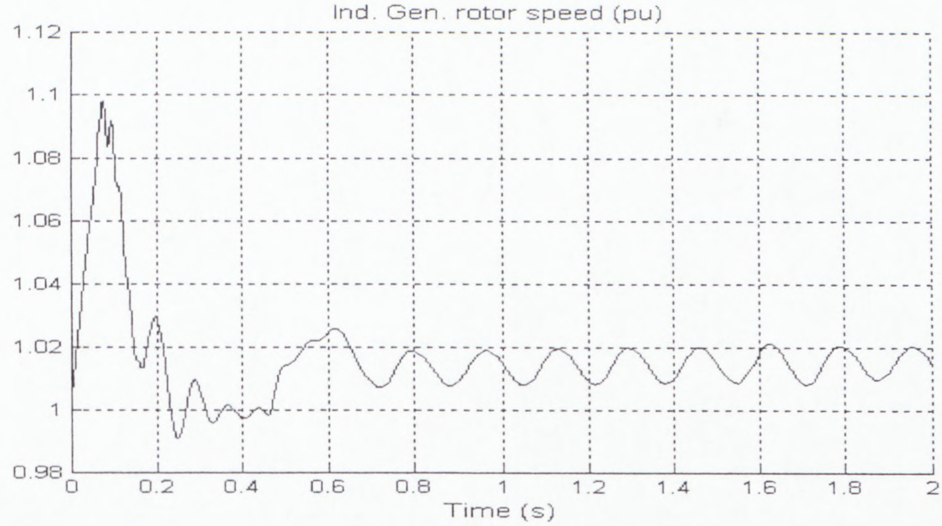


Figure 4.67: Induction Generator Rotor Speed When SVC Output is (-j500 to j500) kvar

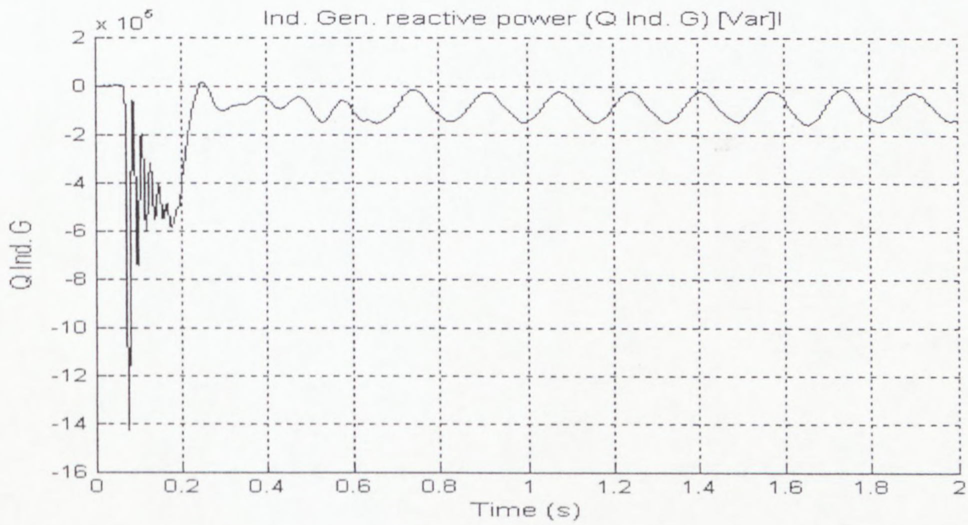


Figure 4.68: Induction Generator Reactive Power When SVC Output is (-j500 to j500) kvar

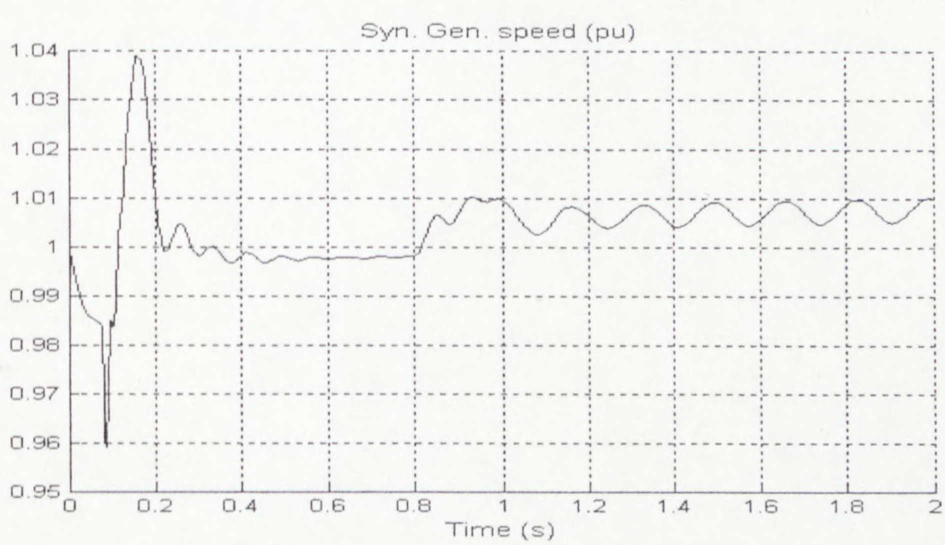


Figure 4.69: Synchronous Generator Rotor Speed When SVC Output is (-j600 to j600) kvar

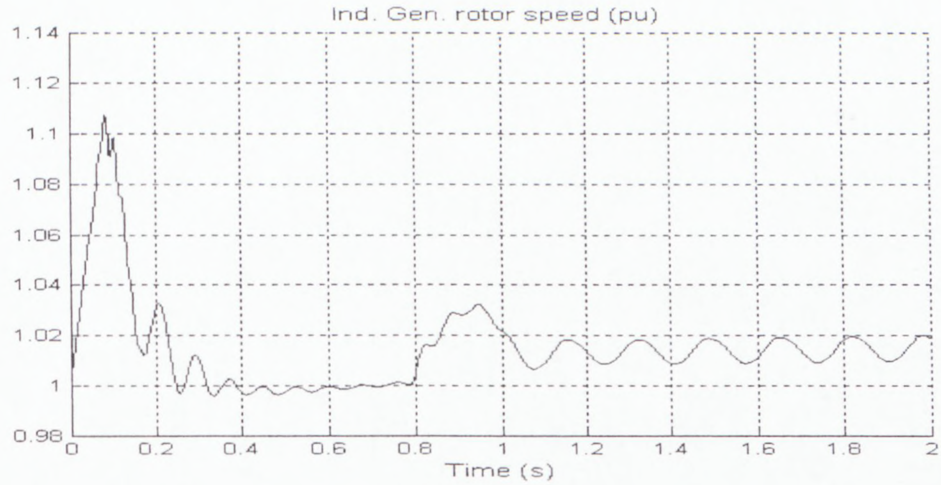


Figure 4.70: Induction Generator Rotor Speed When SVC Output is (-j600 to j600) kvar

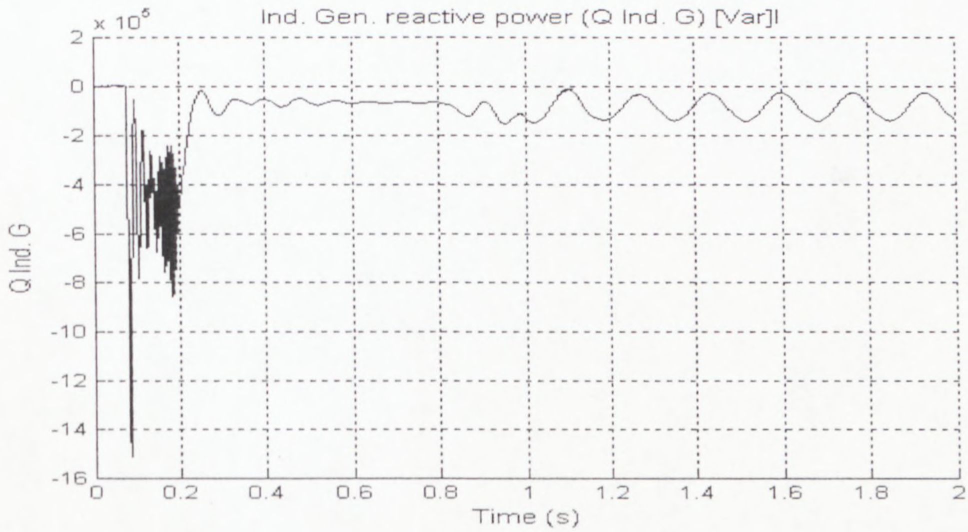


Figure 4.71: Induction Generator Reactive Power Output When SVC Output is (-j600 to j600) kvar

The increase in active power output of the induction generator in the system cause the synchronous generator to generate more reactive power forcing SVC to operate in inductive mode absorbing the excess reactive power to control the voltage at generator bus as observed in Figure 4.72 and Figure 4.73, Figure 4.75 and Figure 4.76, Figure 4.78 and Figure 4.79 and finally Figure 4.81 and Figure 4.82.

At steady state, the generator bus voltage (Figure 4.74, Figure 4.77, Figure 4.80 and Figure 4.83) was found to fluctuate around 1.05 pu. The increase in generator bus voltage is attributed to speed voltage according to Equations 2.58 and 2.59.

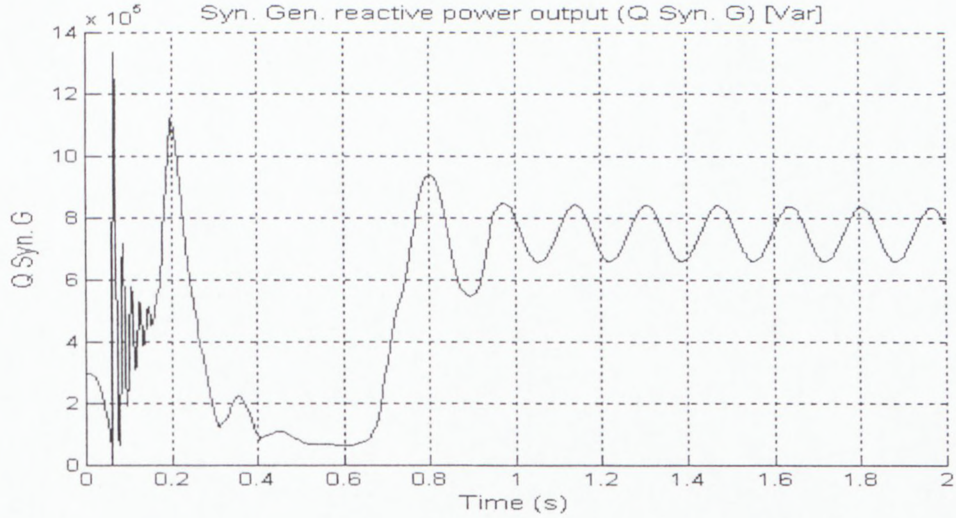


Figure 4.72: Synchronous Generator Reactive Power Output When SVC Output is (-j300 to j300) kvar

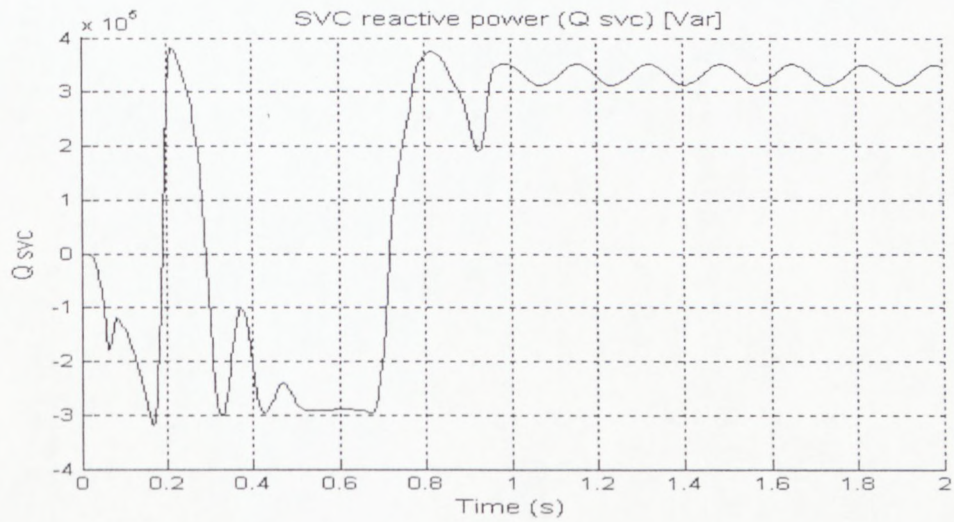


Figure 4.73: SVC Reactive Power Output When the Output Range is (-j300 to j300) kvar

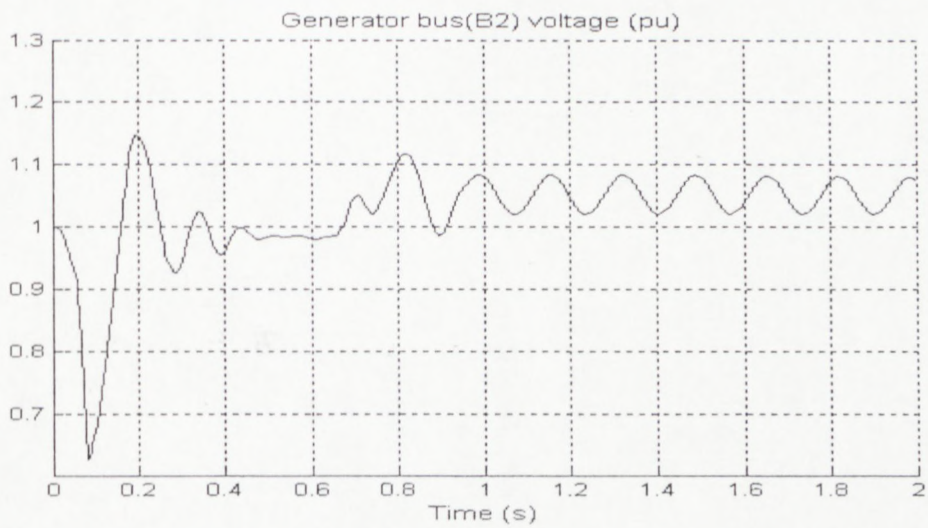


Figure 4.74: Generator Bus Voltage When SVC Output is (-j300 to j300) kvar

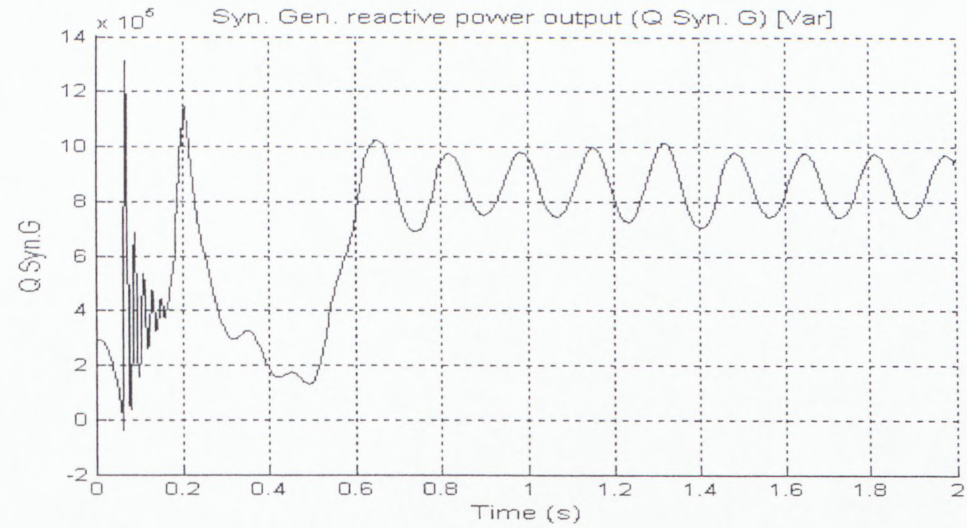


Figure 4.75: Synchronous Generator Reactive Power Output When SVC Output is (-j400 to j400) kvar

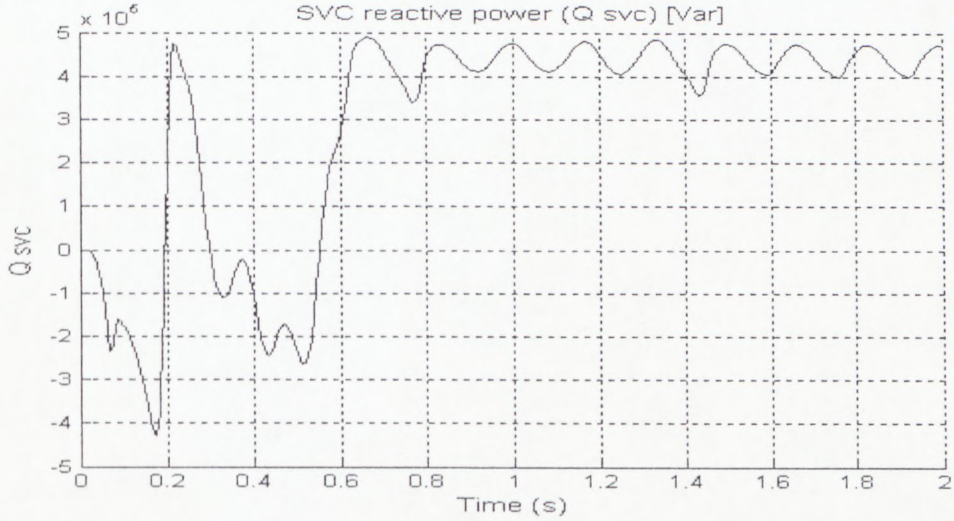


Figure 4.76: SVC Reactive Power When the Output Range is (-j400 to j400) kvar

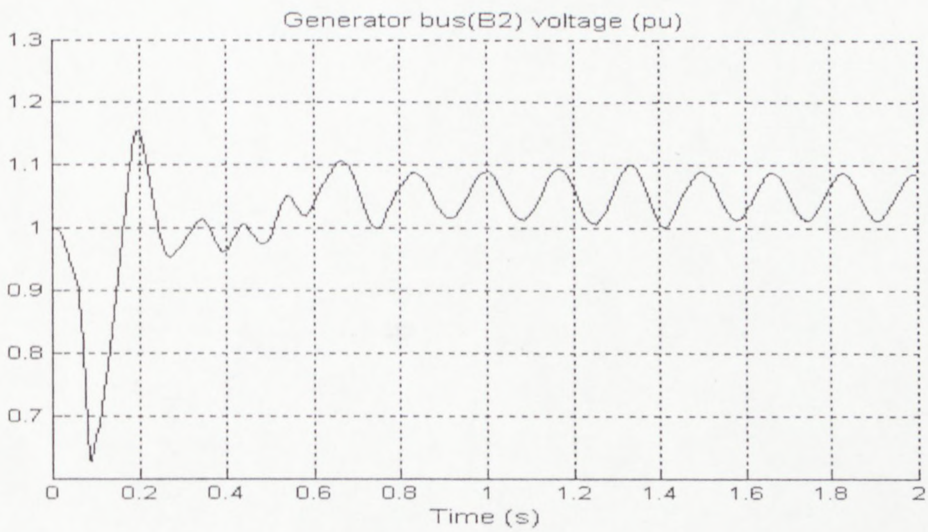


Figure 4.77: Generator Bus Voltage When SVC Output is (-j400 to j400) kvar

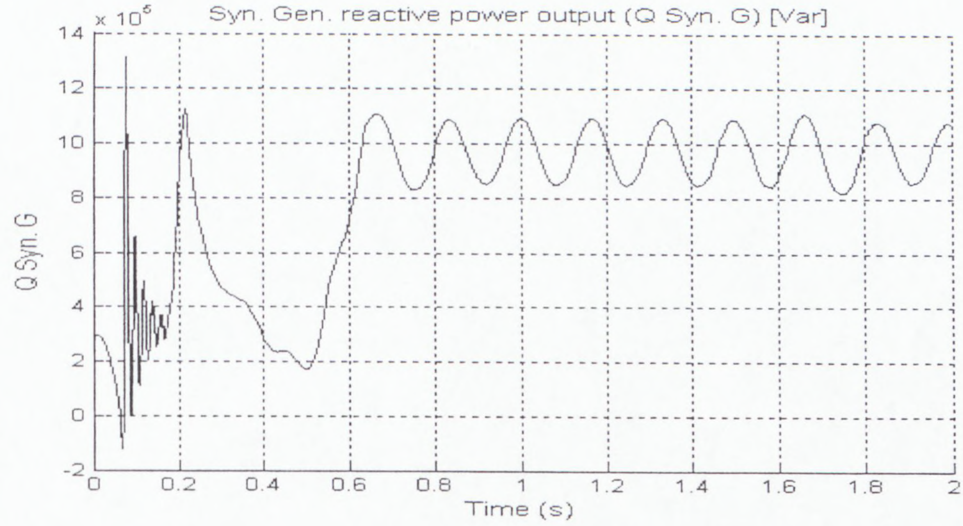


Figure 4.78: Synchronous Generator Reactive Power Output When SVC Output is (-j500 to j500) kvar

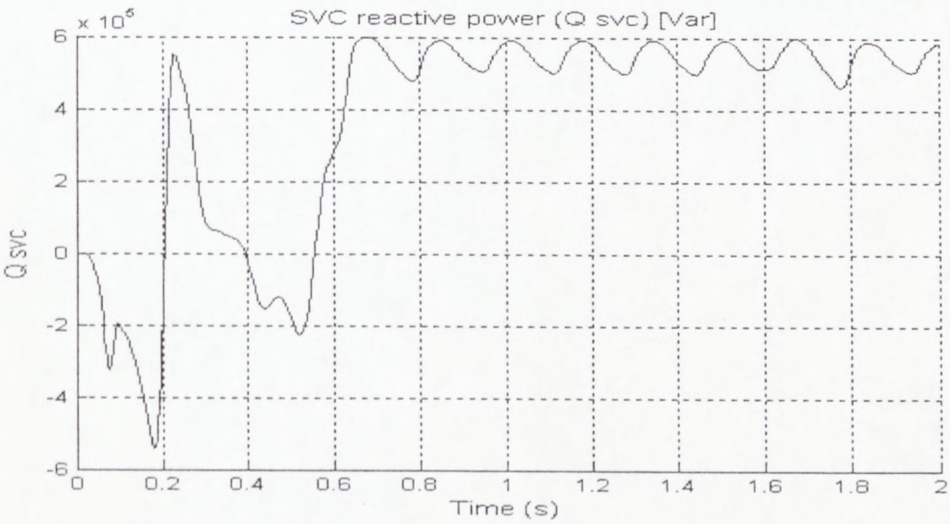


Figure 4.79: SVC Reactive Power When the Output Range is (-j500 to j500) kvar

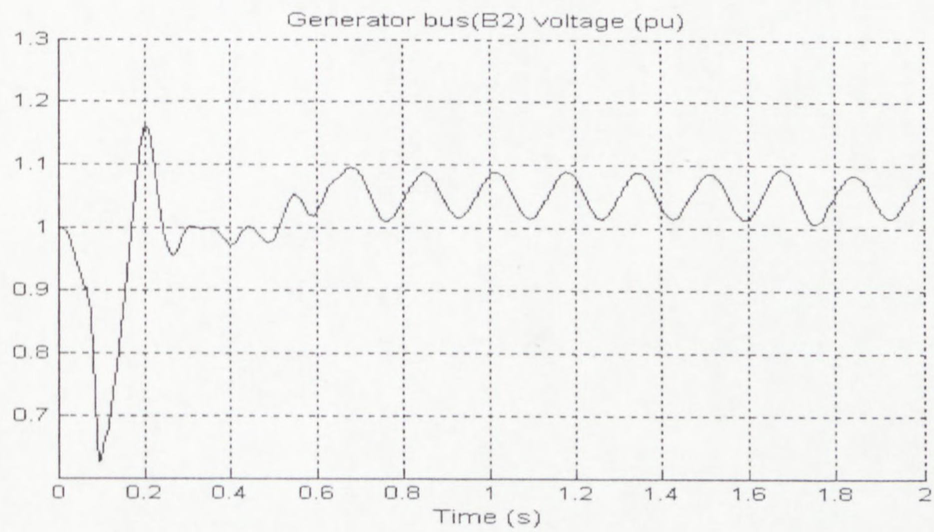


Figure 4.80: Generator Bus Voltage When SVC Output is (-j500 to j500) kvar

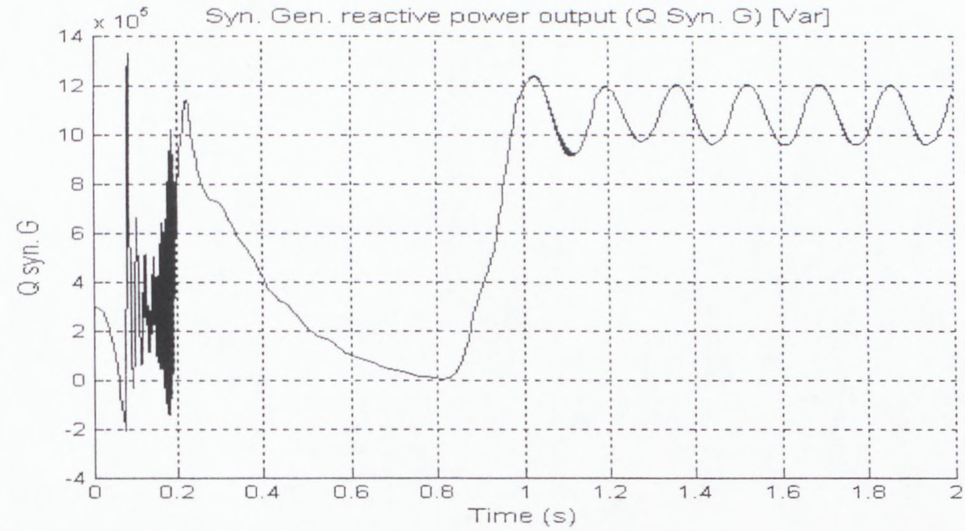


Figure 4.81: Synchronous Generator Reactive Power Output When SVC Output is (-j600 to j600) kvar

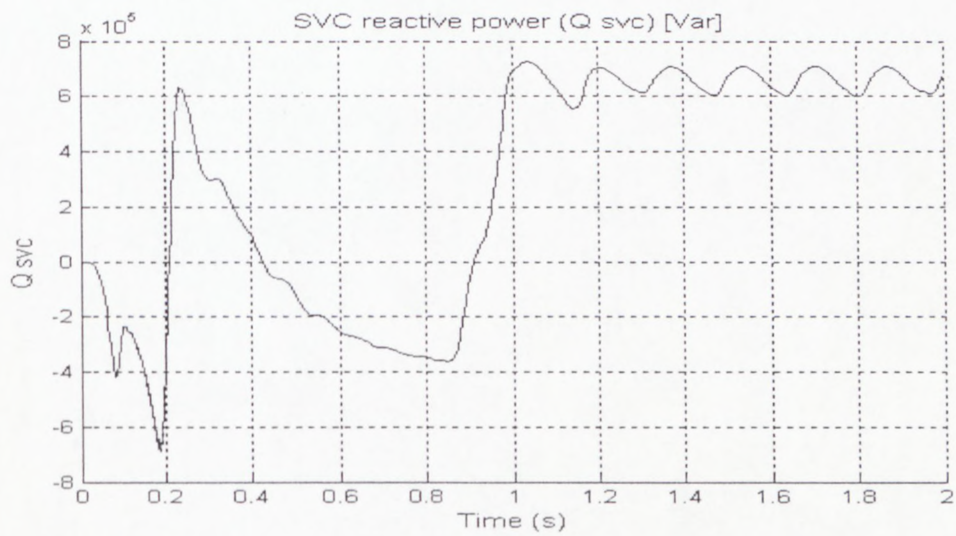


Figure 4.82: SVC Reactive Power Output When the Output Range is (-j600 to j600) kvar

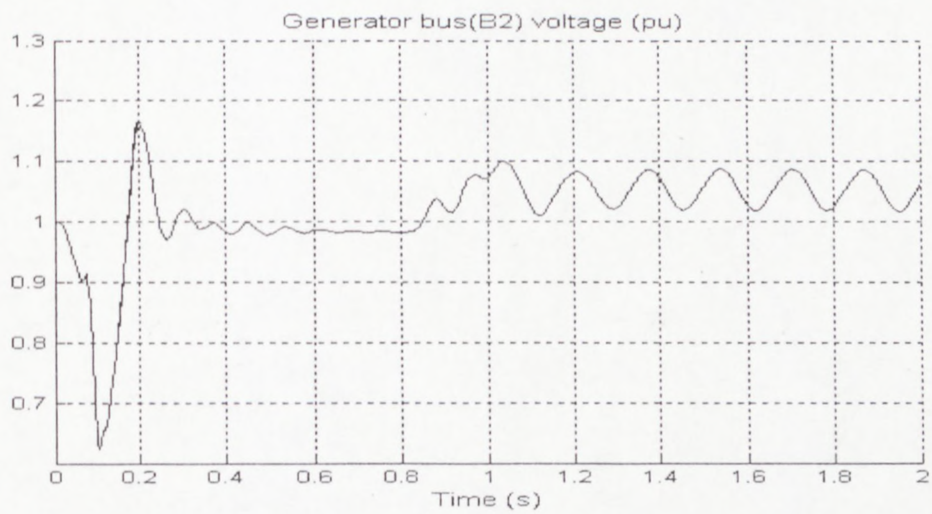


Figure 4.83: Generator Bus Voltage When SVC Output is (-j600 to j600) kvar

Both active and reactive power output of the proposed plant supplied to the connected load was seen to fluctuate after increase in induction generator power output Figure 4.84 to Figure 4.91.

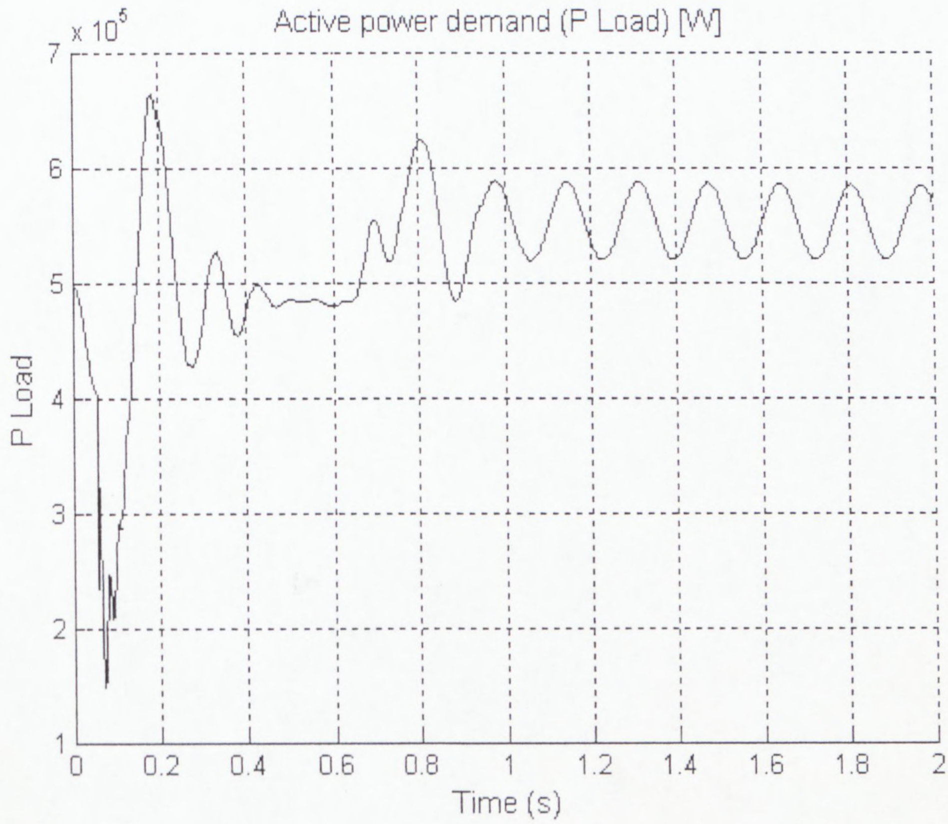


Figure 4.84: Active Power Output Of the SHP When SVC Output is (-j300 to j300) kvar

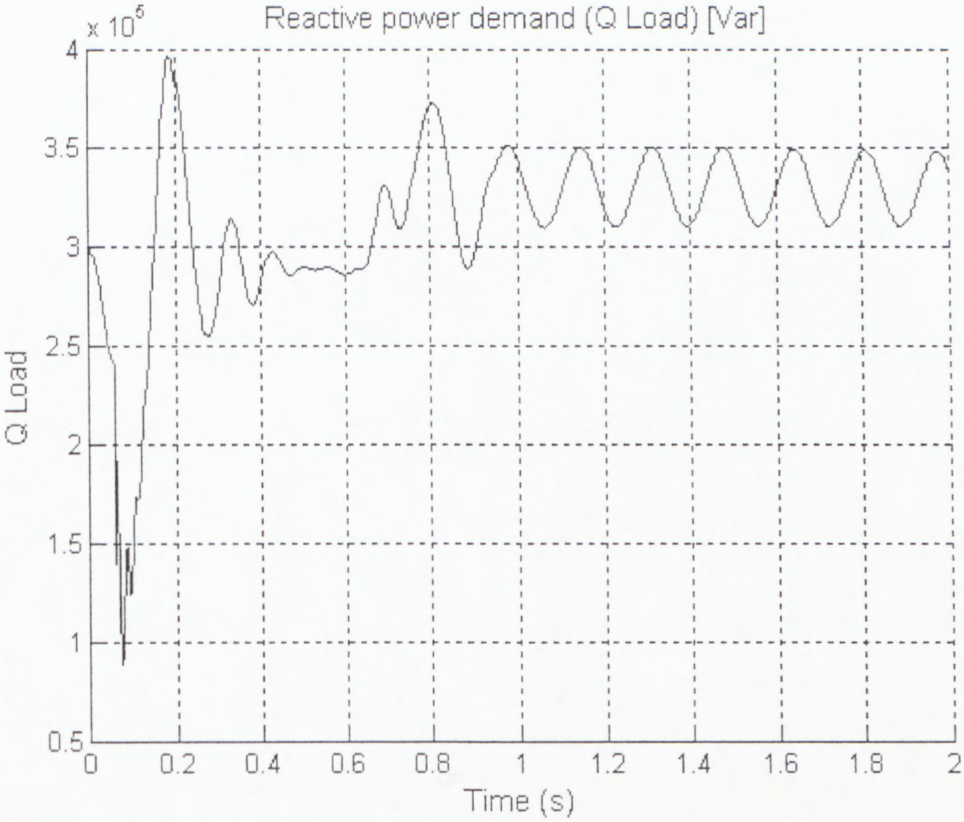


Figure 4.85: Reactive Power Output Of the SHP When SVC Output is (-j300 to j300) kvar

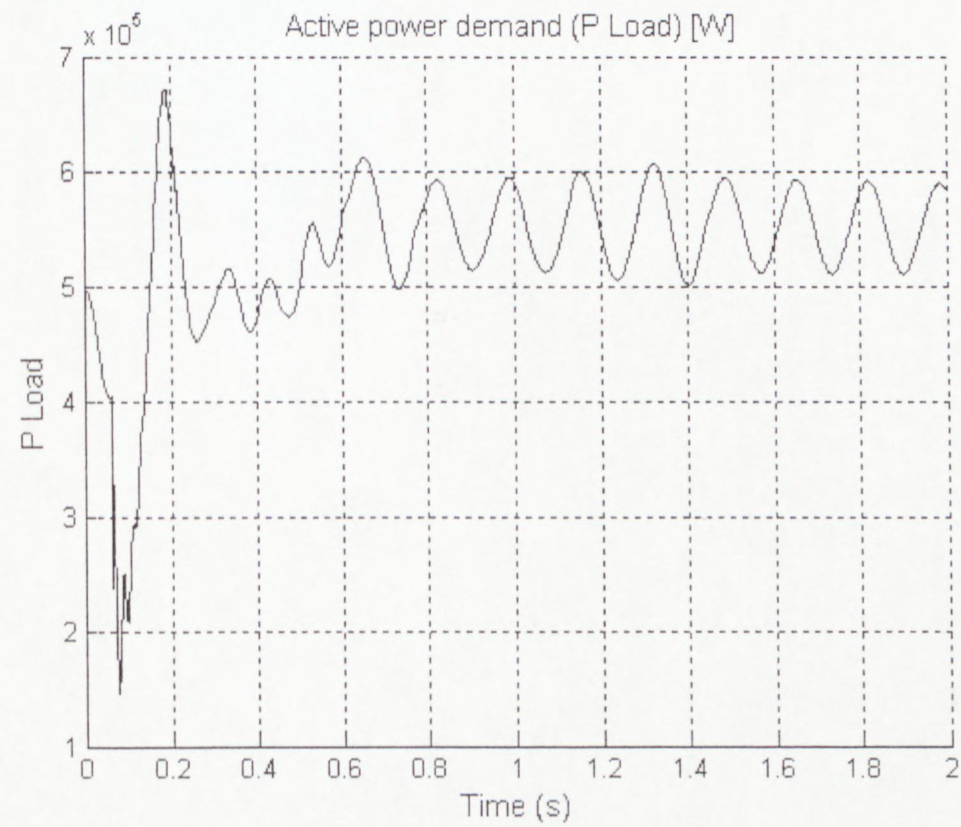


Figure 4.86: Active Power Output Of the SHP When SVC Output is (-j400 to j400) kvar

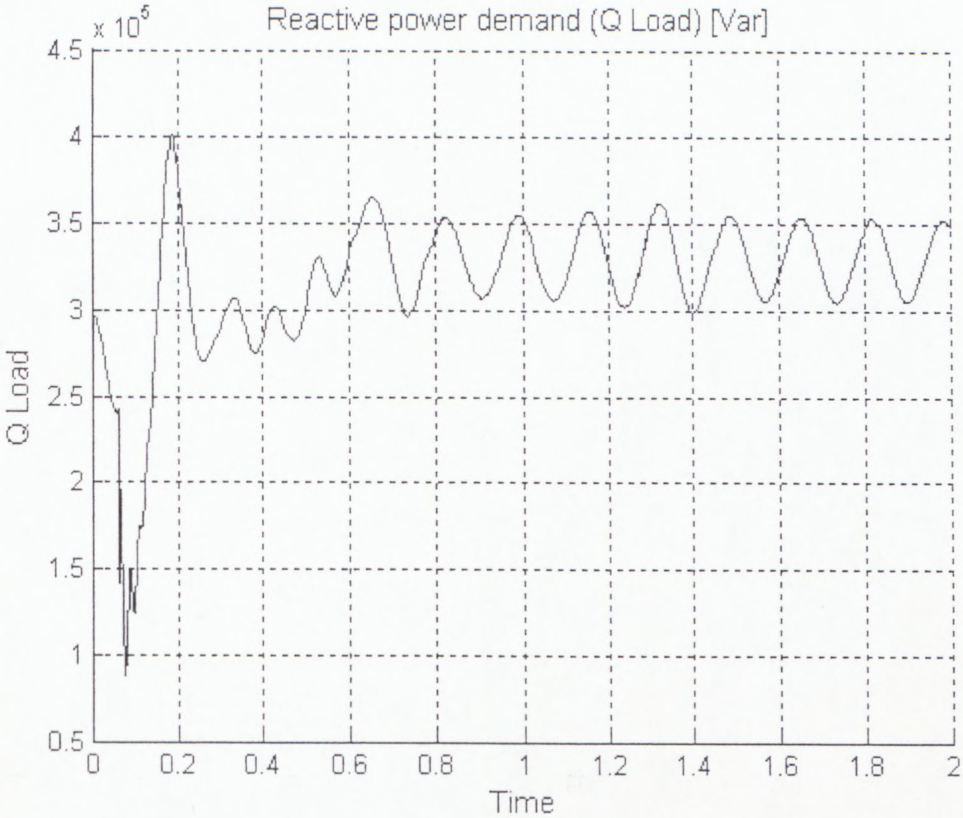


Figure 4.87: Reactive Power Output of the SHP When SVC Output is (-j400 to j400) kvar

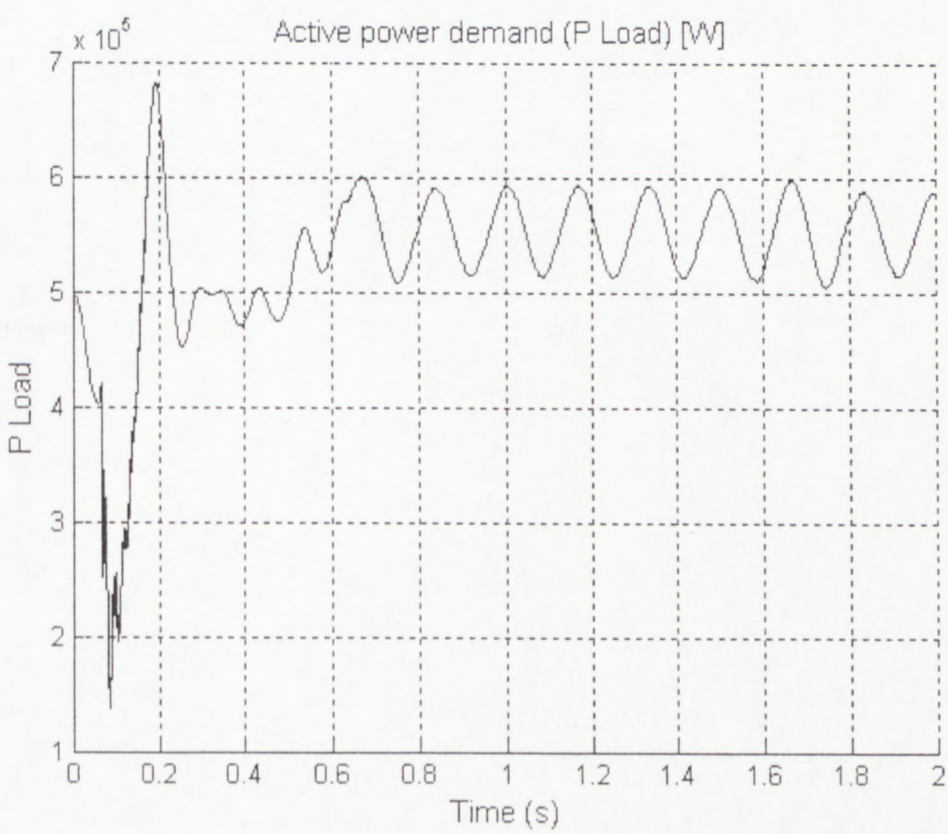


Figure 4.88: Active Power Output of the SHP When SVC Output is (-j500 to j500) kvar

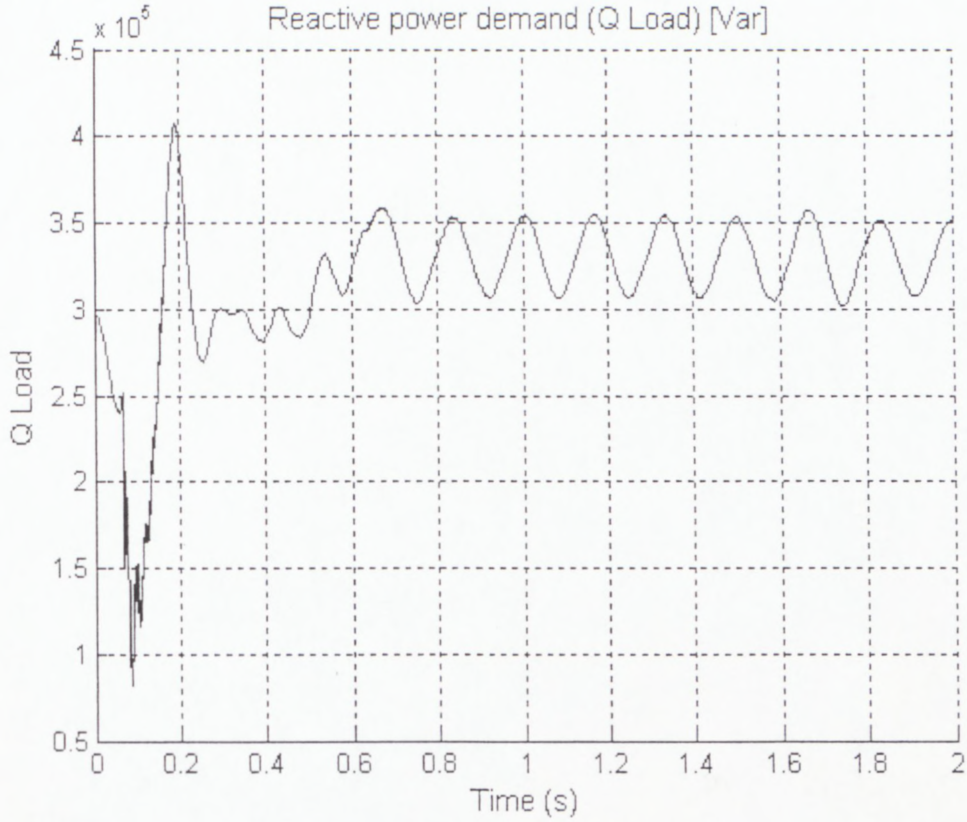


Figure 4.89: Reactive Power Output of the SHP When SVC Output is (-j500 to j500) kvar

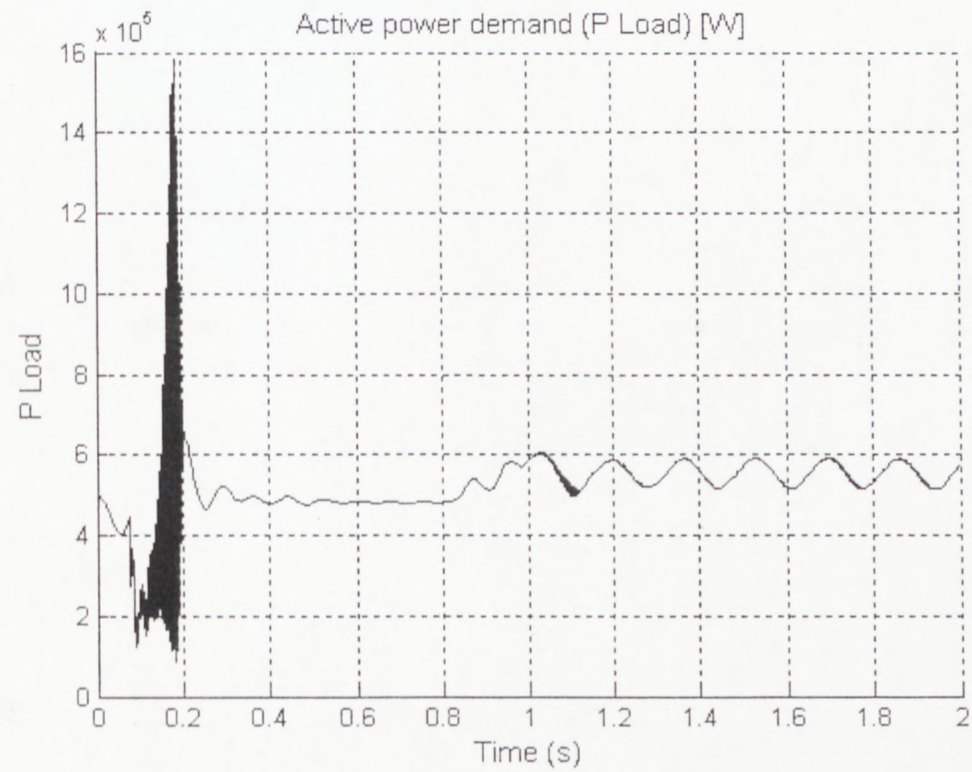


Figure 4.90: Active Power Output of the SHP When SVC Output is (-j600 to j600) kvar

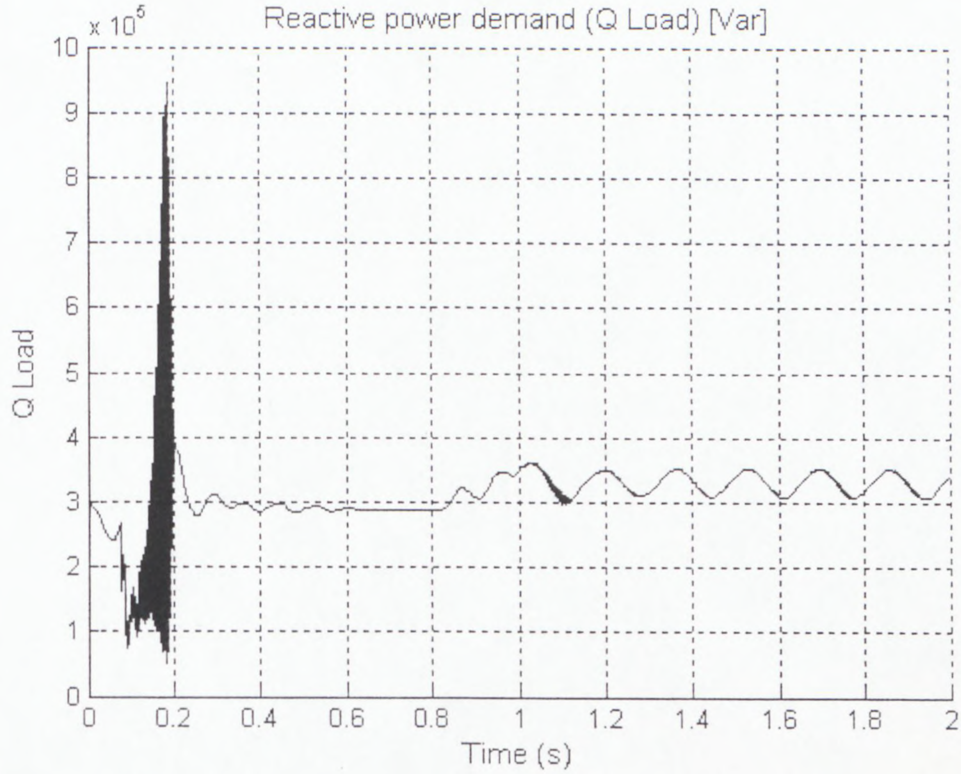


Figure 4.91: Reactive Power Output of the SHP When SVC Output is (-j600 to j600) kvar

It is worth to note that performance of the proposed plant as depicted by Figure 4.90 and 4.91 is much smoother compared to any other.

4.3.2 Small Signal Stability of the Proposed SHP

In order to ascertain operation of the plant under normal conditions, a small signal stability or performance of the proposed SHP when the induction generator is allowed to be loaded to its full load capacity while the load to the plant is increased by gradually adding more load to the plant was tested. For this purpose several simulations of the plant were performed employing SVC of different reactive power output rage connected to the generator bus one at a time. In all simulations, initial speed of the induction generator rotor was set above synchronous speed such that the slip was -0.001 while torque driving the induction generator was initially 0.6 of its full load value to generate 96 kW then increased to the full load value delivering 160 kW.

Simulations were programmed to start with the plant operating in steady state condition supplying the same inductive load with (500 + j300) KVA from synchronous generator. After the connection of the induction generator into the system two cycles from the initiation of the simulation, the load to the plant was increased first by 50 kW at the moment when time t = 1s and then increased further by 40 kW when t = 1.8s through operation of respective circuit breakers. Performance of the plant in the simulated conditions was as shown in the graphs bellow.

In these series of simulations, power relay sent switching signal to increase active power output of the induction generator at a moment when time t was approximately 0.5s as it sensed increase in power output of the plant. Figure 4.92 shows the operation signals of the power relay. Operation of the power relay resulted to increase the power output of induction generator from 96 kW to its full load capacity of 160 kW. Therefore further added load to the power plant resulted in increasing loading of synchronous generator.

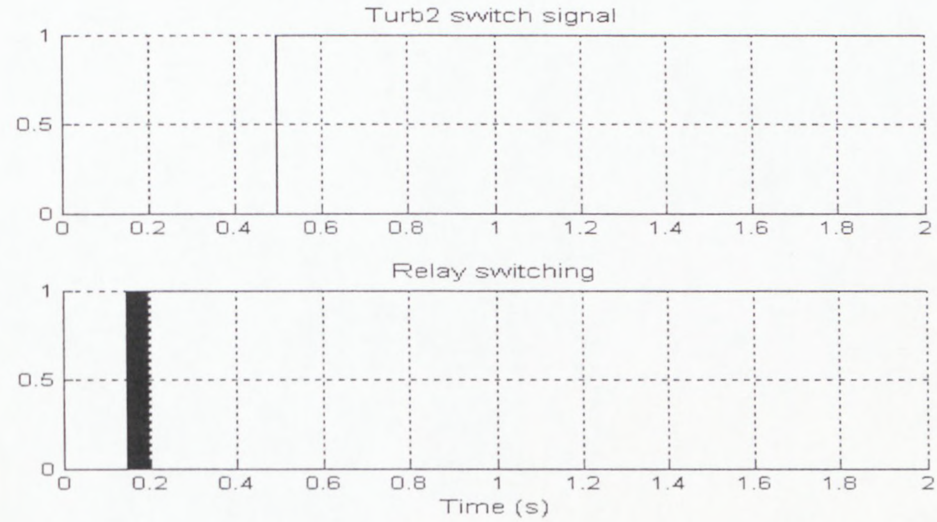


Figure 4.92: Power Relay Switching Signals

When the SVC connected to the generator bus active power output of synchronous and induction generators together could cope with the increase of 50 kW at t = 1s as shown in Figure 4.93 and Figure 4.94 below.

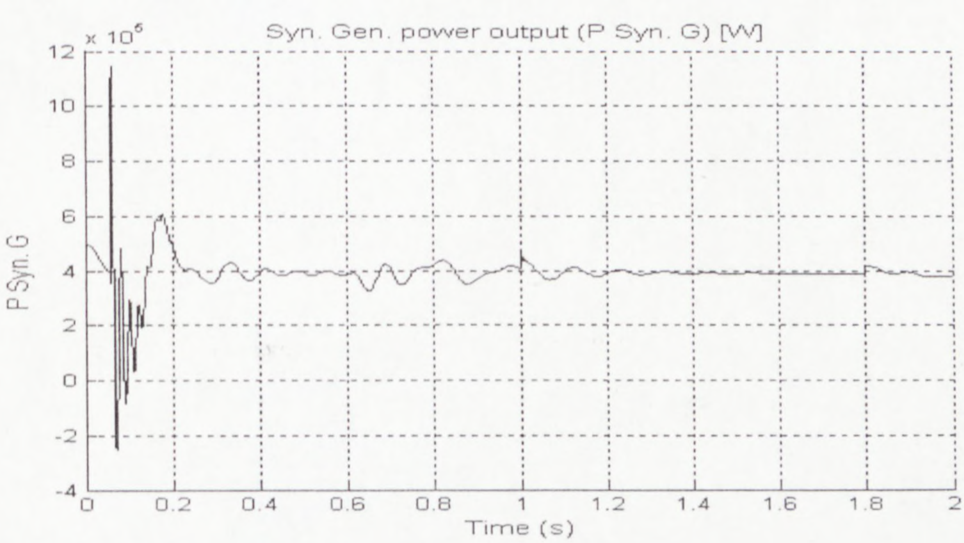


Figure 4.93: Synchronous Generator Power Output When SVC Output is (-j300 to j300) kvar

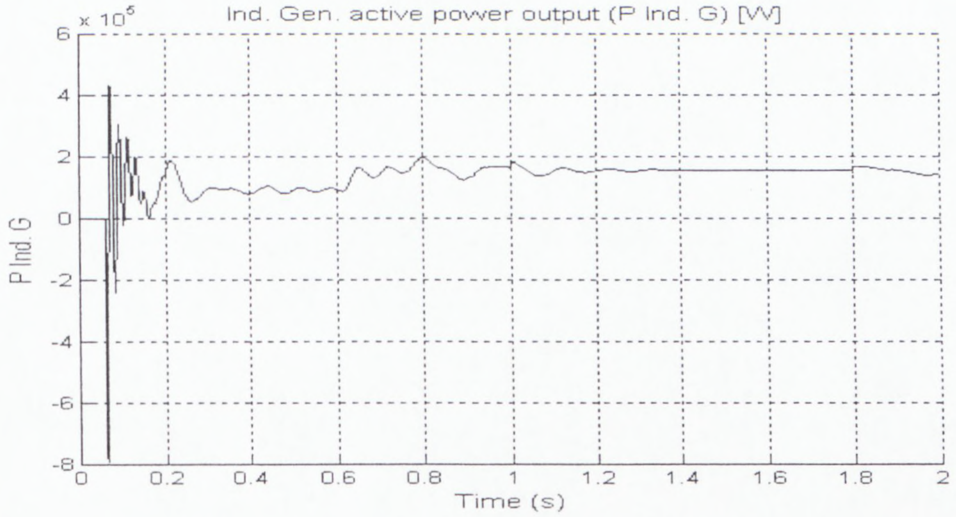


Figure 4.94: Induction Generator Active Power Output When SVC Output is (-j300 to j300) kvar

After addition of further 40 kW at time t = 1.8s both active power of the synchronous generator and that of induction generator was witnessed to drop meaning the generators could not pick the load. Similarly, generator bus voltage in Figure 4.95 showed the dropping trend regardless of operation of synchronous generator and SVC injecting reactive power into the system Figure 4.96 and Figure 4.97 respectively.

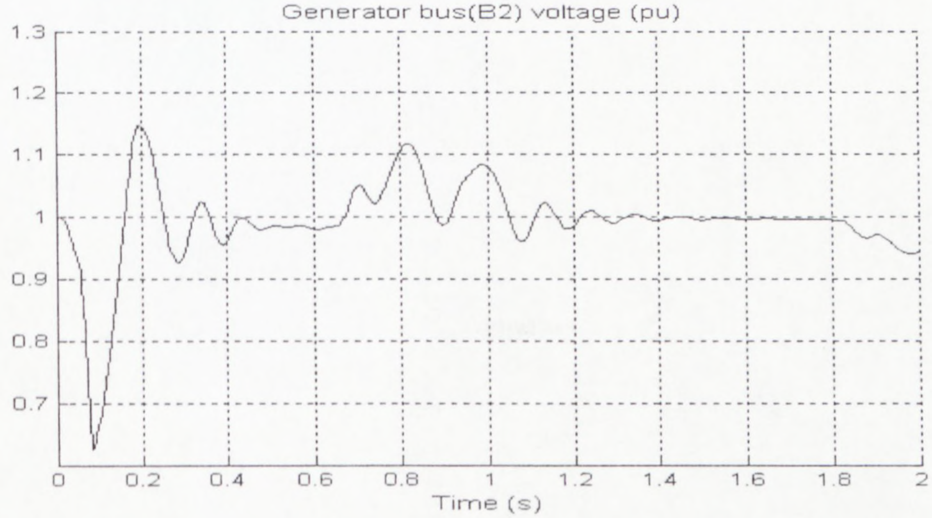


Figure 4.95: Generator Bus Voltage When SVC Output is (-j300 to j300) kvar

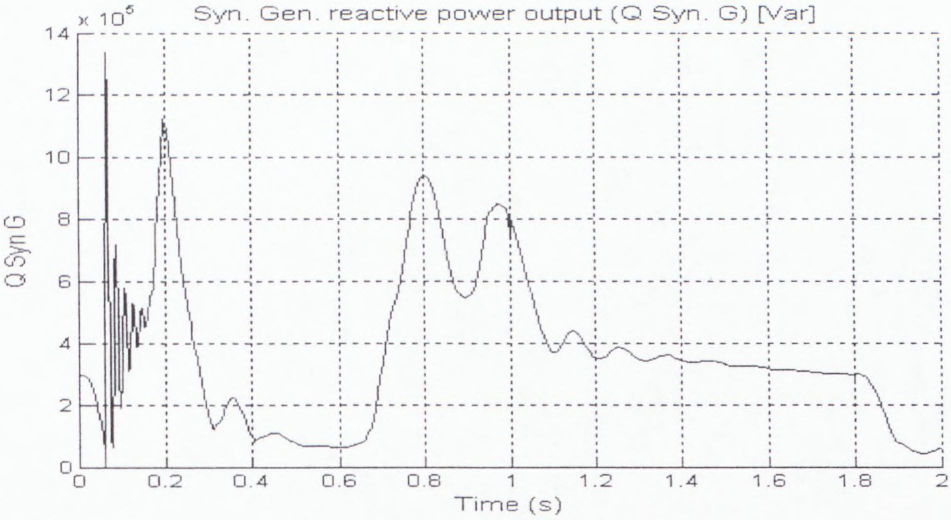


Figure 4.96: Synchronous Generator Reactive Power Output When SVC Output is (-j300 to j300) kvar

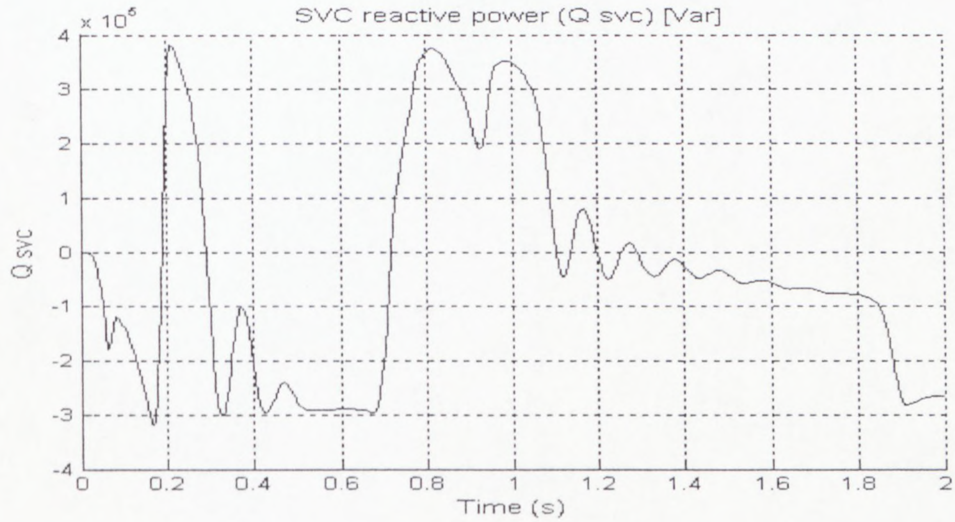


Figure 4.97: SVC Reactive Power When the Output Range is (-j300 to j300) kvar

Although speed rotor of the induction generator is higher than that of the synchronous generator as seen when comparing Figure 4.98 and Figure 4.99, the reactive power absorbed by induction generator as shown in Figure 4.100 is dropping implying drop in its active power output.

The active and reactive power output of the plant as shown in Figure 4.101 and Figure 4.102 respectively could meet load requirements upto the moment t = 1.8s when additional load of 40 kW was connected into the system. Thereafter the plant showed unstable operating behaviour.

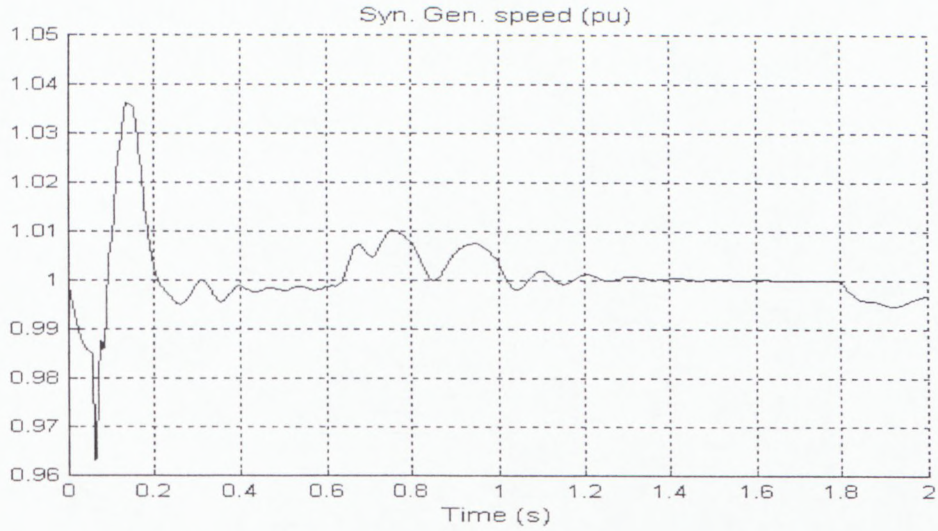


Figure 4.98: Synchronous Generator Rotor Speed When SVC Output is (-j300 to j300) kvar

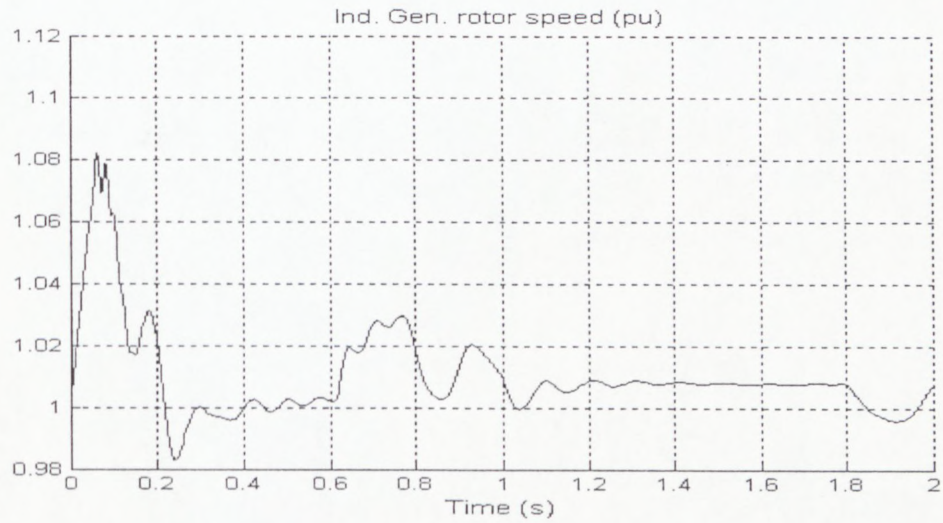


Figure 4.99: Induction Generator Rotor Speed When SVC Output is (-j300 to j300) kvar

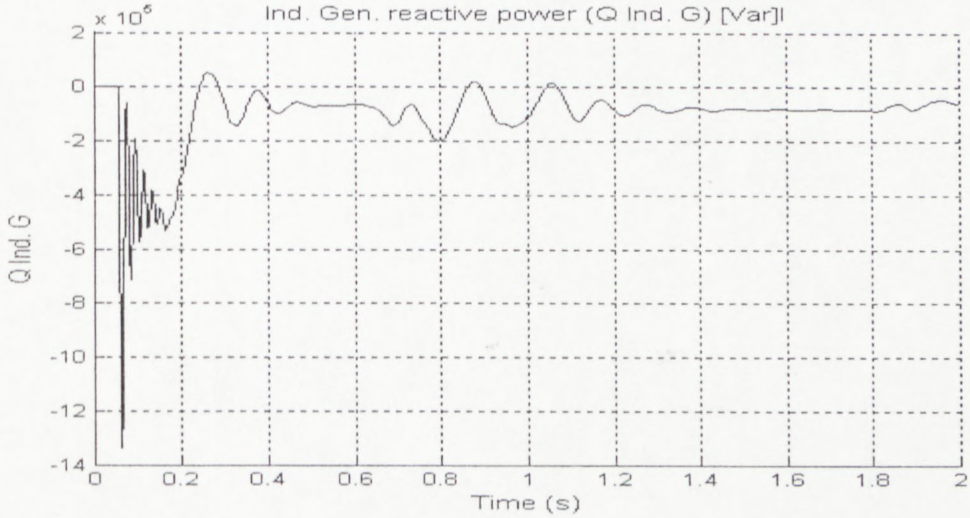


Figure 4.100: Induction Generator Reactive Power When SVC Output is (-j300 to j300) kvar

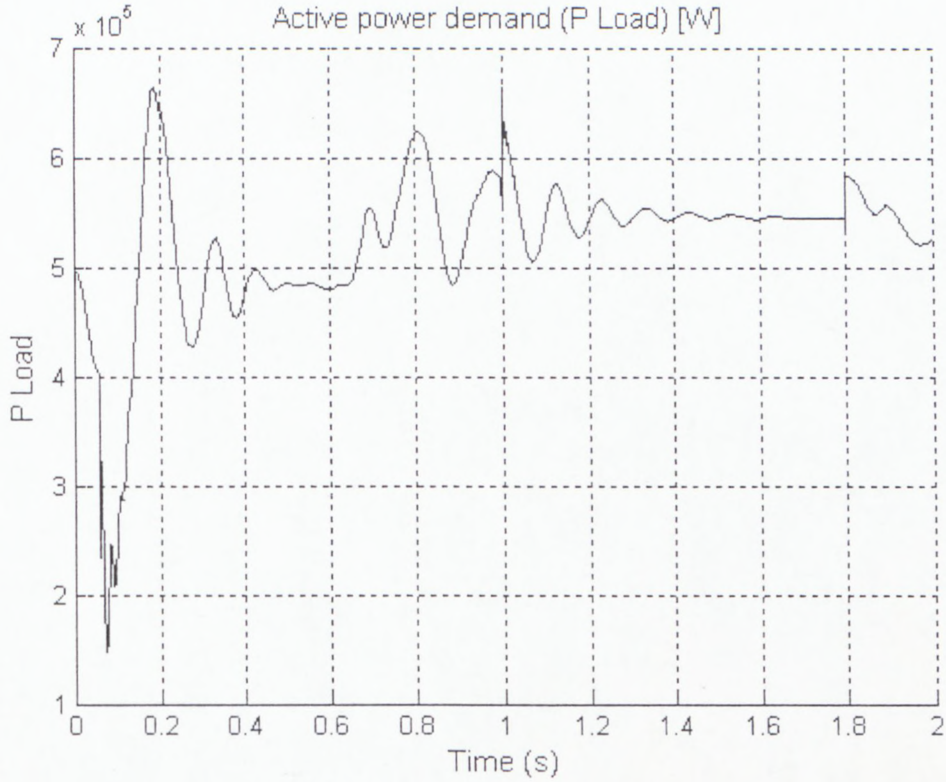


Figure 4.101: Active Power Output of the SHP When SVC Output is (-j300 to j300) kvar

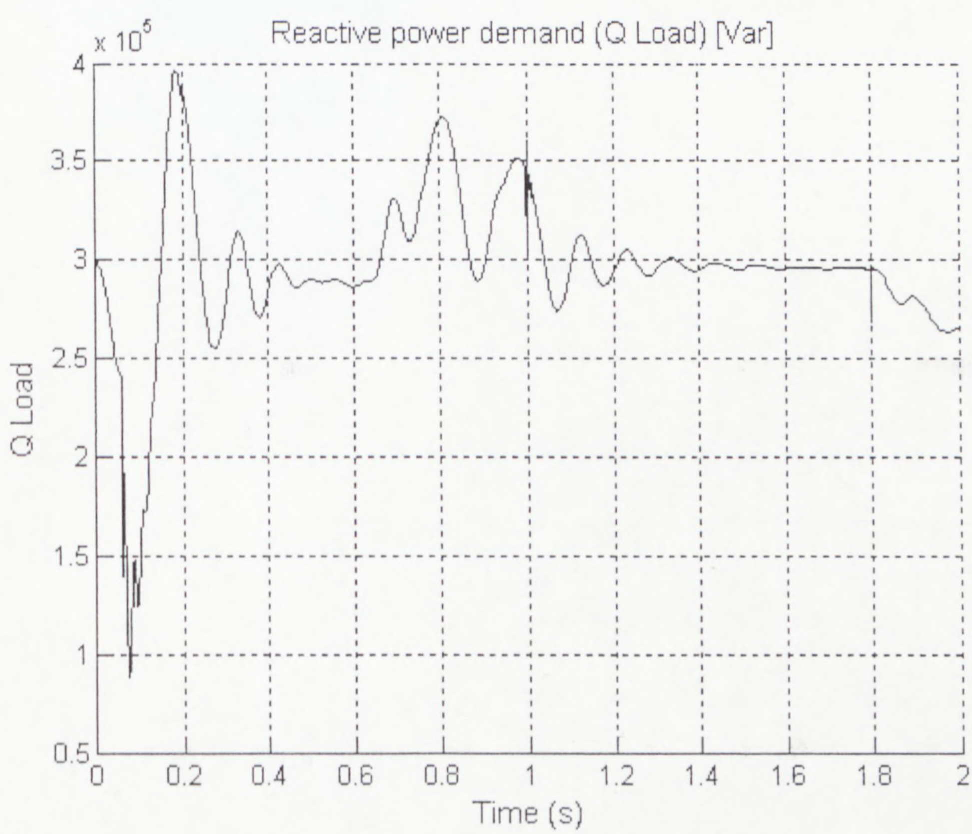


Figure 4.102: Reactive Power Output of the SHP When SVC Output is (-j300 to j300) kvar

When simulation of the plant with (-j400 to j400) kvar SVC connected to generator bus was conducted, the plant performance characteristics were as shown in Figure 4.103 to Figure 4.112 which are very similar to those when SVC of (-j300 to j300) kvar output was employed.

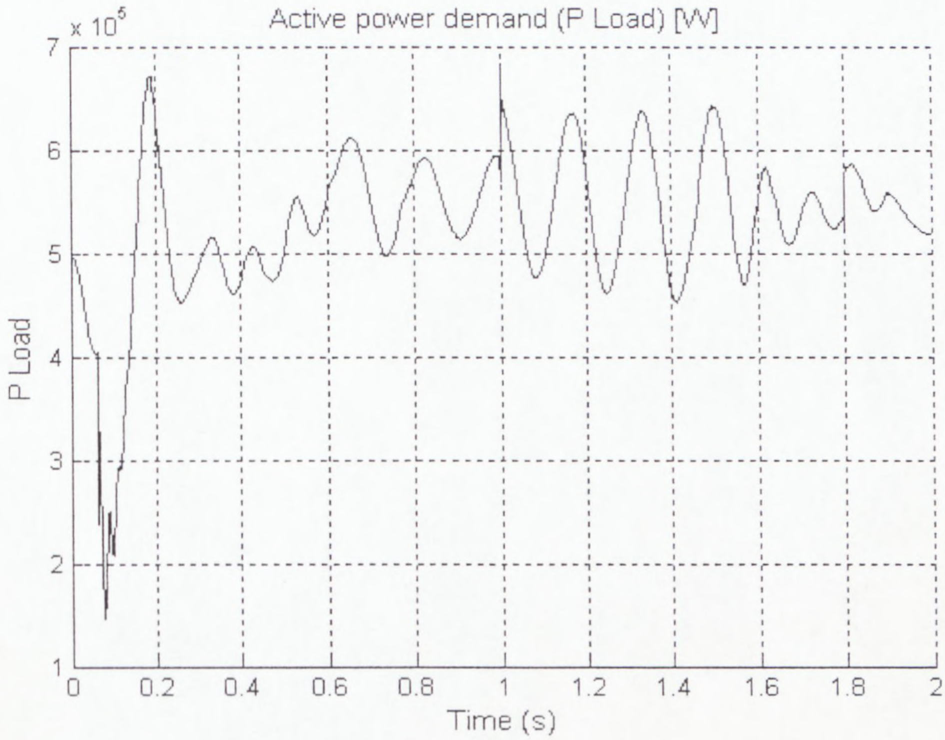


Figure 4.103: Active Power Output of the SHP When SVC Output is (-j400 to j400) kvar

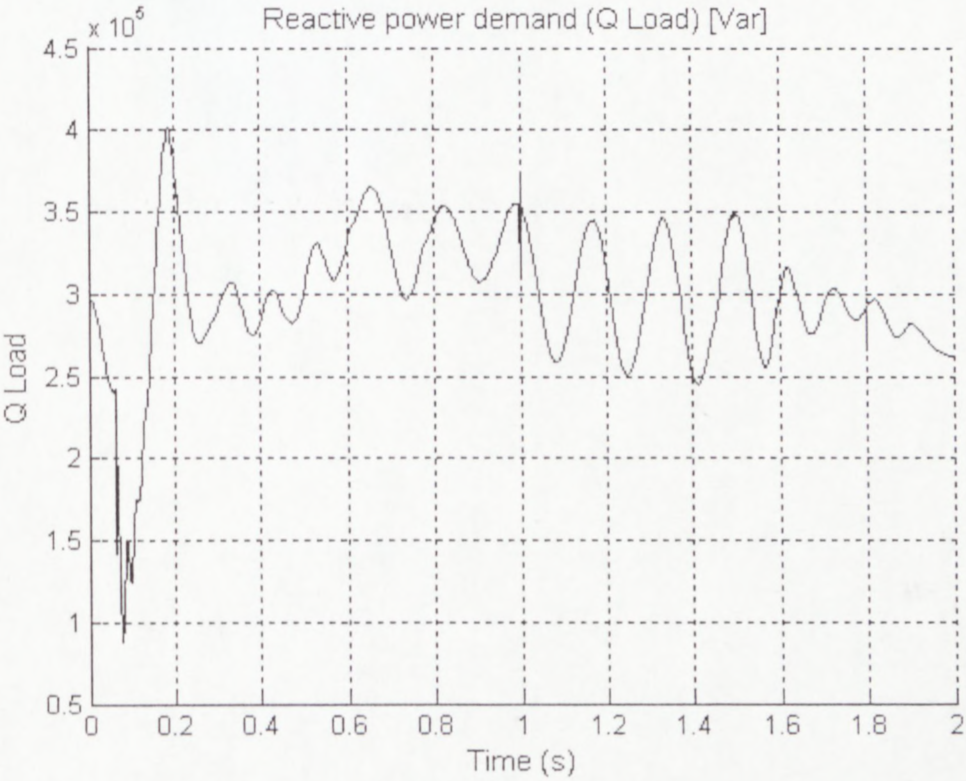


Figure 4.104: Reactive Power Output of the SHP When SVC Output is (-j400 to j400) kvar

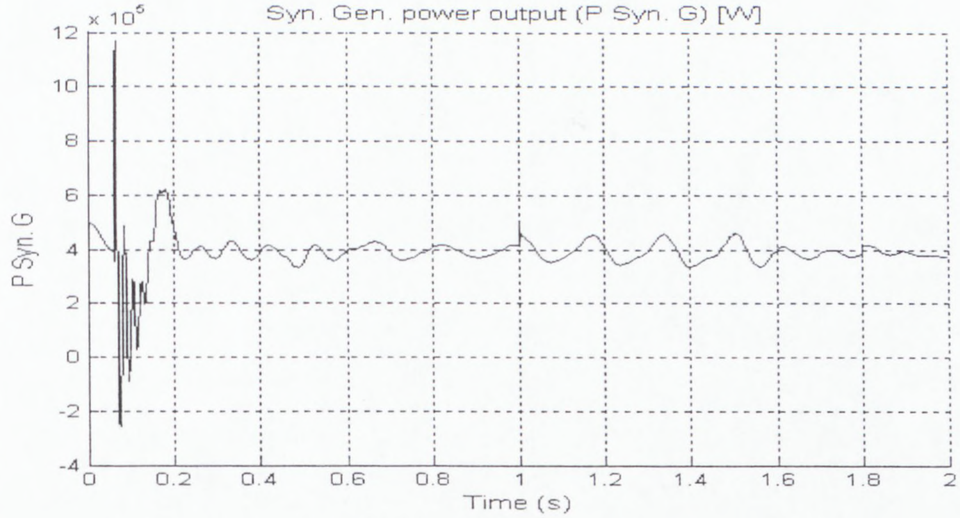


Figure 4.105: Synchronous Generator Power Output When SVC Output is (-j400 to j400) kvar

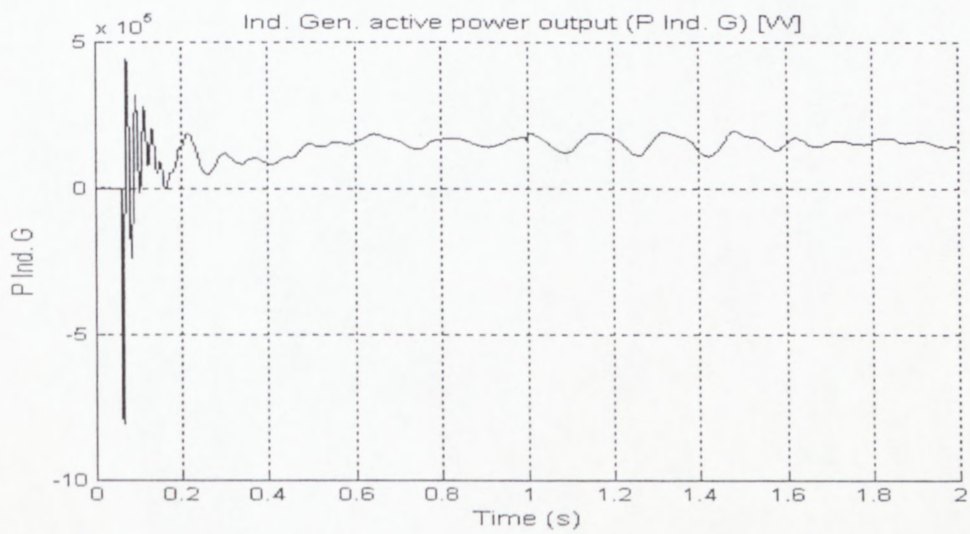


Figure 4.106: Induction Generator Active Power Output When SVC Output is (-j400 to j400) kvar

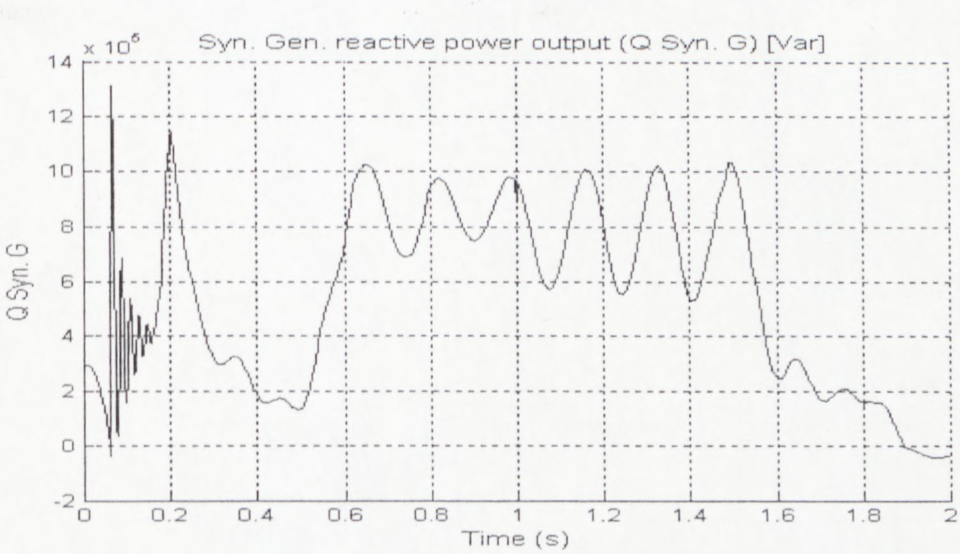


Figure 4.107: Synchronous Generator Reactive Power Output When SVC Output is (-j400 to j400) kvar

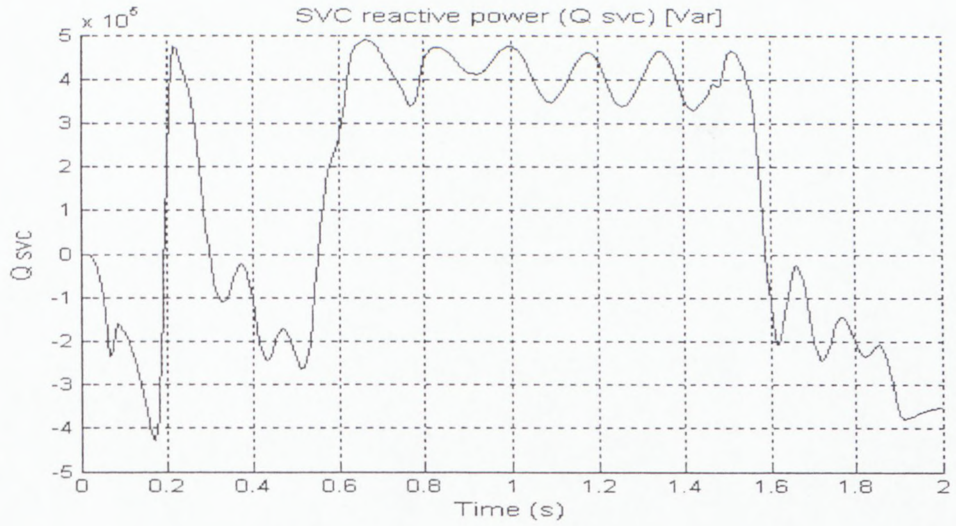


Figure 4.108: SVC Reactive Power When The Output Range is (-j400 to j400) kvar

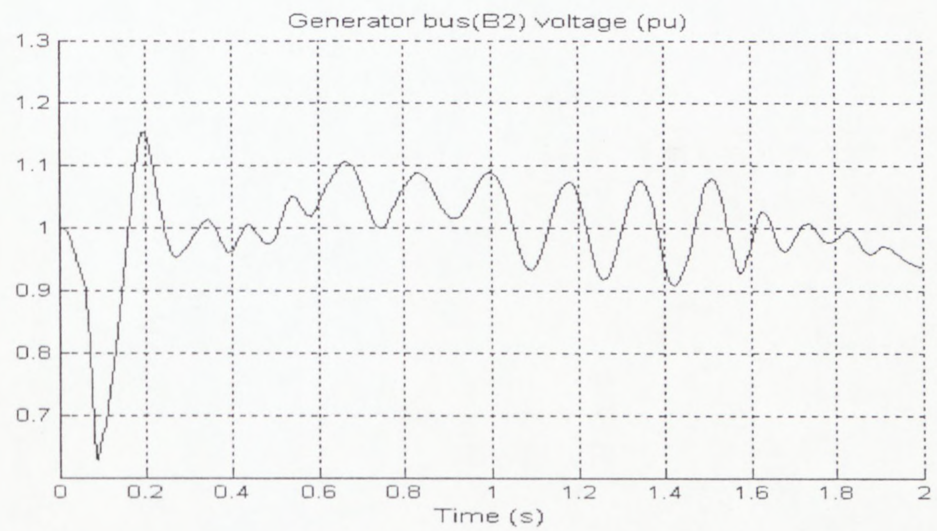


Figure 4.109: Generator Bus Voltage When SVC Output is (-j400 to j400) kvar

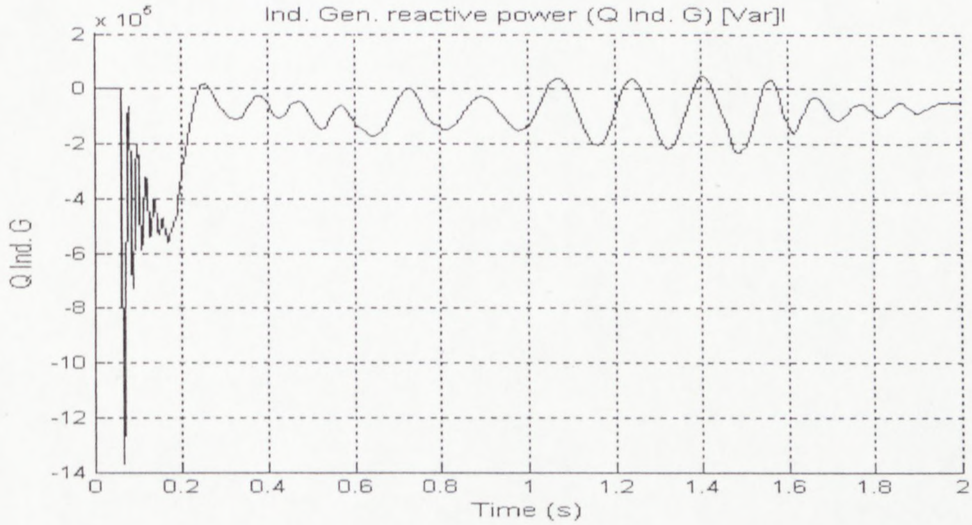


Figure 4.110: Induction Generator Reactive Power When SVC Output is (-j400 to j400) kvar

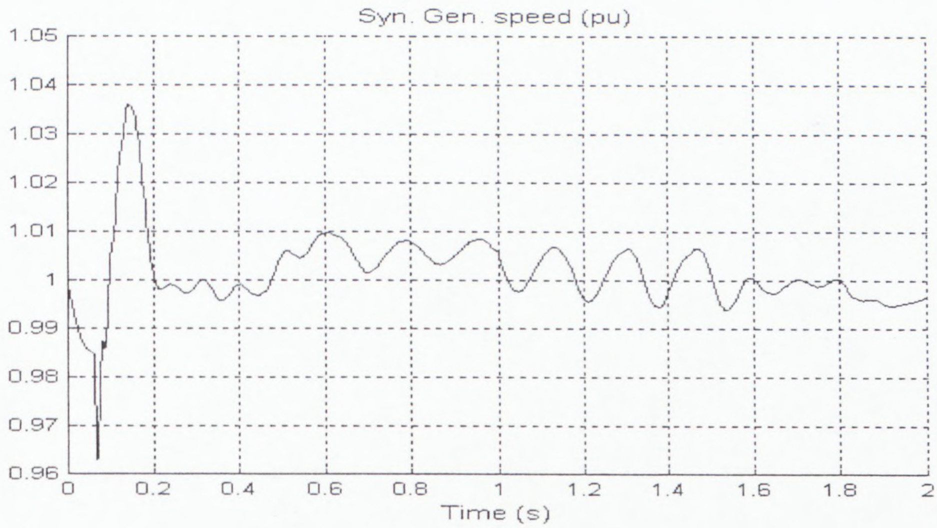


Figure 4.111: Synchronous Generator Rotor Speed When SVC Output is (-j400 to j400) kvar

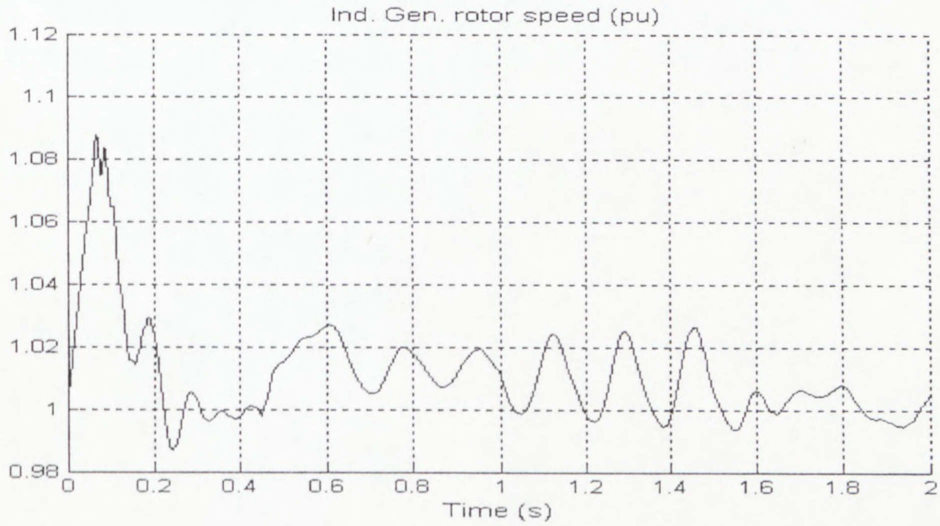


Figure 4.112: Induction Generator Rotor Speed When SVC Output is (-j400 to j400) kvar

The power plant performance and its small signal stability showed some improvement when the plant was simulated with (-j500 to j500) kvar SVC connected to the generator bus. However, the active and reactive power output of the plant as displayed in Figure 4.113 and Figure 4.114 respectively were not stable enough to ensure successful operation of the SHP.

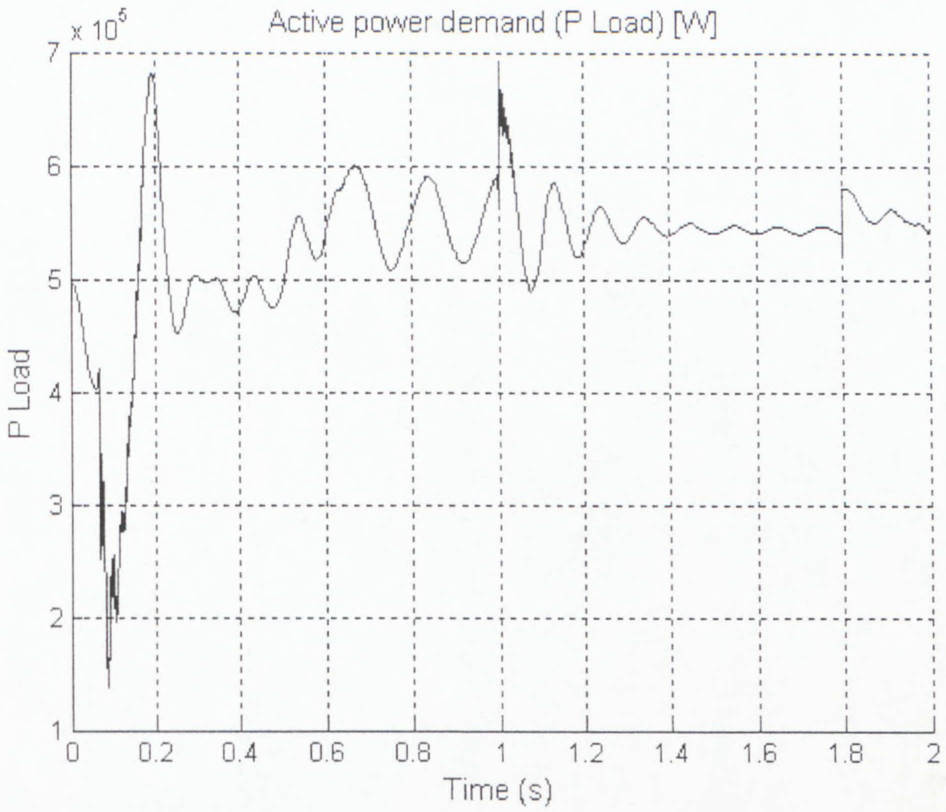


Figure 4.113: Active Power Output of the SHP When SVC Output is (-j500 to j500) kvar

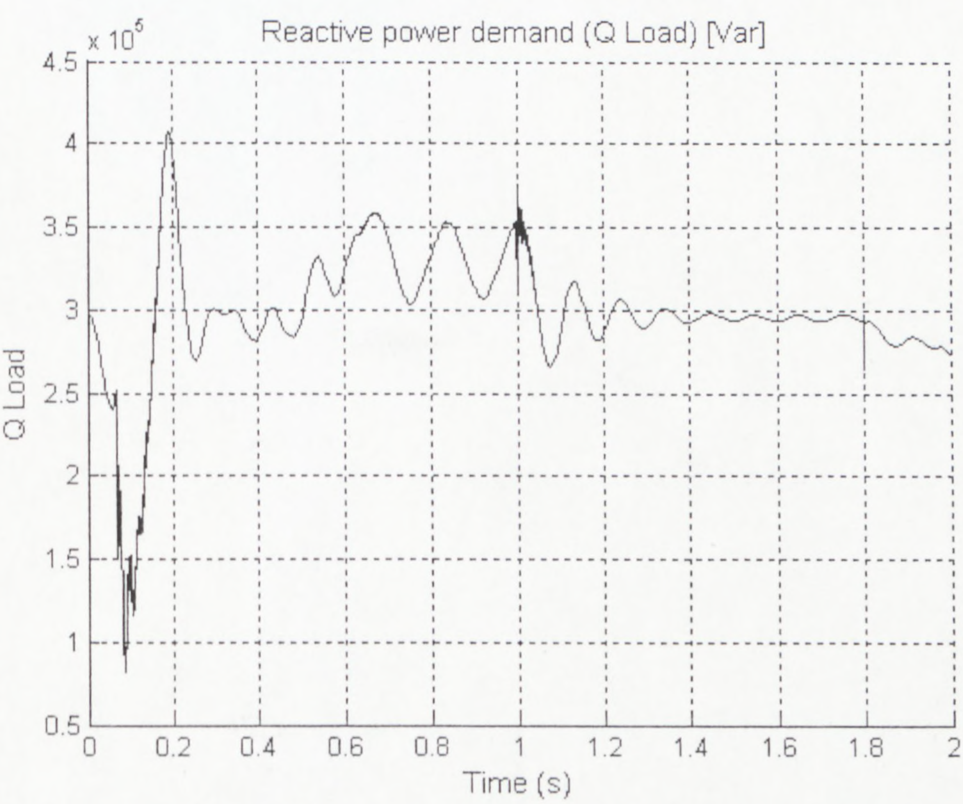


Figure 4.114: Reactive Power Output of the SHP When SVC Output is (-j500 to j500) kvar

Induction machine in this case showed stable performance as generator, absorbing reactive power from the system (Figure 4.116) and its rotor running at a speed higher than the speed of synchronous generator rotor (Figure 4.117 and Figure 4.118) it was supplying active power to the connected load as shown in Figure 4.115 at its full load capacity.

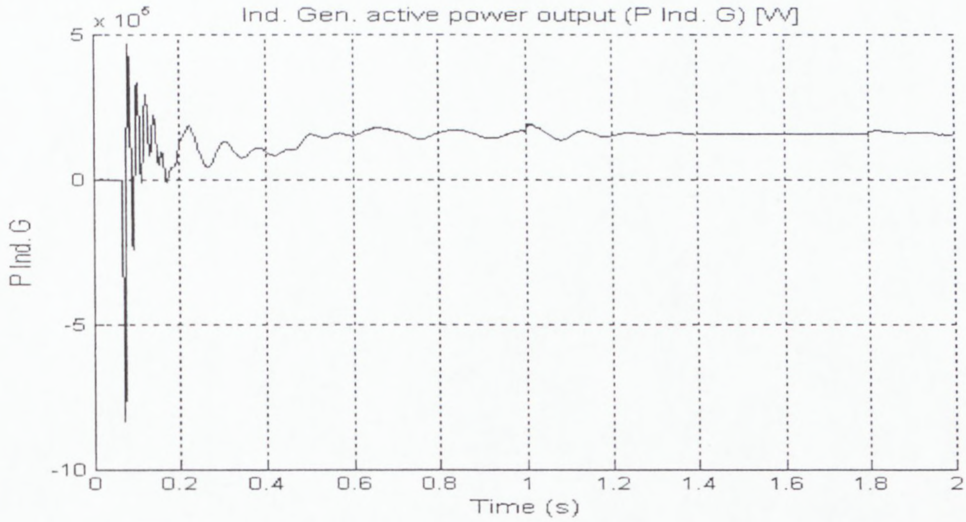


Figure 4.115: Induction Generator Active Power Output When SVC Output is (-j500 to j500) kvar

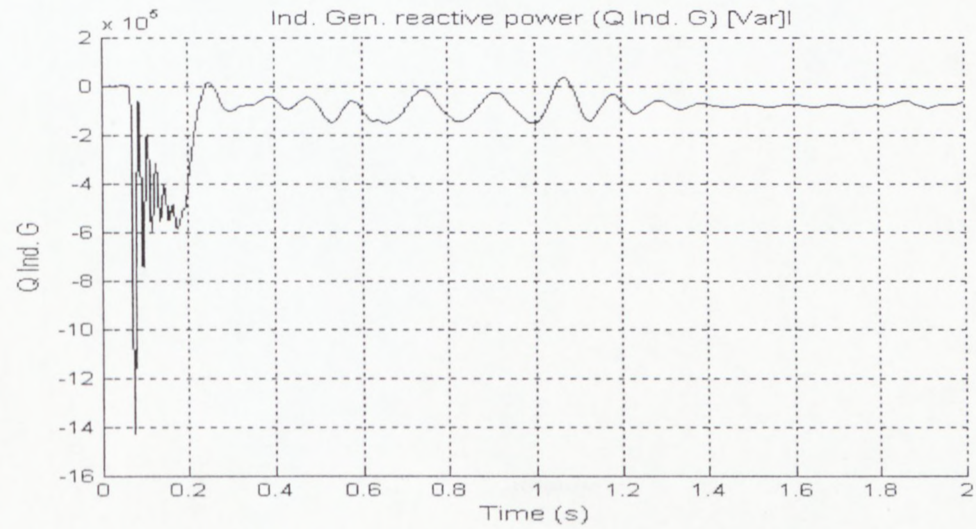


Figure 4.116: Induction Generator Reactive Power When SVC Output is (-j500 to j500) kvar

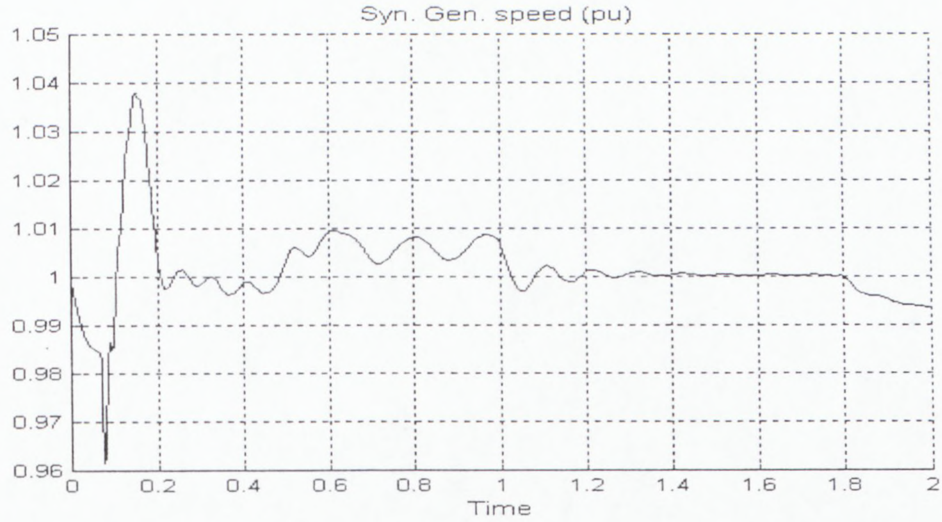


Figure 4.117: Synchronous Generator Speed When SVC Output is (-j500 to j500) kvar

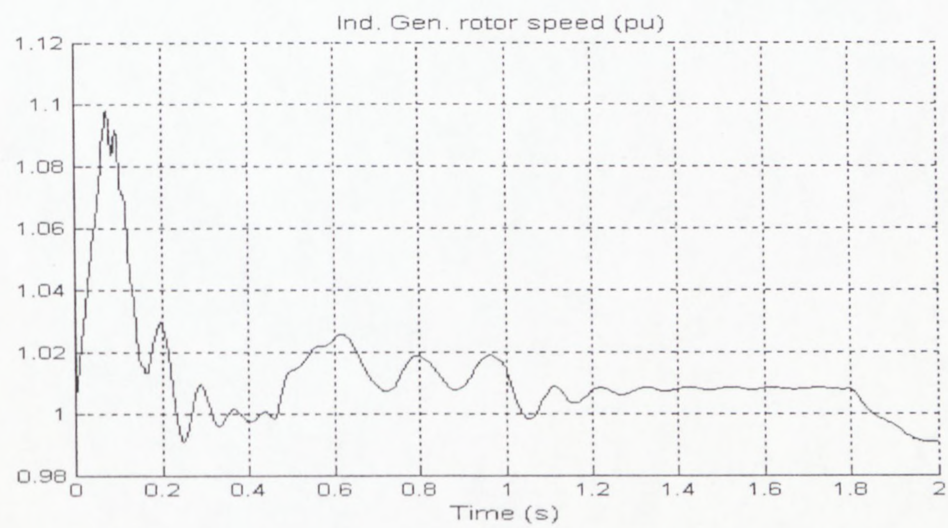


Figure 4.118: Induction Generator Rotor Speed When SVC Output is (-j500 to j500) kvar

Since the induction generator showed to be loaded to its full capacity, the drop in power output of the plant indicates that the synchronous generator fell short of supplying sufficient power as required by the load.

The generator bus voltage on the other hand, dropped to approximately 0.96 pu (Figure 4.122) which is attributed to drop in synchronous generator rotor speed as related to speed voltage.

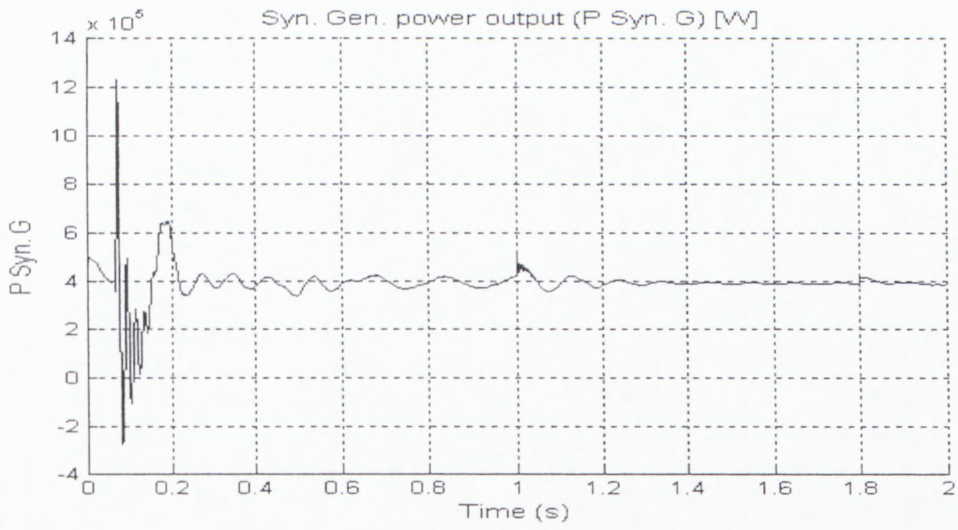


Figure 4.119: Synchronous Generator Power Output When SVC Output is (-j500 to j500) kvar

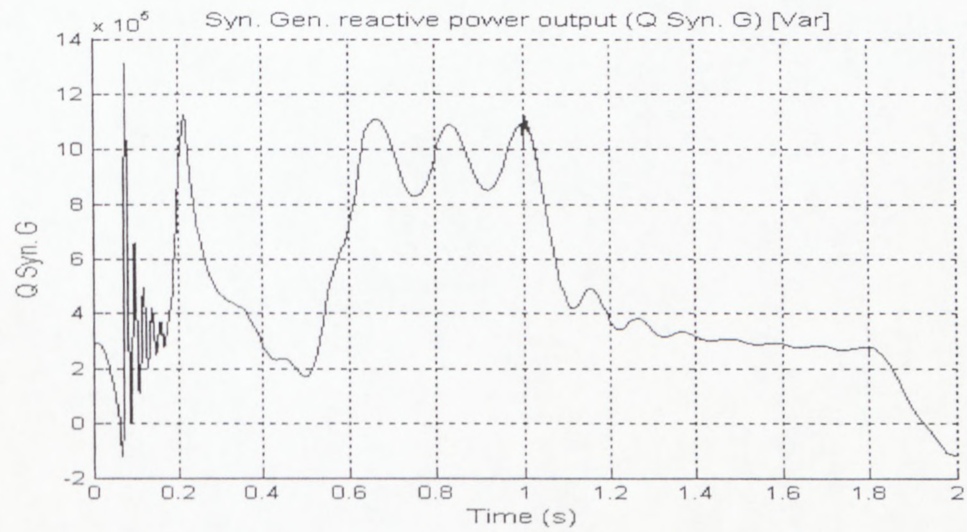


Figure 4.120: Synchronous Generator Reactive Power Output When SVC Output is (-j500 to j500) kvar

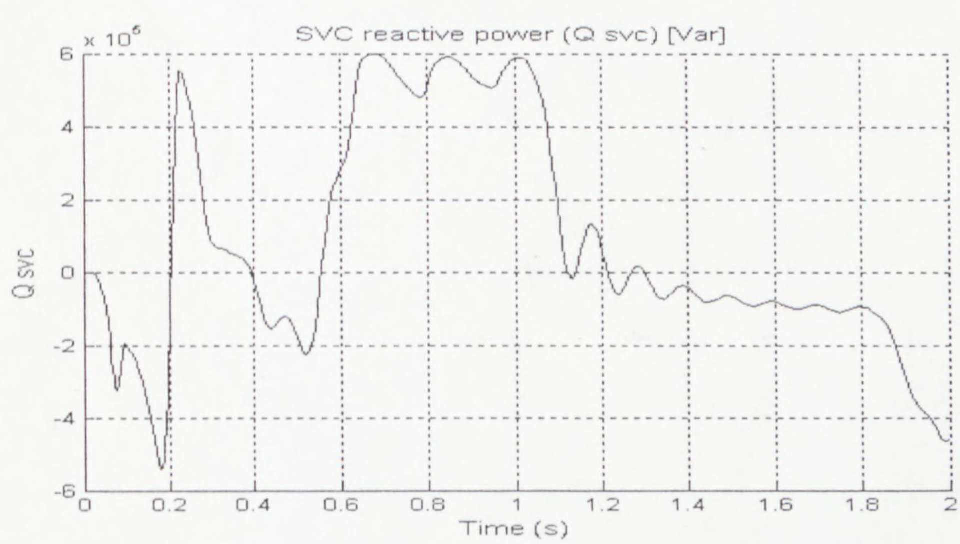


Figure 4.121: SVC Reactive Power When the Output Range is (-j500 to j500) kvar

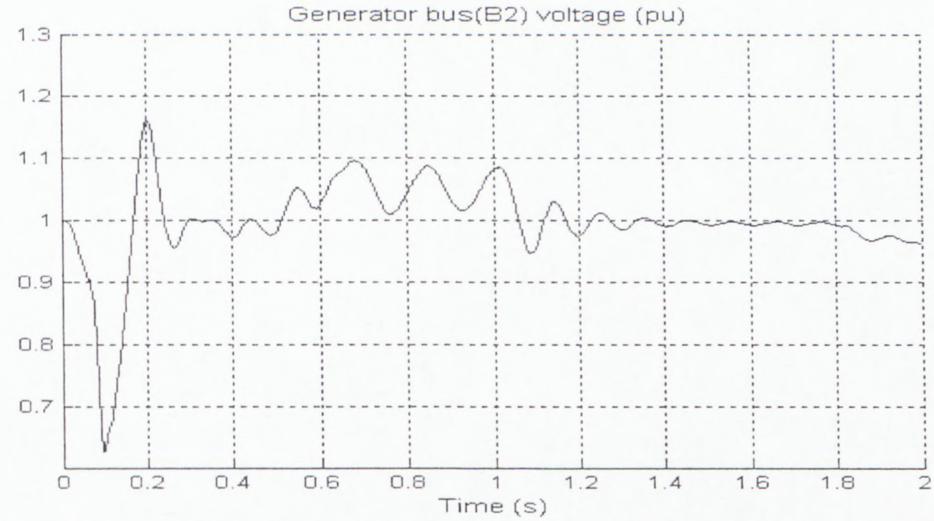


Figure 4.122: Generator Bus Voltage When SVC Output is (-j500 to j500) kvar

Simulation of performance of the proposed SHP with (-j600 to j600) kvar SVC connected to the generator bus gave most satisfying results. The power plant supplied the load with the required active power as shown in Figure 4.123. However, Figure 4.124 shows drop in reactive power supply. This drop is caused by fall of synchronous generator speed which is also generation or power supply frequency due to the relationship between inductive load and frequency of the power supply.

The supply of active power by both synchronous and induction generators as depicted in Figure 4.125 and Figure 4.126 showed stable characteristics with induction generator absorbing reactive power (Figure 4.127) while its rotor running with negative slip which is observed when comparing synchronous generator rotor speed in Figure 4.128 which also reflect synchronous speed in p.u with induction generator rotor speed depicted in Figure 4.129.

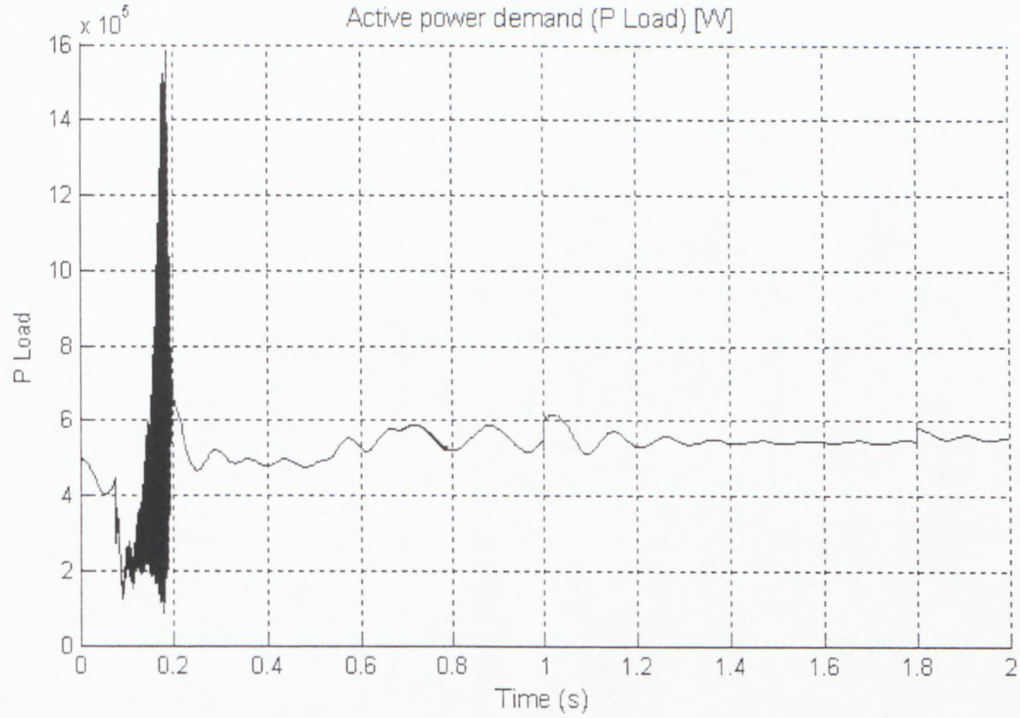


Figure 4.123: Active Power Output of the SHP When SVC Output is (-j600 to j600) kvar

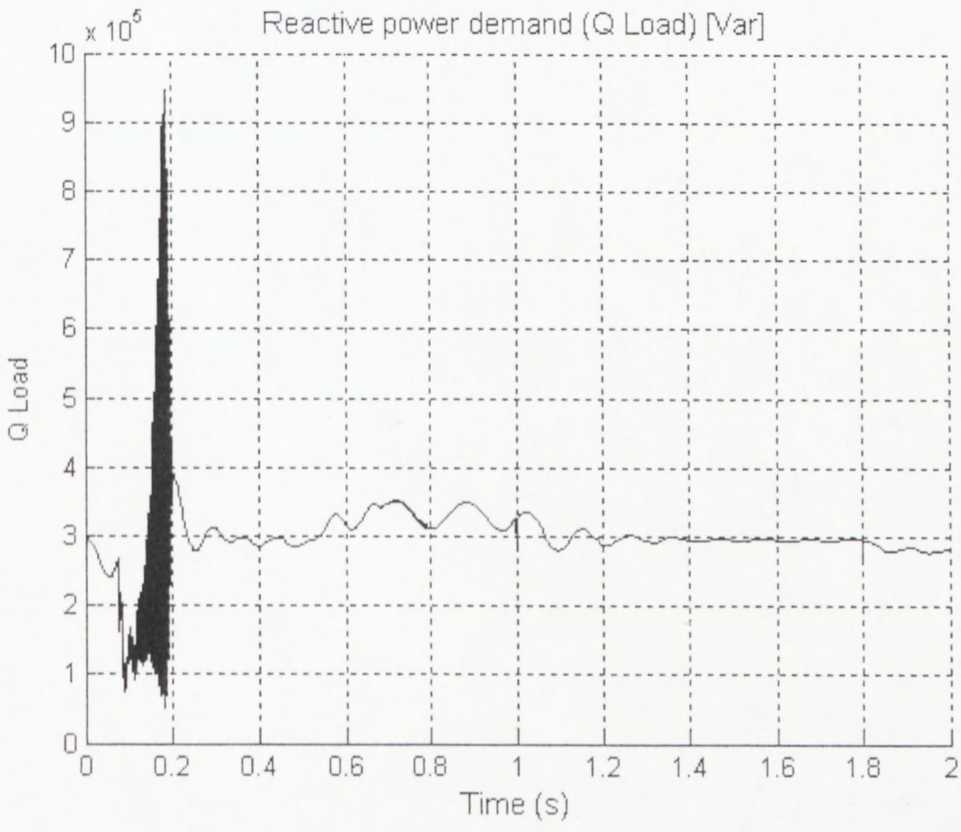


Figure 4.124: Reactive Power Output of the SHP When SVC Output is (-j600 to j600) kvar

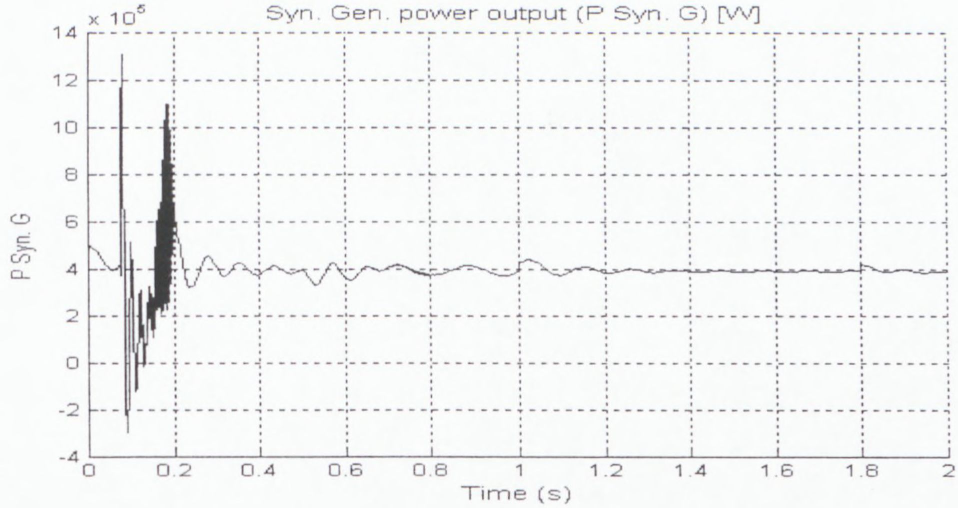


Figure 4.125: Synchronous Generator Power Output When SVC Output is (-j600 to j600) kvar

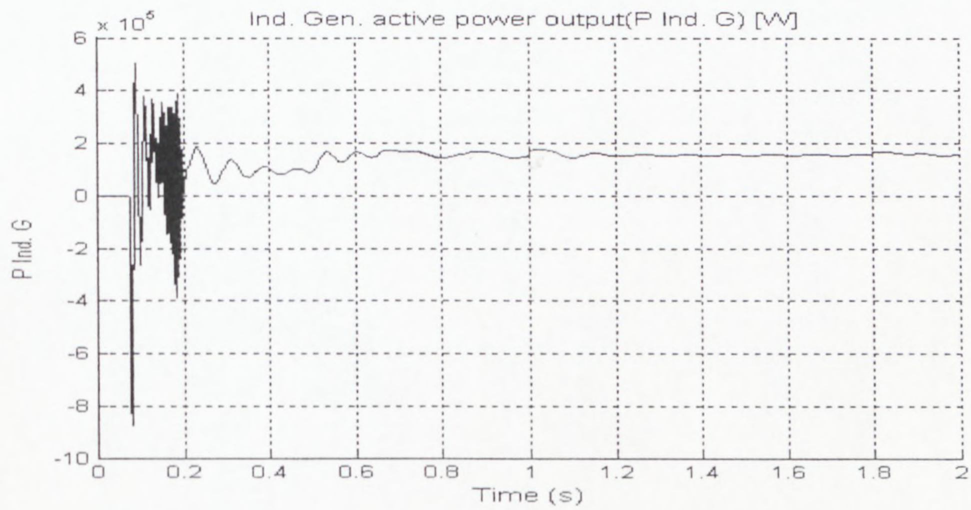


Figure 4.126: Induction Generator Active Power Output When SVC Output is (-j600 to j600) kvar

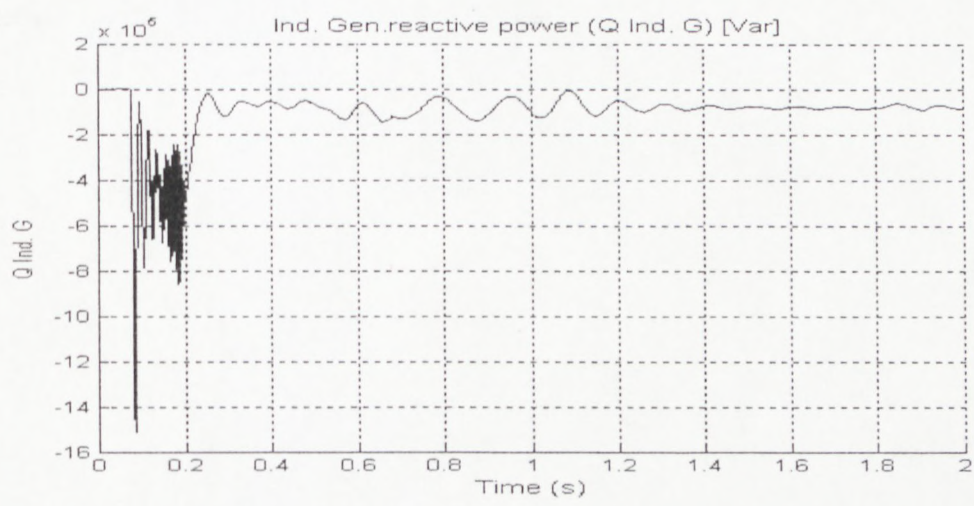


Figure 4.127: Induction Generator Reactive Power When SVC Output is (-j600 to j600) kvar

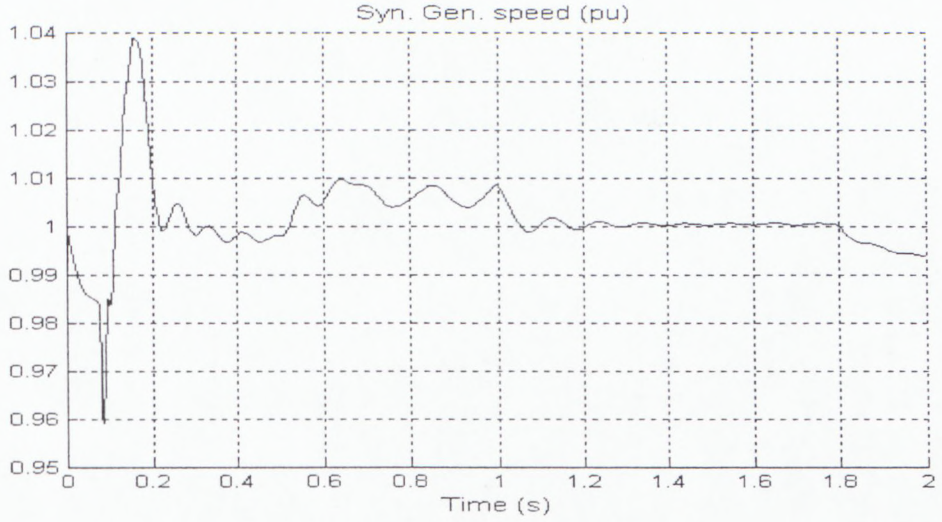


Figure 4.128: Synchronous Generator Rotor Speed When SVC Output is (-j600 to j600) kvar

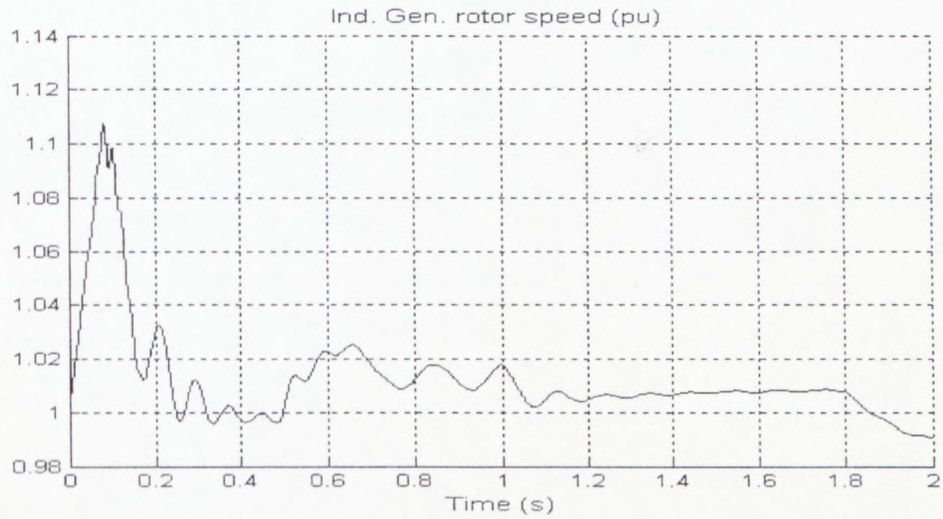


Figure 4.129: Induction Generator Rotor Speed When SVC Output is (-j600 to j600) kvar

Operation of synchronous generator and SVC in generating reactive power as the load to the plant was being increased (Figure 4.130 and Figure 4.131) resulted to maintenance of the generator bus voltage in steady state conditions at the required level. The drop of the voltage after the load to the plant was increased to (590 + j300) kVA is due to speed-voltage characteristics of synchronous generator. And the drop of the generator/turbine speed with increase in active power supplied to the connected load depends on droop characteristics of the governing system of the turbine.

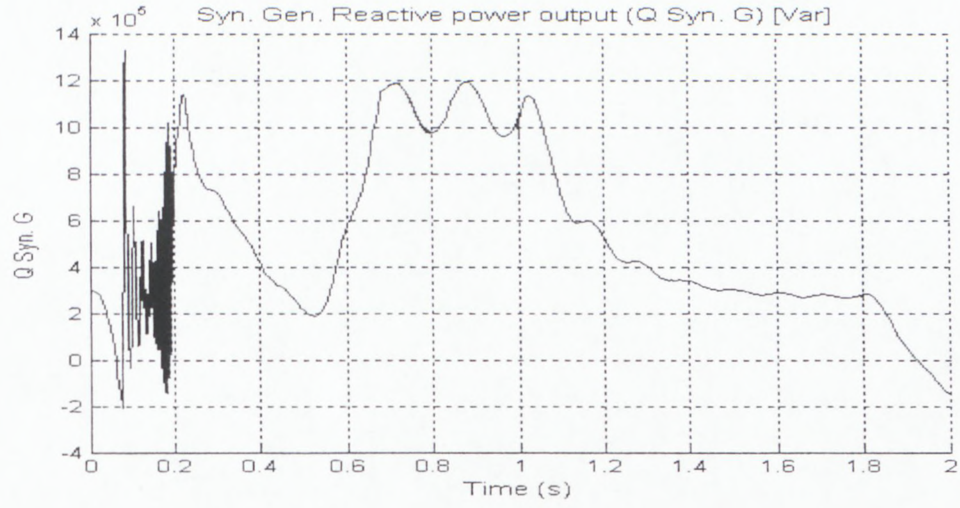


Figure 4.130: Synchronous Generator Reactive Power Output When SVC Output is (-j600 to j600) kvar

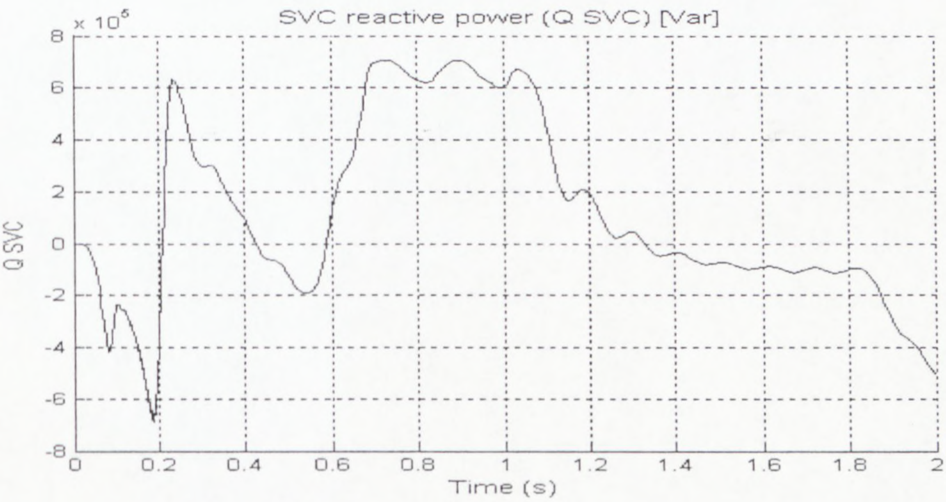


Figure 4.131: SVC Reactive Power Output When the Output Range is (-j600 to j600) kvar

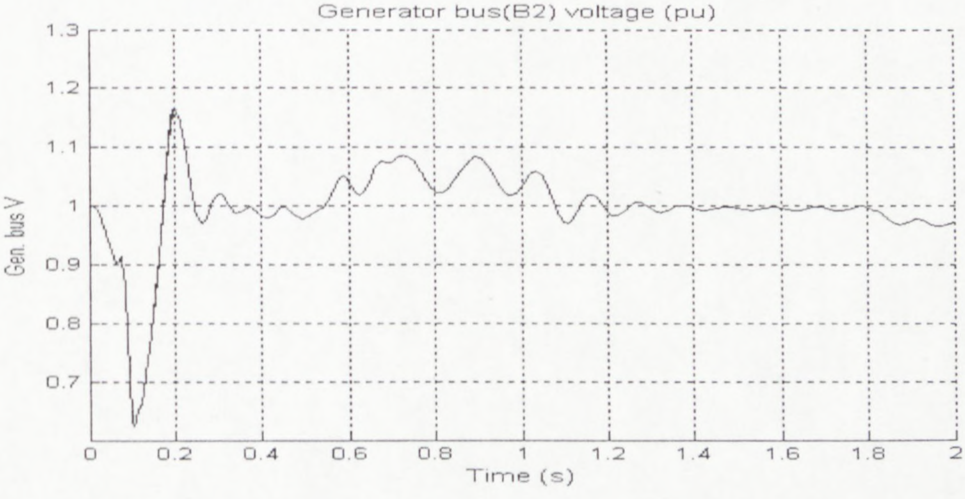


Figure 4.132: Generator Bus Voltage When SVC Output is (-j600 to j600) kvar

4.3.3 Assessment of the Transient and Speed Stability of the Generator in the Proposed SHP

This was undertaken using a simulated fault condition. It was assumed that a three-phase fault occurred on the generator bus when the induction generator was fully loaded and in parallel operation with the synchronous generator. The generator combination fed a (500 +j 300) kVA load connected to the bus. The fault was then cleared in two cycle period from its occurrence. Figure 4.133 depicts the model used for simulating the plant stability. This also depends on the stability of the generator installed.

The occurrence of the three phase fault moment t = 1s was followed by drop of both active and reactive power output of the plant that was supplied to the connected load. Figure 4.134 and Figure 4.135 depict the described scenario.

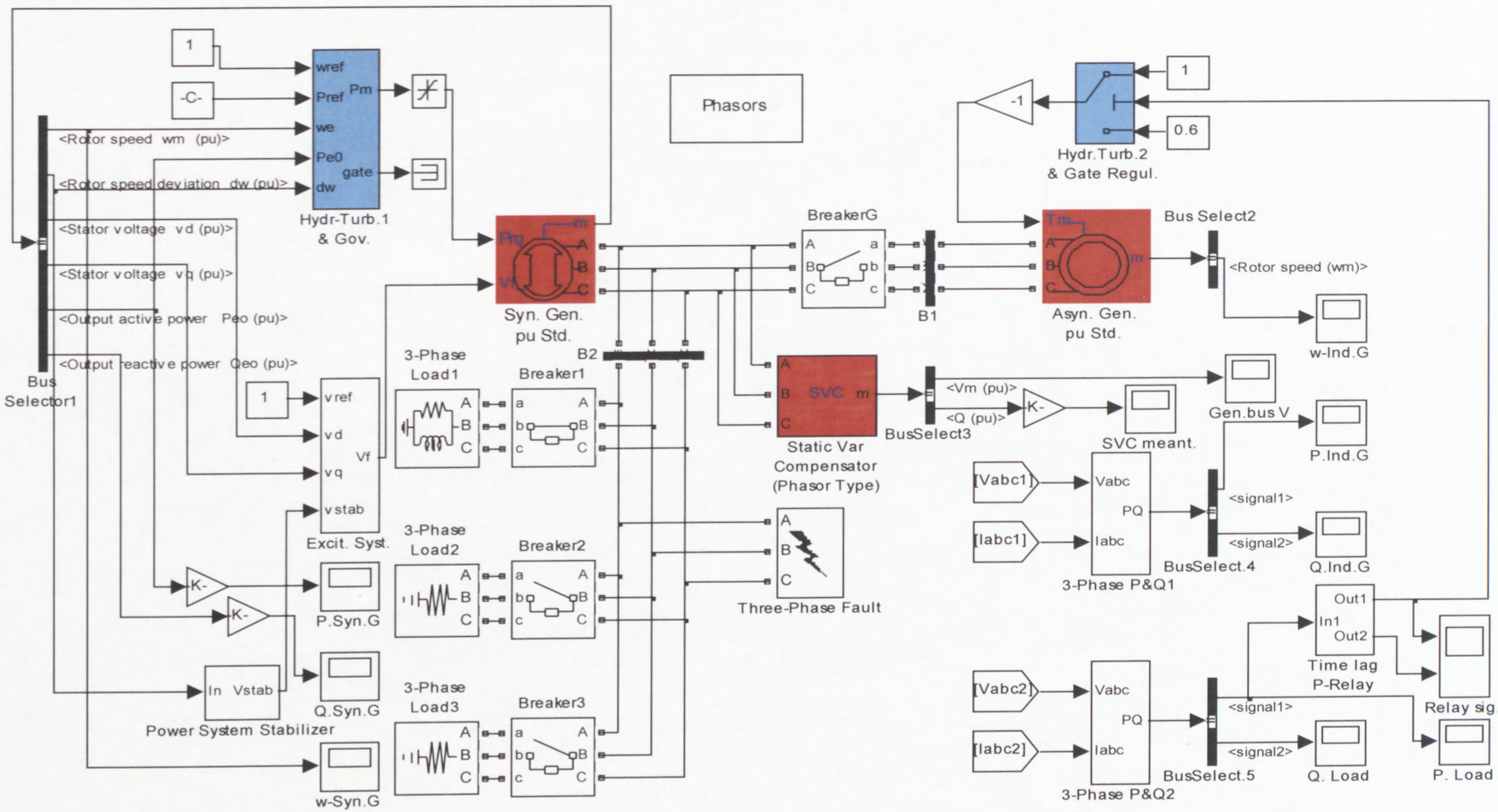


Figure 4.133: Model of the Proposed SHP for Transient Stability Simulation

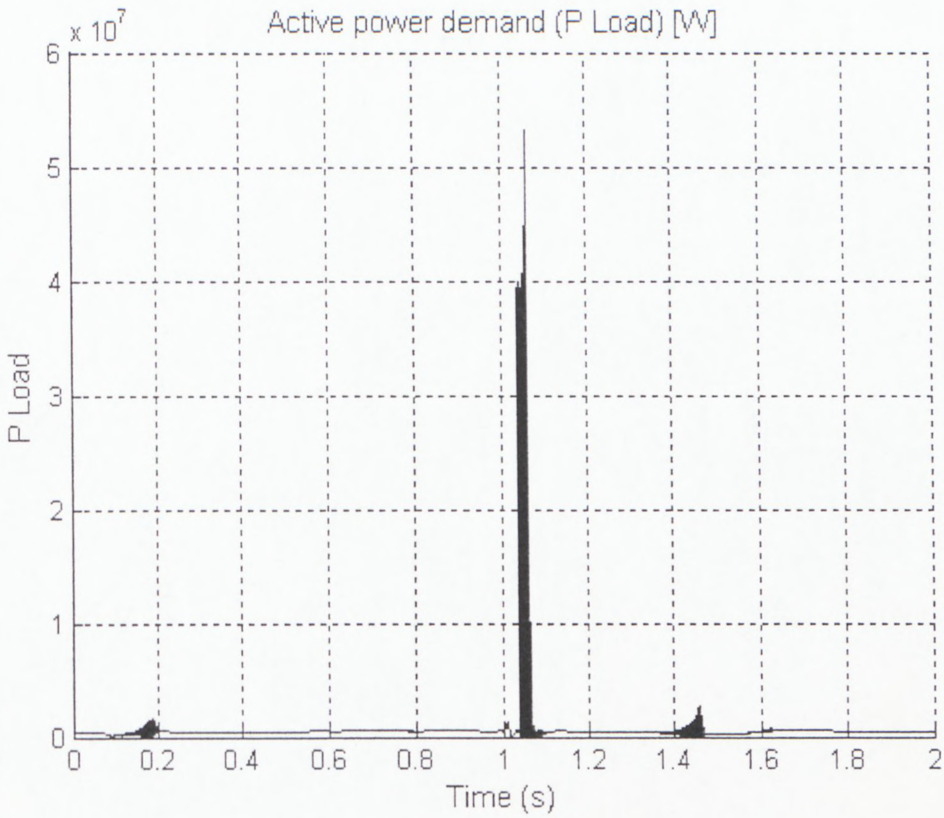


Figure 4.134: Active Power Output of the SHP

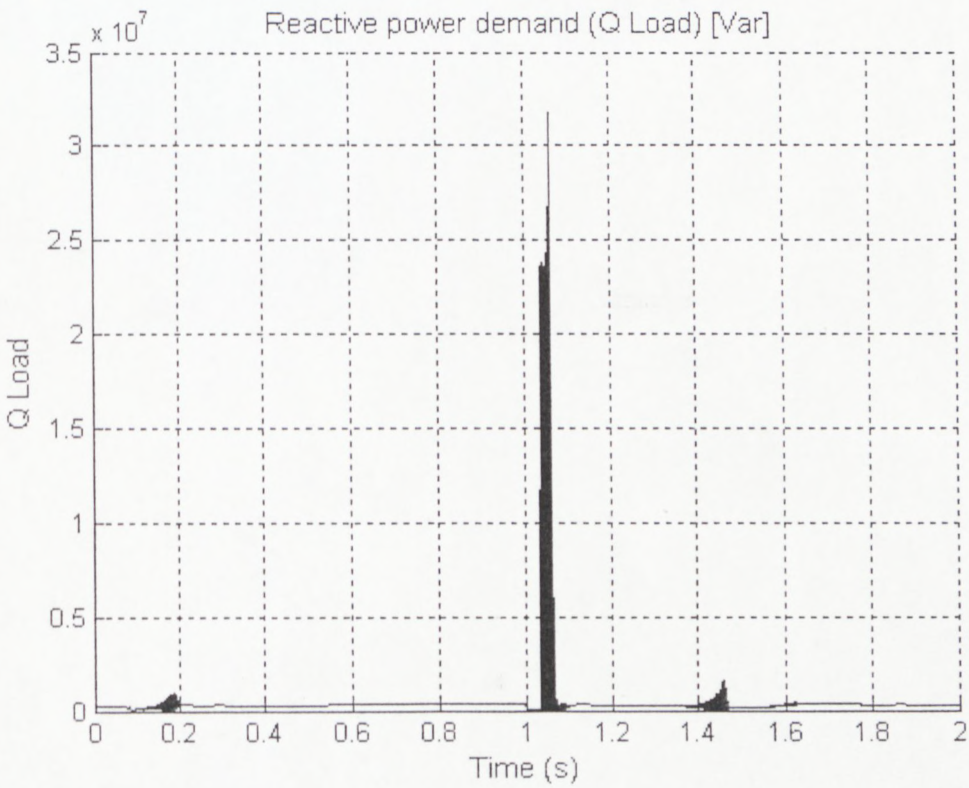


Figure 4.135: Reactive Power Output of the SHP

Sensing the drop in active power output of the plant, power relay terminated the turb2 switching signal as shown in Figure 4.136 leading the mechanical power output of the turbine driving induction generator to be reduced to 0.6 pu i.e. the minimum set power output.

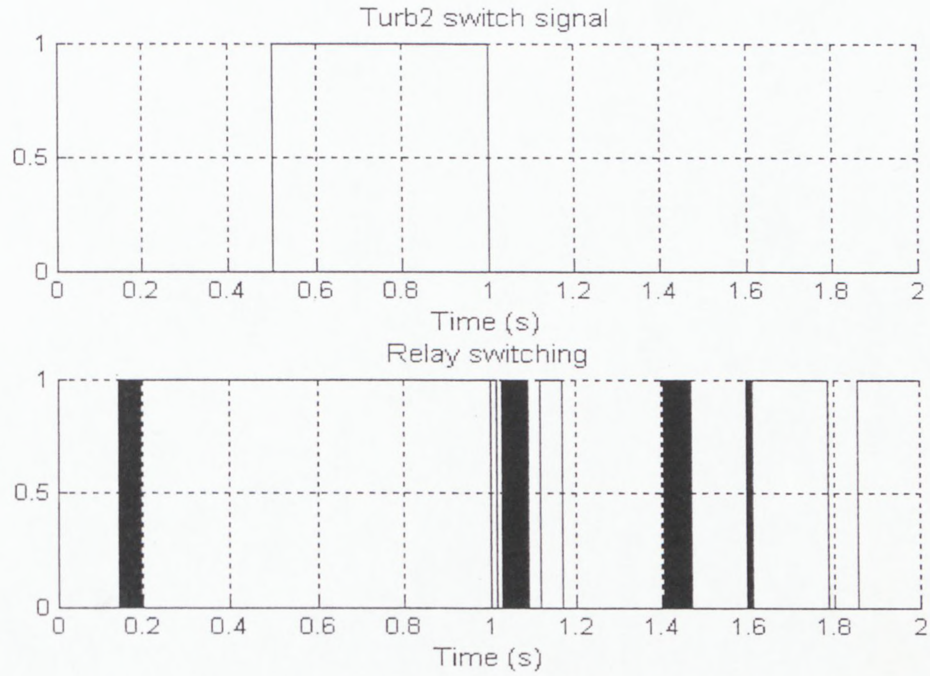


Figure 4.136: Power Relay Switching Signals

The fault caused drop of voltage at the generator bus and also the reactive power output of synchronous generator (Figure 4.137 and Figure 4.138) which made SVC to react by changing its mode of operation from inductive to capacitive injecting reactive power to the system as shown in Figure 4.139.

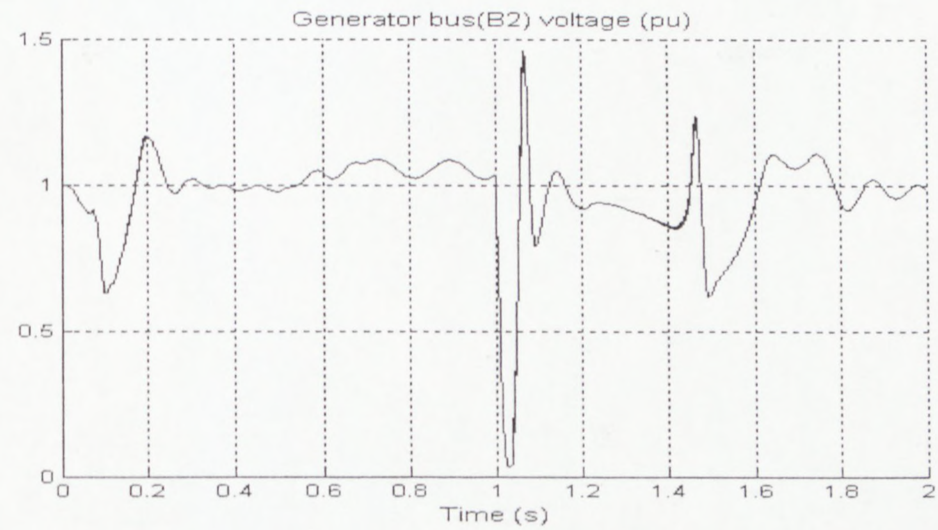


Figure 4.137: Generator Bus Voltage

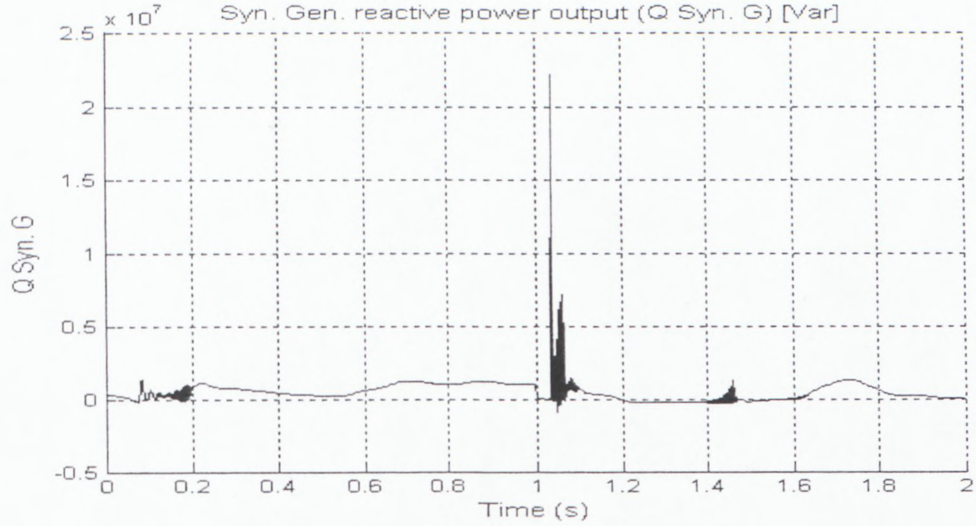


Figure 4.138: Synchronous Generator Reactive Power Output

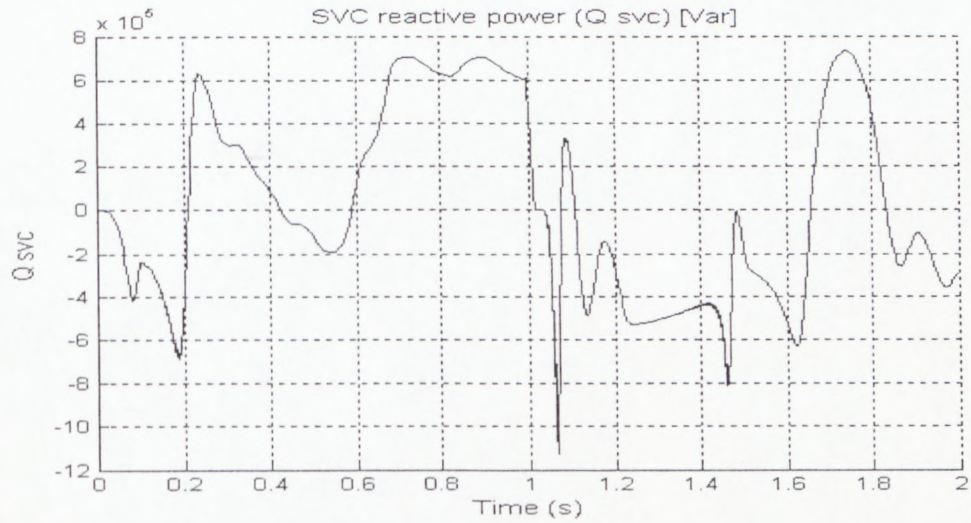


Figure 4.1139: SVC Reactive Power Output

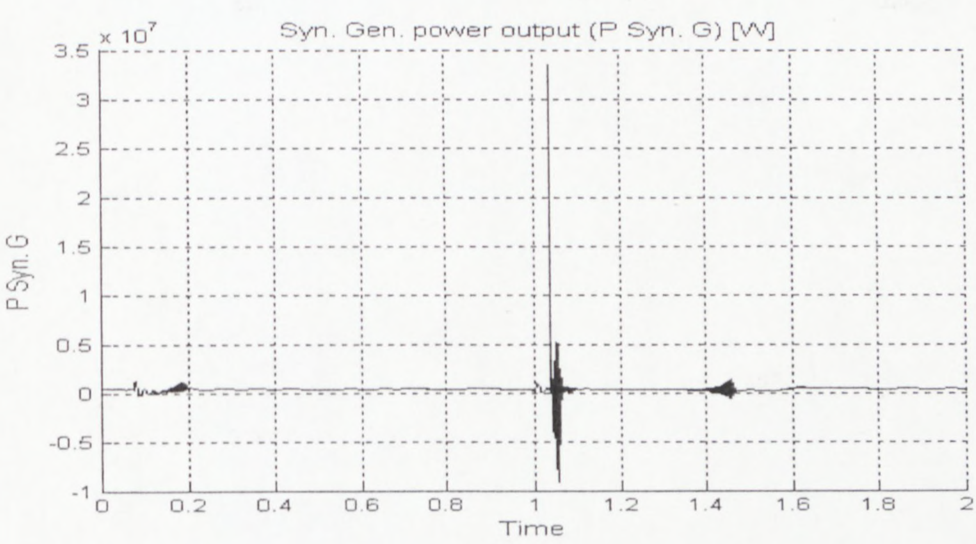


Figure 4.140: Synchronous Generator Power Output

The moment when fault occurred on the generator bus, active power output of synchronous generator dropped to zero with some transients. As soon as the fault was cleared output power of the generator was restored with initial overshoot followed by decreasing power oscillation reached a steady state condition as depicted in Figure 4.140. However, immediately after fault the speed of the synchronous generator rotor dropped first then started to accelerate (Figure 4.141). This behaviour is due to the fact that at the instant of fault occurrence short circuit current flowing in armature i.e. stator winding of the synchronous machine sharply rise leading to instantly rise of the electromagnetic torque in the machine that opposes the driving torque hence mismatch between the two torques resulting to sharp drop of synchronous generator's rotor speed. As the turbine governor respond by opening the gate allowing more water resulting to increase in driving torque at the same time as the initial short circuit current together with the corresponding electromagnetic torque drop to its steady value the rotor started to accelerate.

After clearance of the fault, speed of the rotor of the generator continued to increase to almost 1.04 pu then dropped and lastly reached a steady state value of approximately 0.98 pu which also reflect frequency of power generated by the power plant.

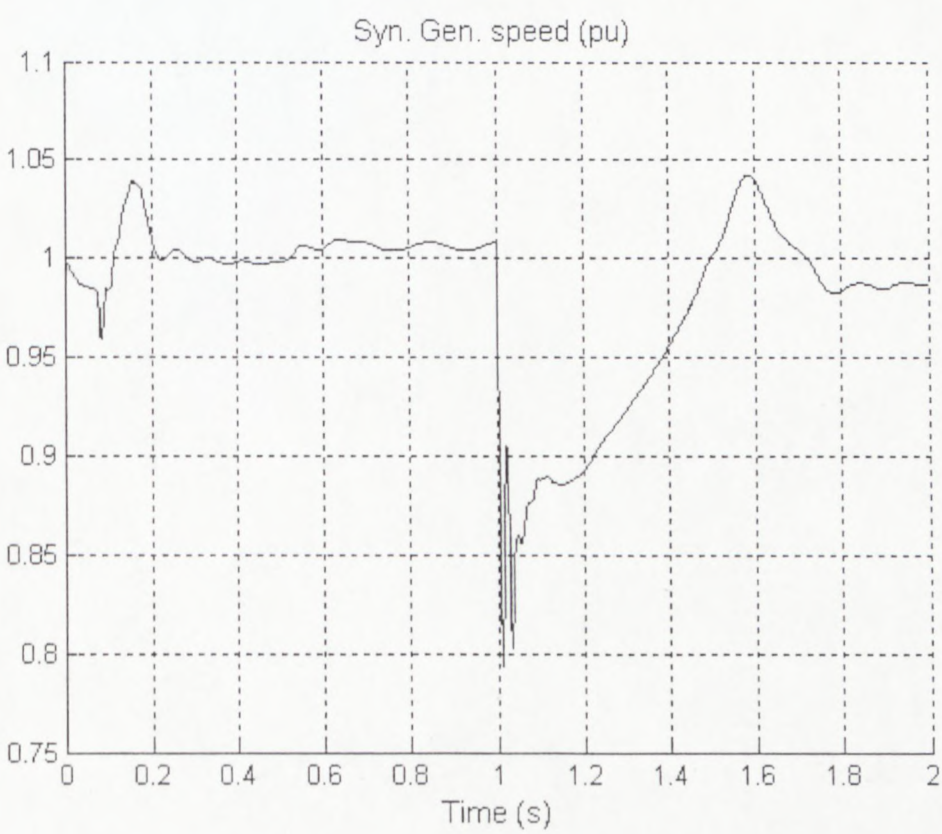


Figure 4.141: Synchronous Generator Rotor Speed

As a result of the fault on the generator bus, the reactive power supply to induction generator dropped to zero Figure 4.142. and consequently, despite of been subjected to mechanical power or driving torque by Tub2 that could enable generation of 96 kW its active power output during fault was zero as exhibited in Figure 4.143. After fault clearance, the generator reactive power characteristics showed oscillatory behaviour then settled with induction generator again absorbing reactive power at the same time delivering active power to the system.

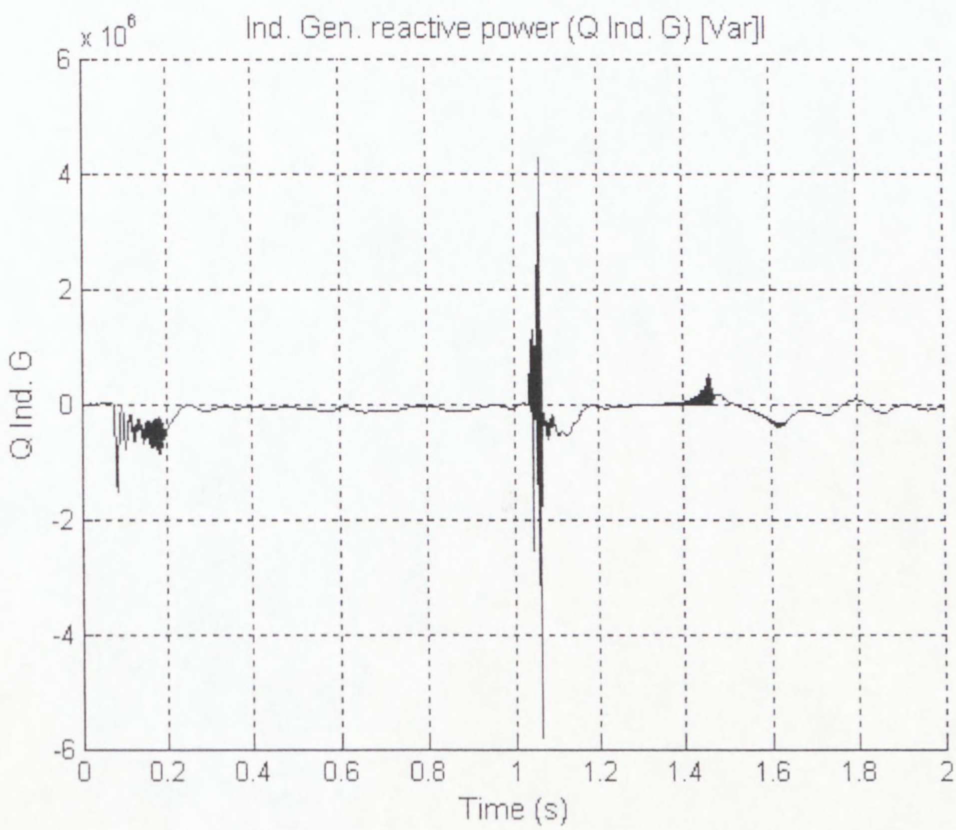


Figure 4.142: Induction Generator Reactive Power

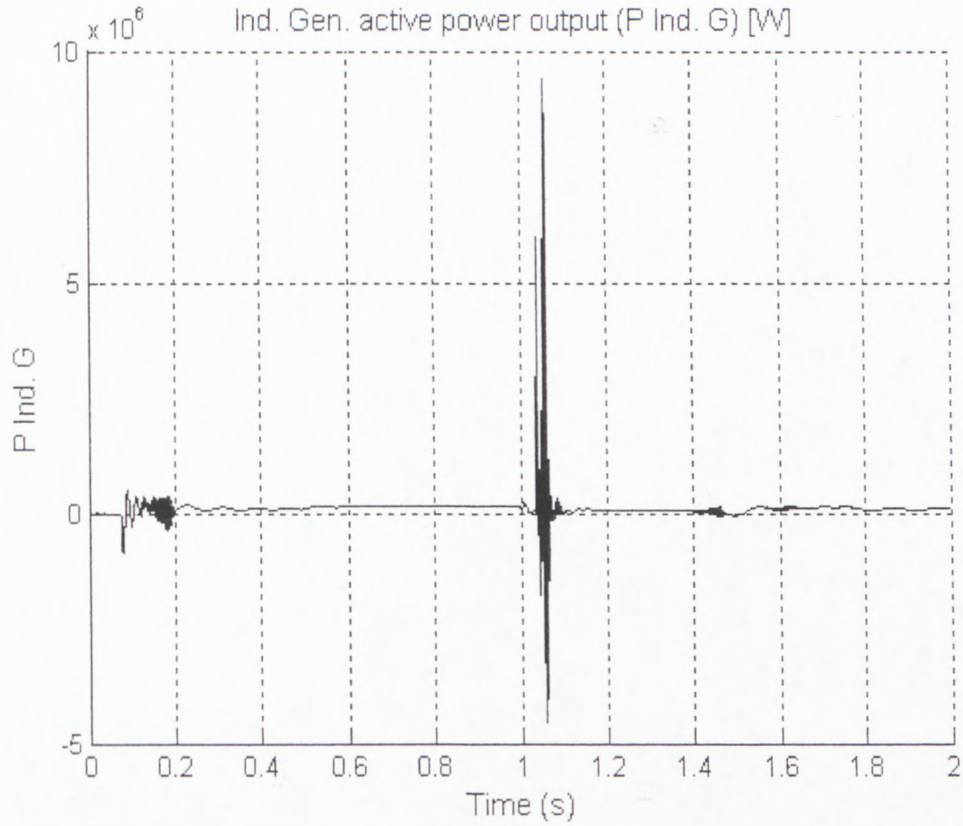


Figure 4.143: Inductive Generator Active Power Output

When the fault occurred, sharp drop in induction generator rotor speed is mainly attributed to the fact that the rotor of the induction generator followed that of synchronous generator since generation of active power by the induction generator did not cease instantly, but then induction generator rotor started to accelerate independently from synchronous as shown in Figure 4.144. After fault clearance as the induction generator once again absorbed reactive power and being driven by the turbine coupled to it, its rotor followed that of synchronous generator with all induction generator behaviour reaching a steady state speed just above synchronous generator rotor speed when comparing the induction generator rotor speed shown in Figure 4.144 with Figure 4.142 which shows synchronous generator rotor speed.

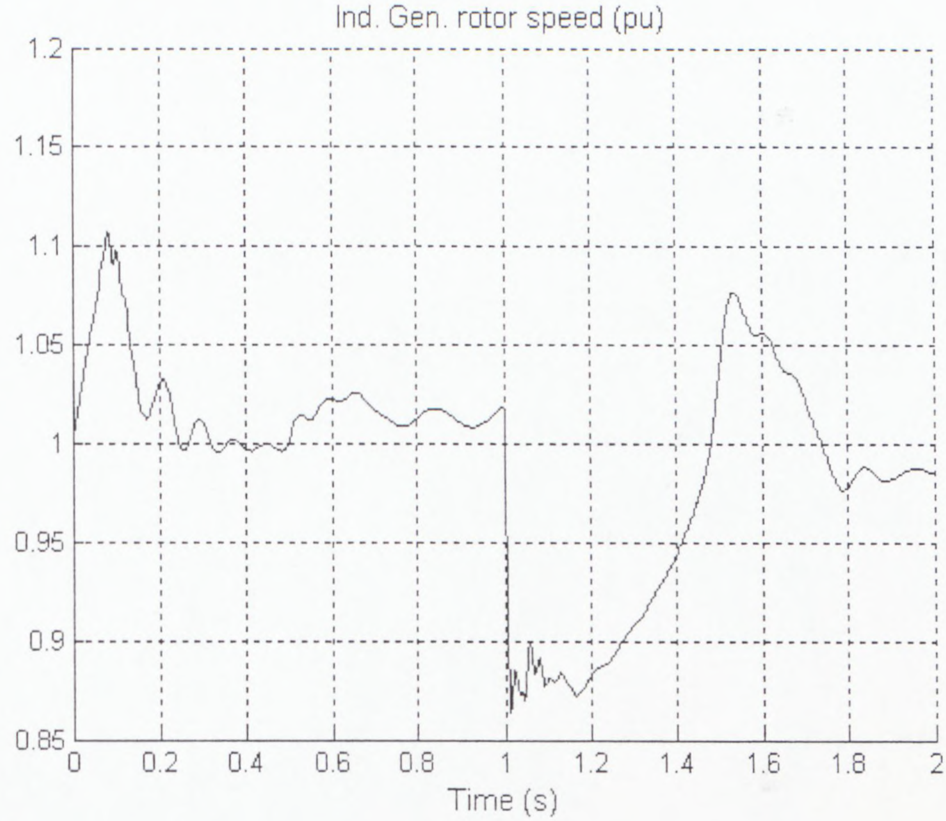


Figure 4.144: Induction Generator Rotor Speed

4.3.4 Rotor Speed for Effective Connection of Induction Generator

Induction generator when connected to an AC system and operated under a steady state condition runs with the negative slip which is proportional to its power output. But the moment when the generator is to be connected to the system, normally its rotor speed is much higher than it would have been to match with the power (torque) supplied by the driving turbine. Therefore, immediately after connection to the system the rotor speed drops according to Equation 2.104. In the proposed SHP similar phenomena had been observed whereby the connection of the induction generator resulted to energy exchange between the induction and synchronous generators in the plant causing some oscillations before reaching the steady state condition.

For assessment of effects of induction generator rotor during its connection on the performance of the proposed plant, simulations were done with different initial negative slip of induction generator rotor i.e. different rotor speed above the synchronous speed. The simulations were started with the plant operating in a steady state condition supplying an inductive load with 500 kW and 300 kvar from synchronous generator and (-j600 to j600) kvar SVC. Like in the previous cases the induction generator was brought into the system after two cycle of operation while the driving torque to the generator is 0.6 of its full load driving torque and increased to full load torque as load connected to the plant increases. The load to the plant was increased firstly by 50 kW and later by 40 kW to make the total active power demanded by the load to be 590 kW. Performance of the plant in each case was analysed so as to identify any changes that could be caused by connection of the induction generator into the system at different speed of its rotor.

From Equation 2.88 it is deduced that negative slip indicates extent at which the induction generator rotor speed is higher than synchronous speed at the beginning of simulation and since the rotor is continuously subjected to driving torque, which means by the time induction generator is connected into the system its rotor speed has further increased and the bigger the magnitude of initial slip the higher the rotor speed at the moment of connection as shown in Figure 4.145 to Figure 4.148. Immediately after the connection of induction generator into the system the speed of its rotor drops and after some oscillations assumes a steady state value at which slip is proportional to active power output of the induction generator.

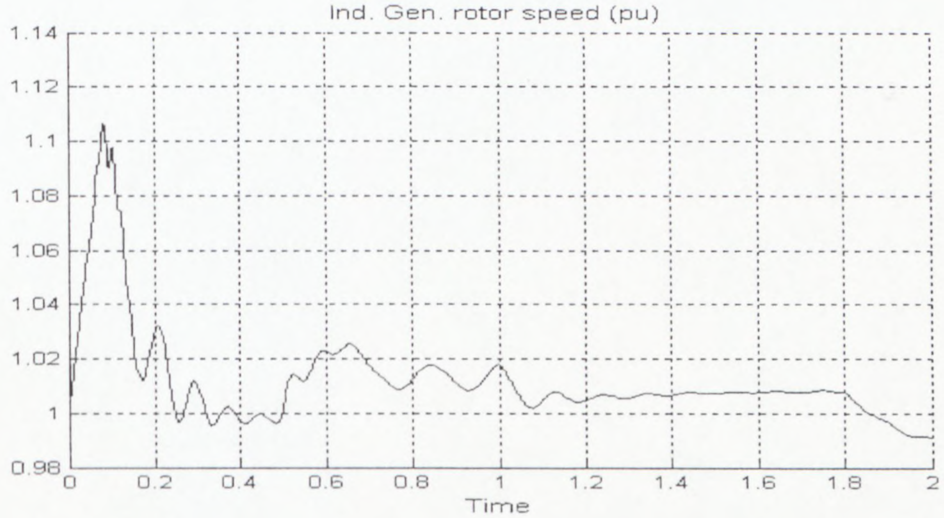


Figure 4.145: Induction Generator Rotor Speed When Initial Slip Set at -0.00001

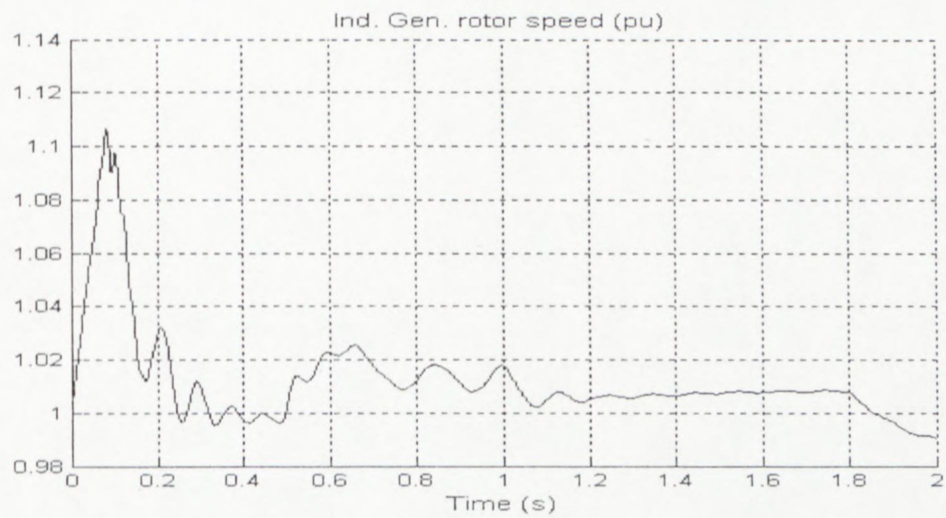


Figure 4.146: Induction Generator Rotor Speed When Initial Slip Set at -0.0001

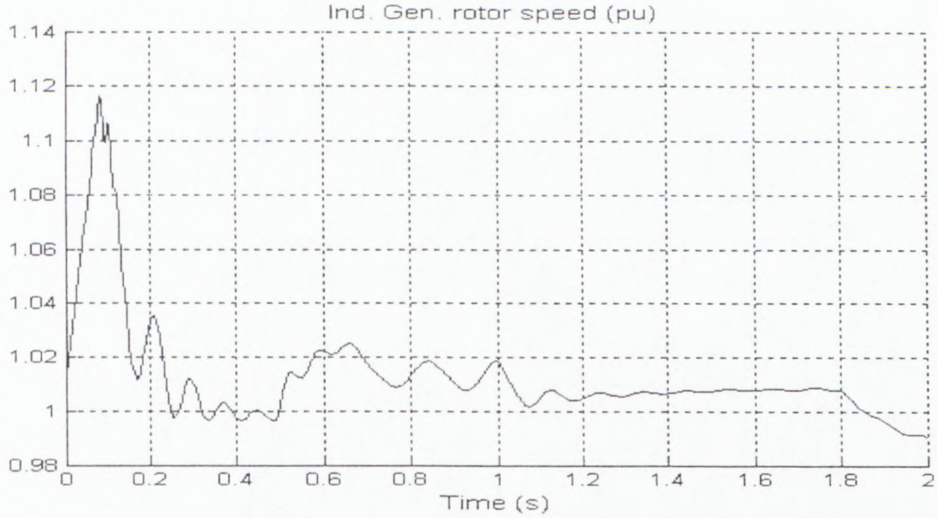


Figure 4.147: Induction Generator Rotor Speed When Initial Slip Set at -0.01

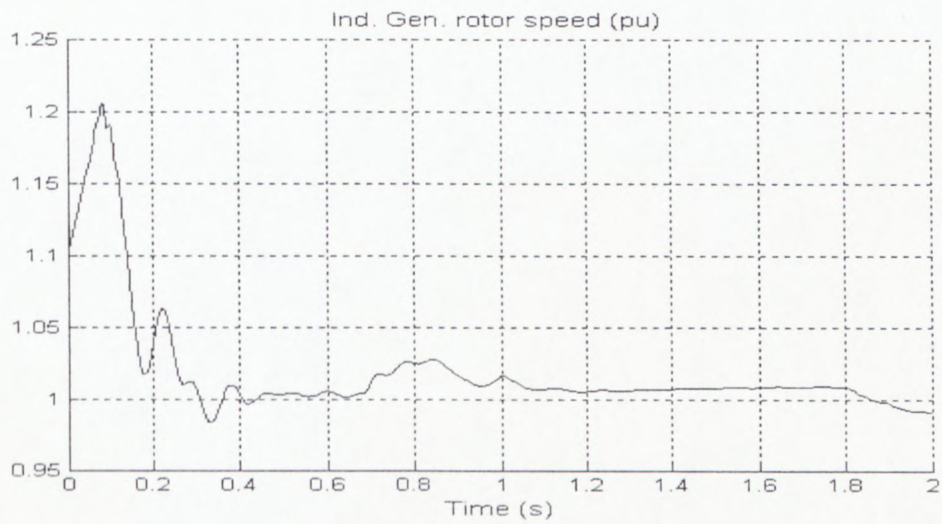


Figure 4.148: Induction Generator Rotor Speed When Initial Slip Set at -0.1

After connection of the generator into the system, the rotor of induction generator loses its speed at the same rate as speed it also gives up the kinetic energy attained due to inertia in a form of real power supplied to the connected load. The power released from induction generator rotor mass cause power surges in the power plant's power output and peak of the surges increase with increase of rotor speed at the connection moment or with increase in magnitude of initial slip of induction generator rotor. Resulting active power output of the power plant supplied to the connected load for simulations of the plant with initial slip of induction generator set at different values are presented in Figure 4.149 to Figure 4.152.

Looking at the active power output graphs bellow, it is observed that major effect of initial slip and as consequence the speed of induction generator rotor at the moment of generator's connection into the system on active (real) power output is the peak of the caused surges in active power output of the power plant which is found to be highest when the initial slip was (-

0.1) in Figure 4.152 which approaches 2000 kW as compared to 1600 kW when initial slip was (-0.00001) in Figure 4.149.

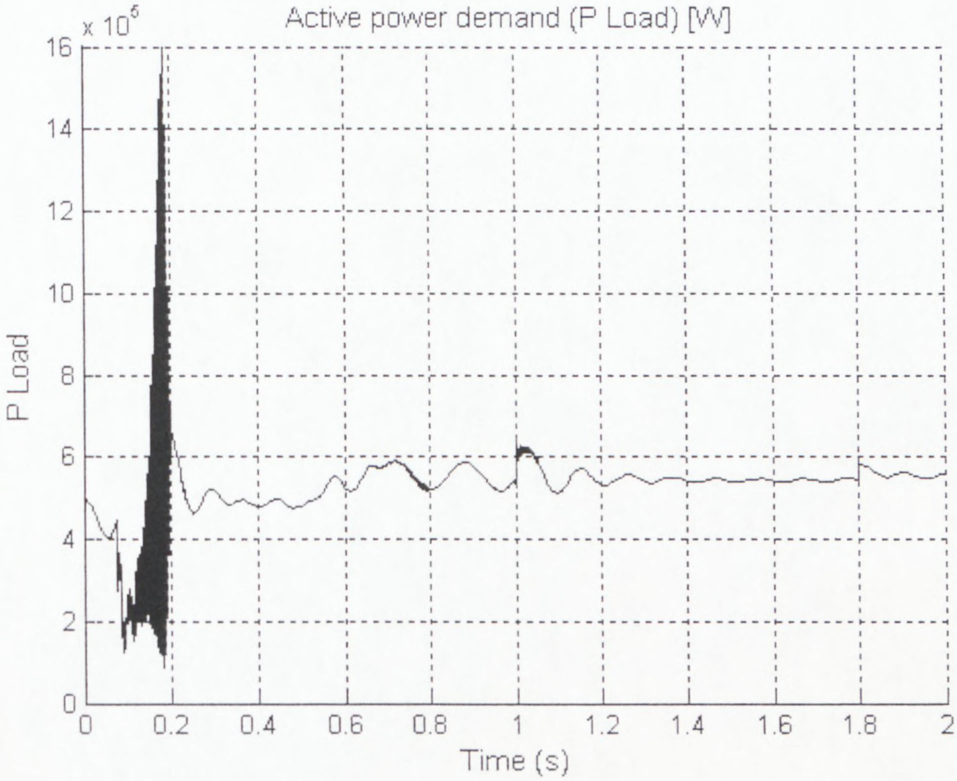


Figure 4.149: Active Power Output of the SHP When Initial Slip Set at -0.00001

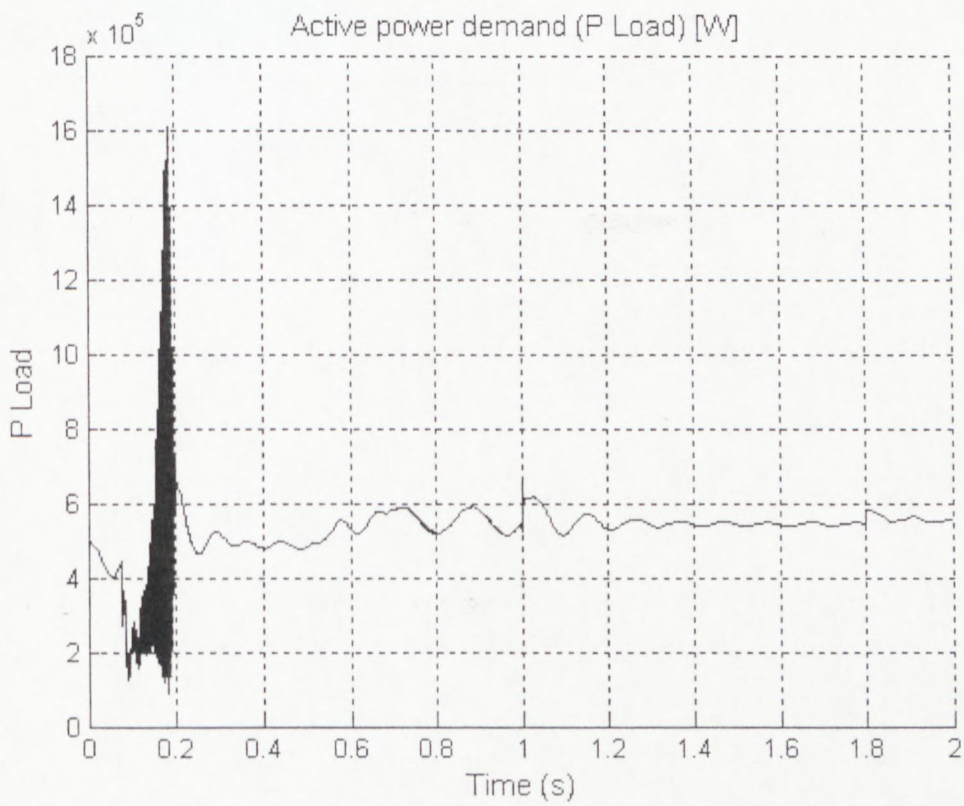


Figure 4.150: Active Power Output of the SHP When Initial Slip Set at -0.0001

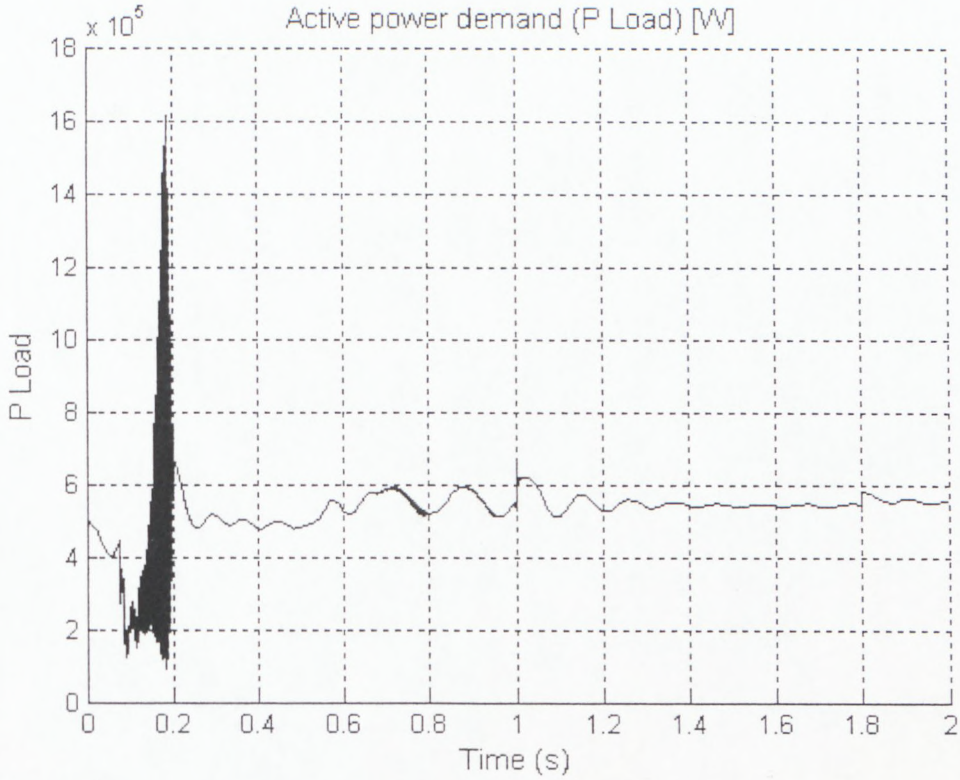


Figure 4.151: Active Power Output of the SHP When Initial Slip Set at -0.01

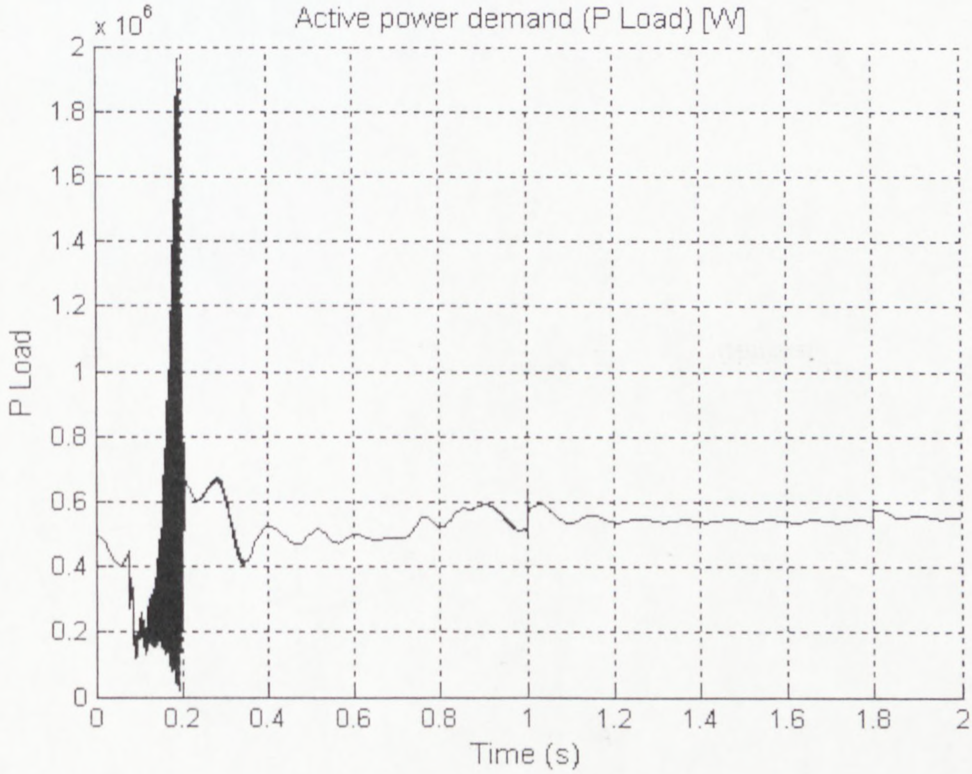


Figure 4.152: Active Power Output of the SHP When Initial Slip Set at -0.1

Figure 4.153 to Figure 4.156 displays behaviour of reactive power output of the power plant according to speed of induction generator rotor when the generator is connected into the system. Like in the case of active power, connection of induction generator into the system caused surges in reactive power output of the power plant however, it is noted from the graphs that impact of the rotor speed on peak of the reactive power surges is less than on active power surges.

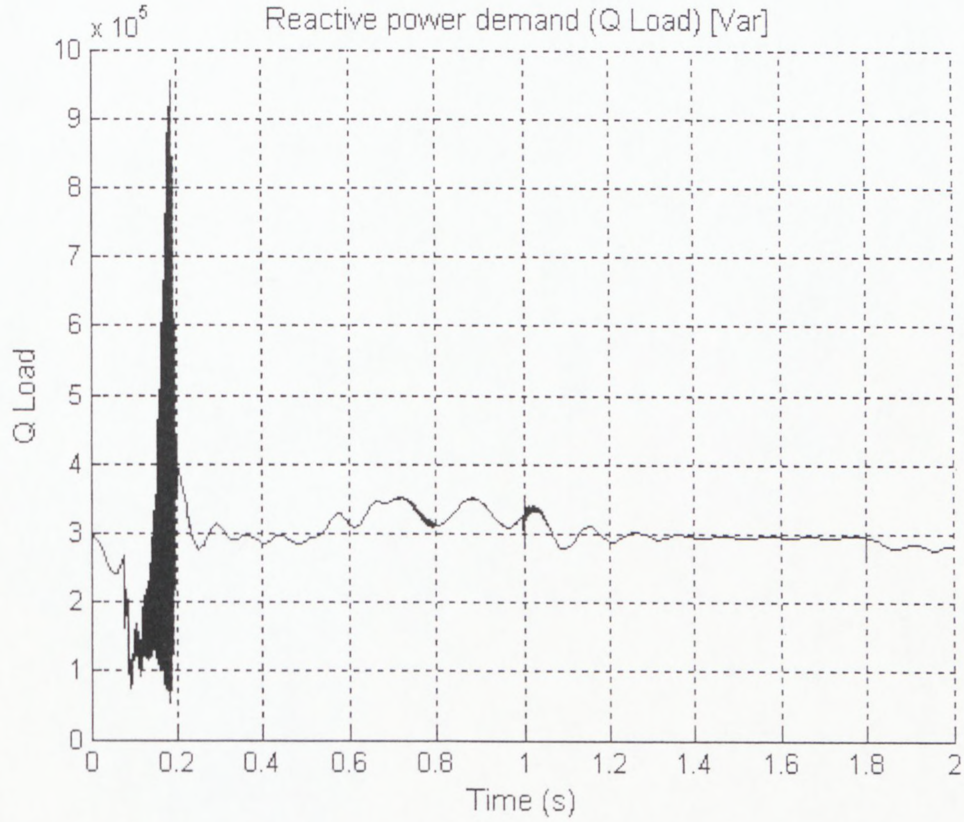


Figure 4.153: Reactive Power Output of the SHP When Initial Slip Set at -0.00001

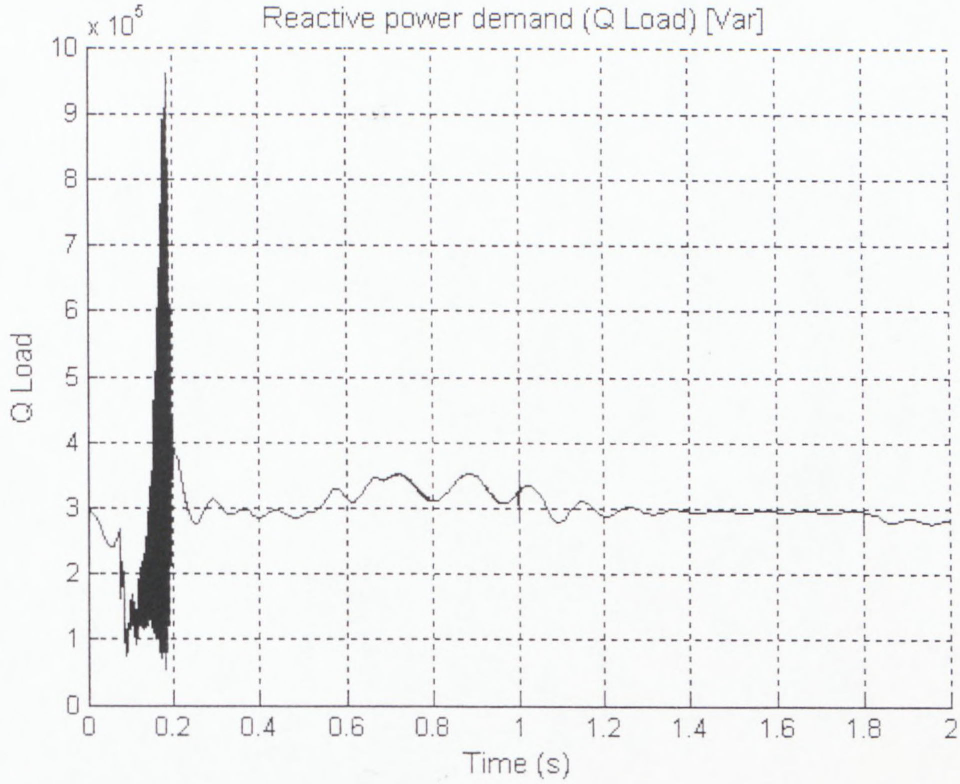


Figure 4.154: Reactive Power Output of the SHP When Initial Slip Set at -0.0001

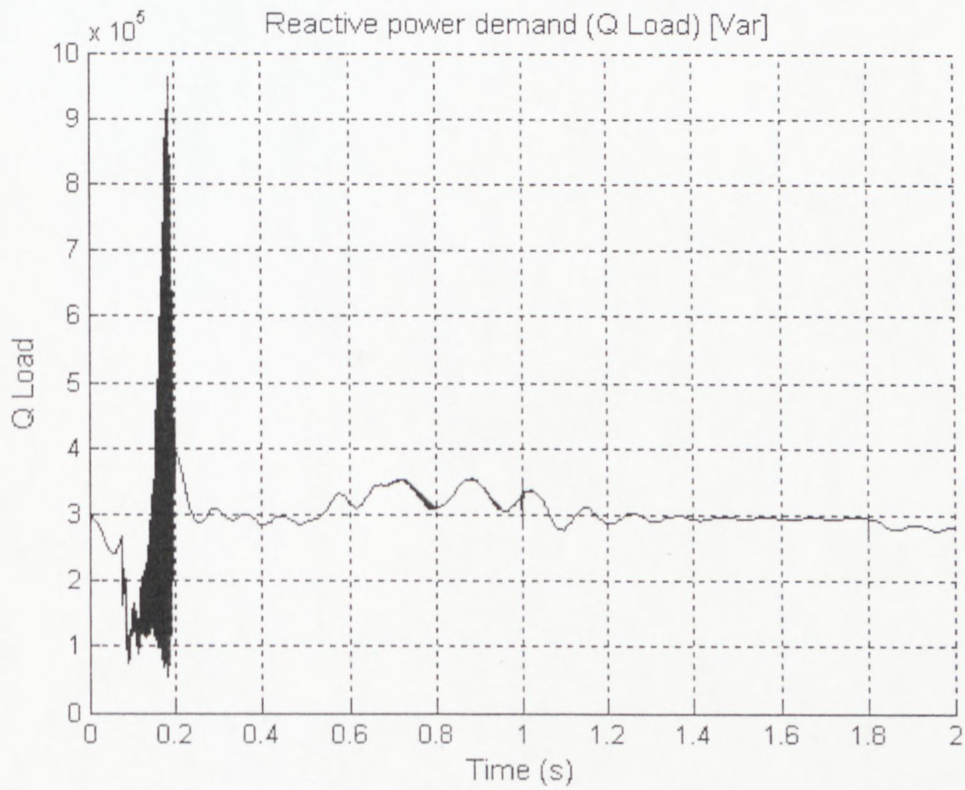


Figure 4.155: Reactive Power Output of the SHP When Initial Slip Set at -0.01

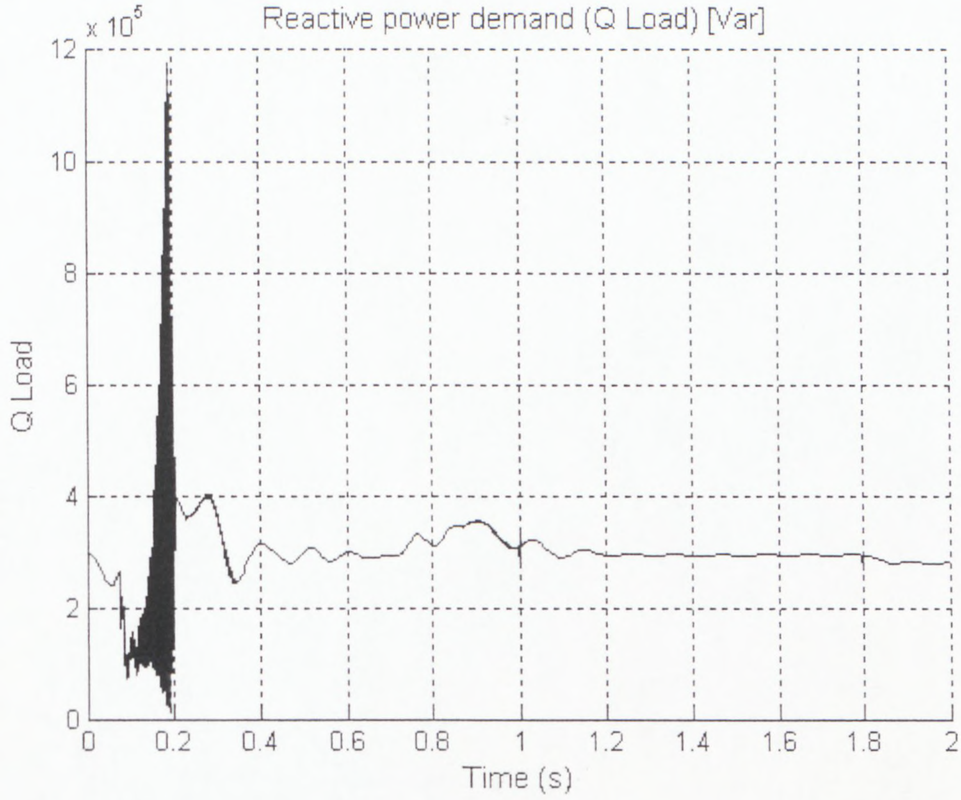


Figure 4.156: Reactive Power Output of the SHP When Initial Slip Set at -0.1

Active power output of the proposed power plant constitutes sum of power output of the synchronous generator and that of induction generator in the system but in summation attention should be paid to the meaning of sign attached to induction generator power output. Figure 4.157 to Figure 4.160 represents behaviour of active power output of the synchronous generator when the induction generator at different rotor speed is brought in parallel operation to it. The corresponding behaviour for the induction generator is depicted in Figure 4.161 to Figure 4.164. The negative sign for induction generator power output indicates power flowing from the induction generator to the connected load.

Variations of active power output of synchronous generator as shown in the graphs exhibit increase in peak value with increase of induction generator rotor speed at the moment of connection into the system. It can also be observed that induction generator on the hand do not show much changes in its active power output behaviour with increase in its rotor speed during inclusion into system. But the resultant power output of the plant includes corresponding effects of both machine installed in the plant.

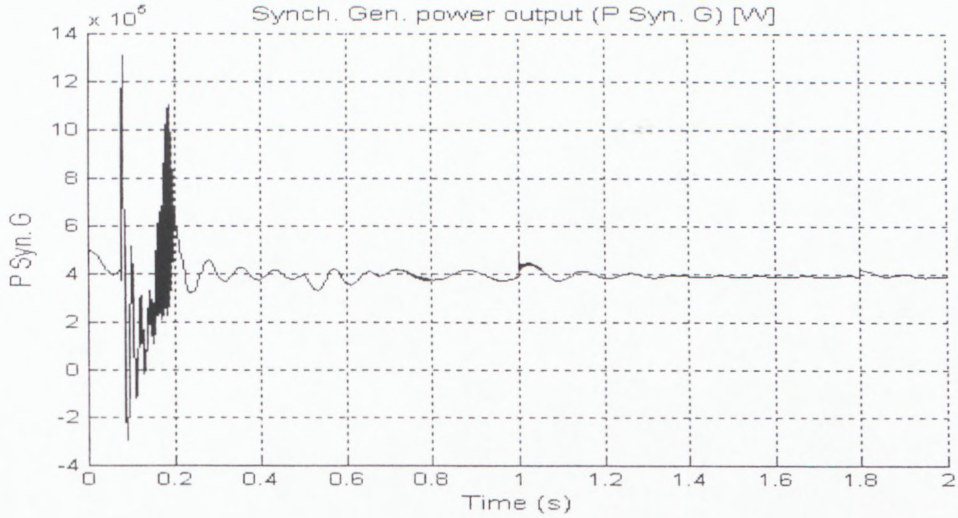


Figure 4.157: Synchronous Generator Power Output When Initial Slip Set at -0.00001

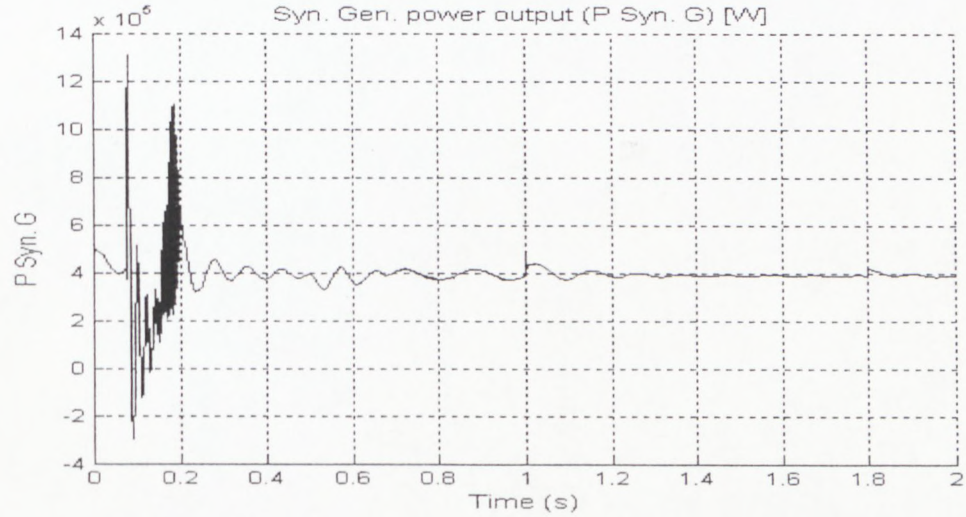


Figure 4.158: Synchronous Generator Power Output When Initial Slip Set at -0.0001

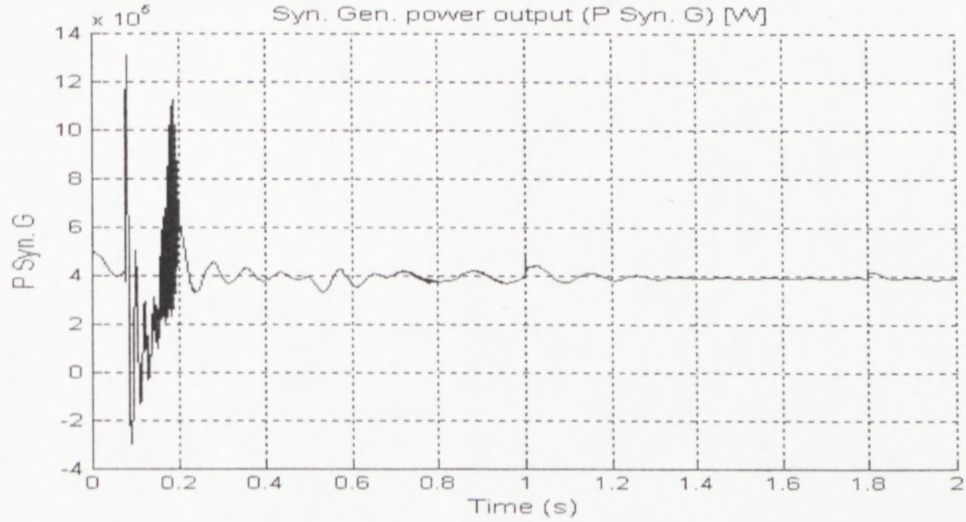


Figure 4.159: Synchronous Generator Power Output When Initial Slip Set at -0.01

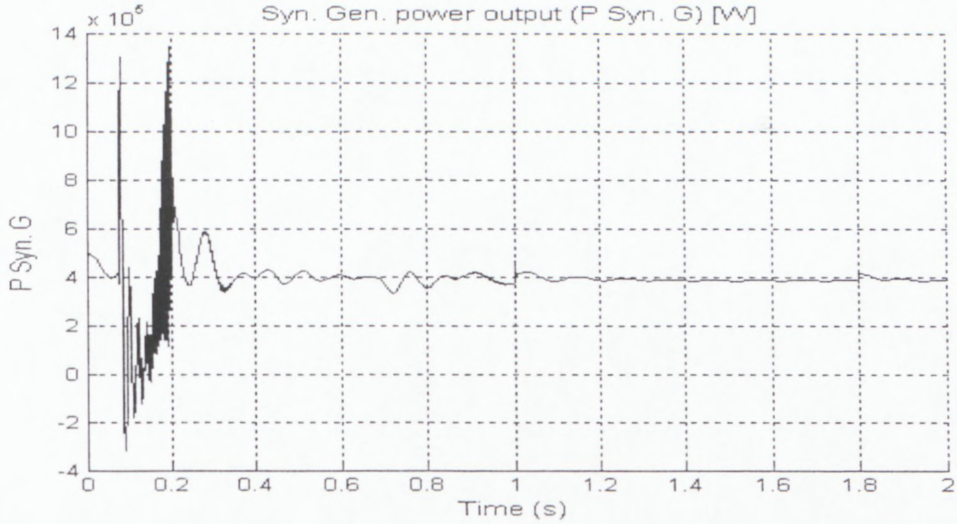


Figure 4.160: Synchronous Generator Power Output When Initial Slip Set at -0.1

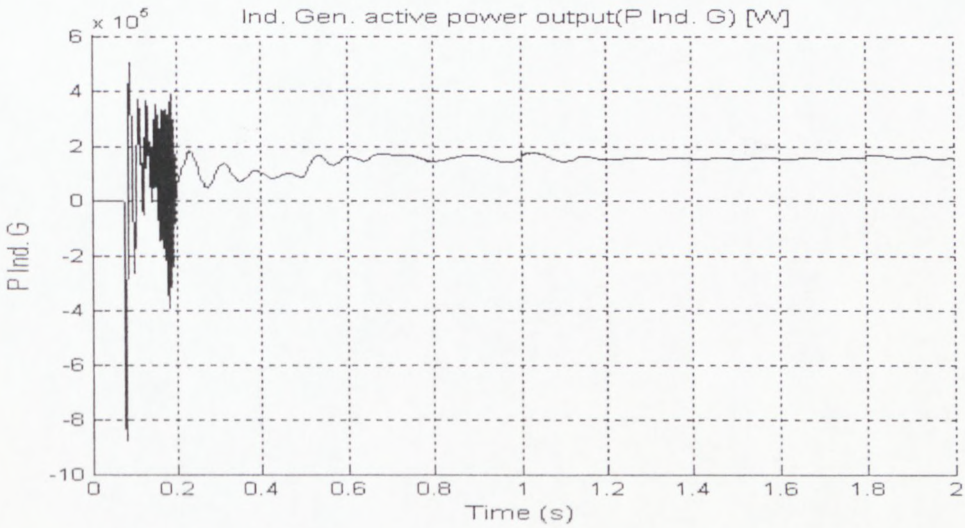


Figure 4.161: Induction Generator Active Power Output When Initial Slip Set at -0.00001

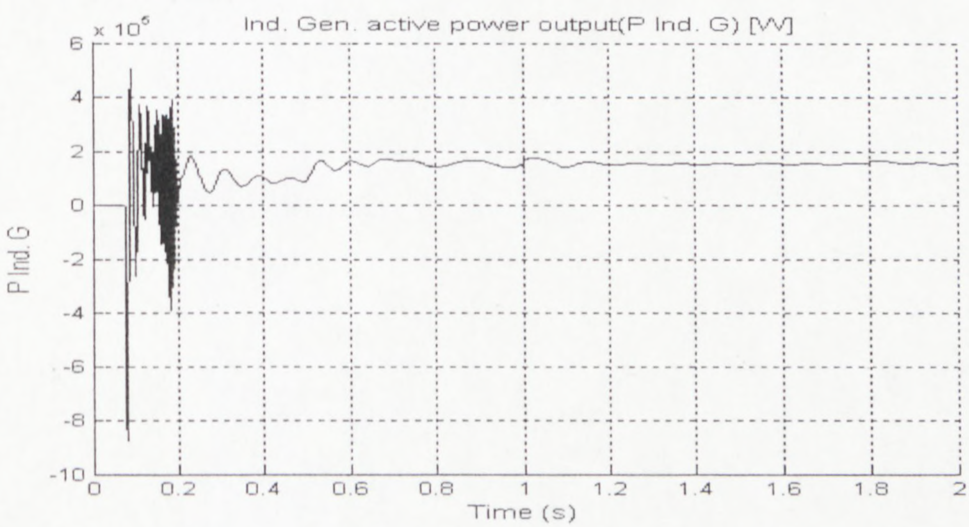


Figure 4.162: Induction Generator Active Power Output When Initial Slip Set at -0.0001

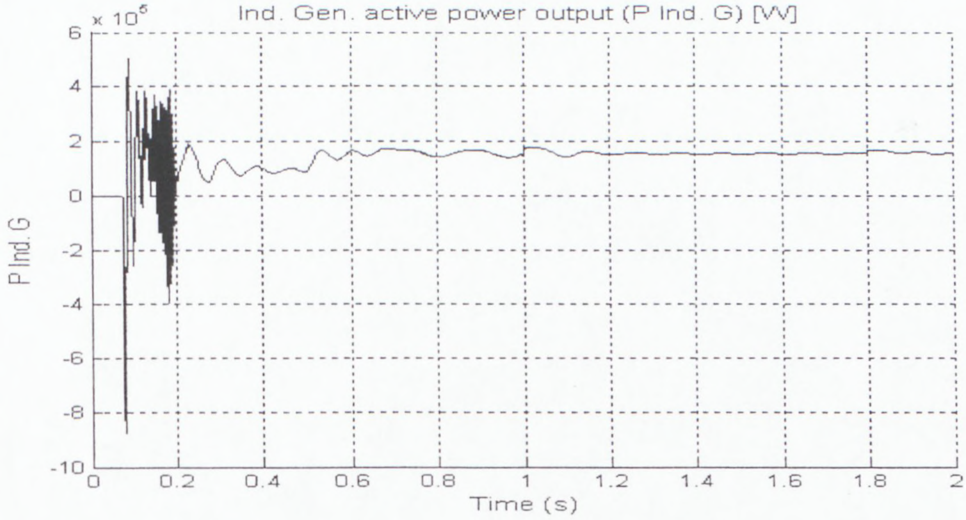


Figure 4.163: Induction Generator Active Power Output When Initial Slip Set at -0.01

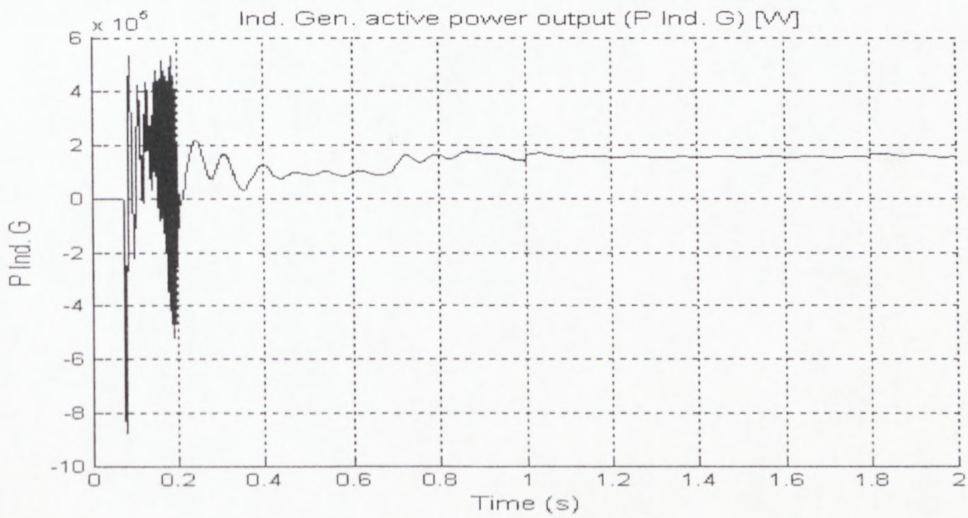


Figure 4.164: Induction Generator Active Power Output When Initial Slip Set at -0.1

Operation of power relay depends upon the settings and power output of the plant supplied to the connected load in order to actuate increase in active power output of induction generator (Figure 4.165 to Figure 4.168).

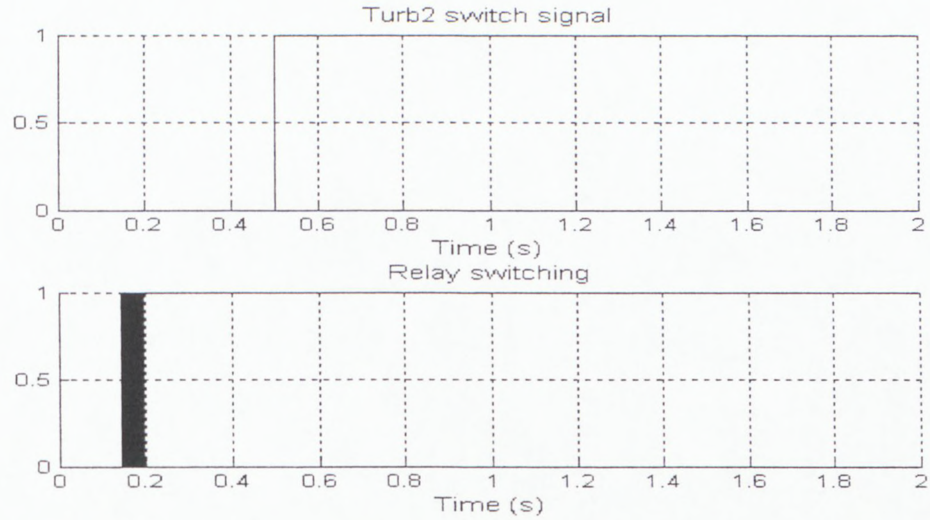


Figure 4.165: Power Relay Operation Signals When Initial Slip Set at -0.00001

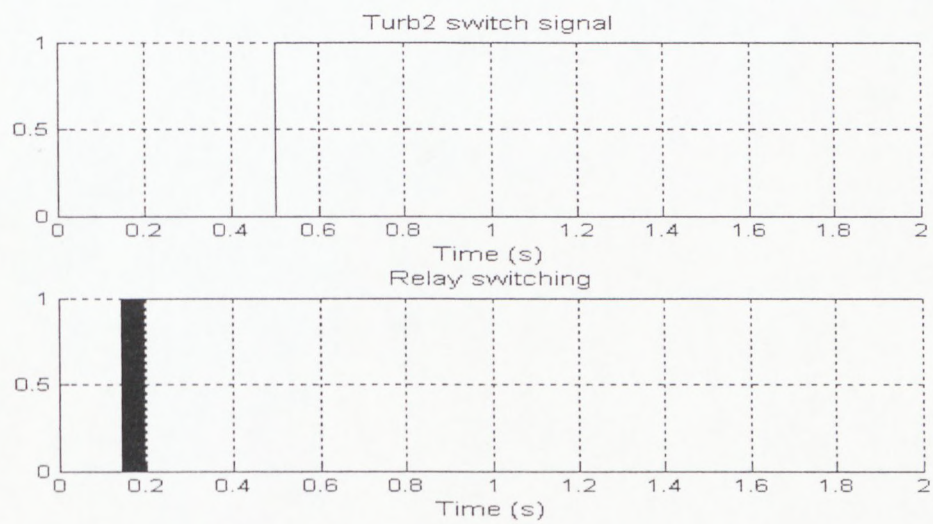


Figure 4.166: Power Relay Operation Signals When Initial Slip Set at -0.0001

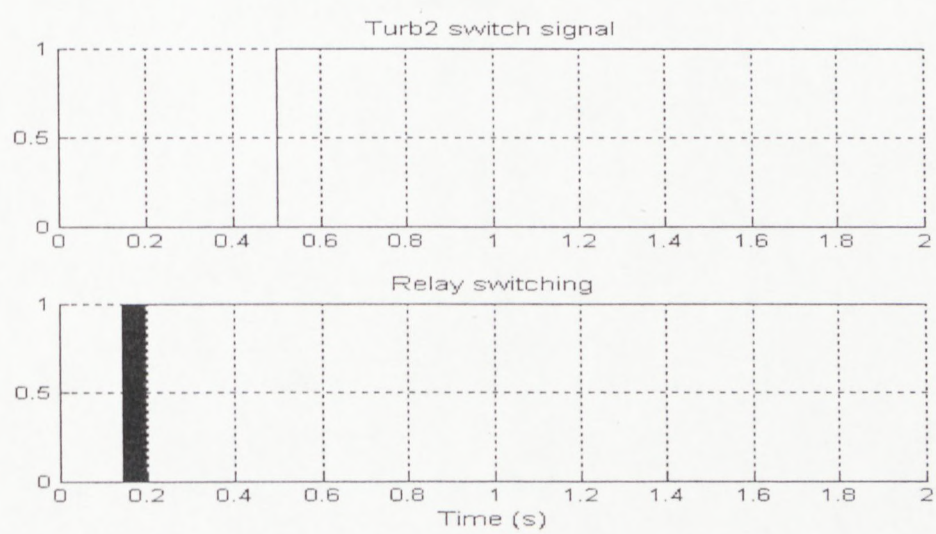


Figure 4.167: Power Relay Operation Signals When Initial Slip Set at -0.01

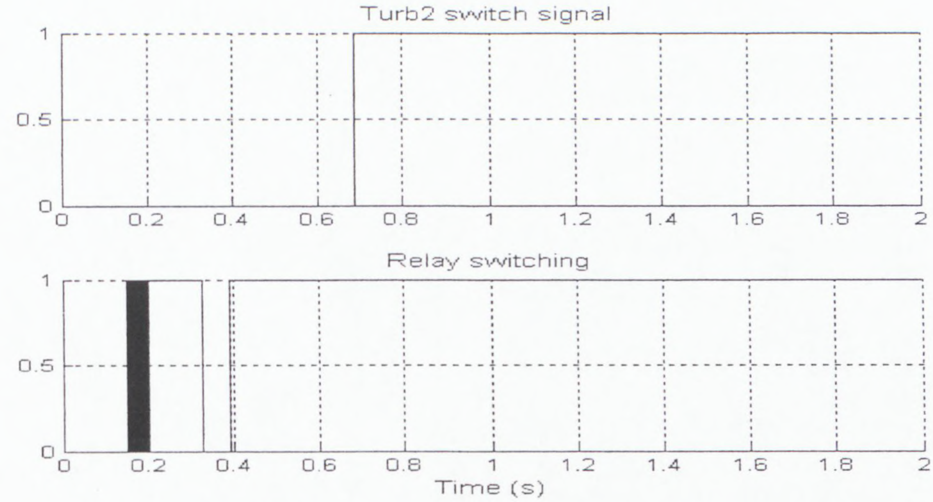


Figure 4.168: Power Relay Operation Signals When Initial Slip Set at -0.1

The behaviour of the synchronous generator in the plant with regard to its reactive power output (Figure 4.169 to Figure 4.172) and that of the SVC as shown in Figure 4.173 to Figure 4.176 is based efforts of the equipment to maintain the generator bus voltage by supplying the system with the required amount of reactive power. So when the generator supply excess reactive power, SVC operate in inductive mode and absorb the surplus reactive power but when there is deficit in the supplied reactive power SVC operate in capacitive mode to supplement the reactive power supply. As a result the generator bus voltage is regulated as shown in Figure 4.177 to Figure 4.180. In this case the influence of induction generator rotor speed at the moment of connection is not observed.

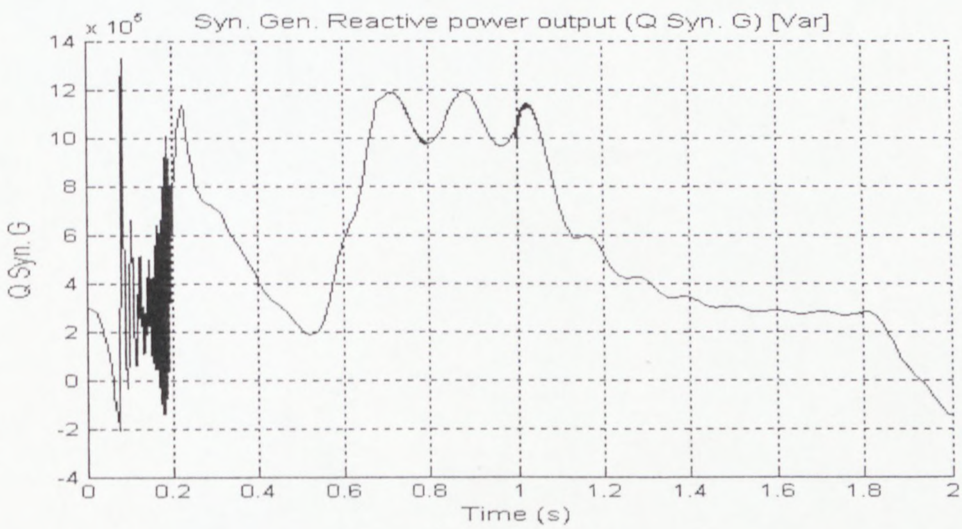


Figure 4.169: Synchronous Generator Reactive Power Output When Initial Slip Set at -0.00001

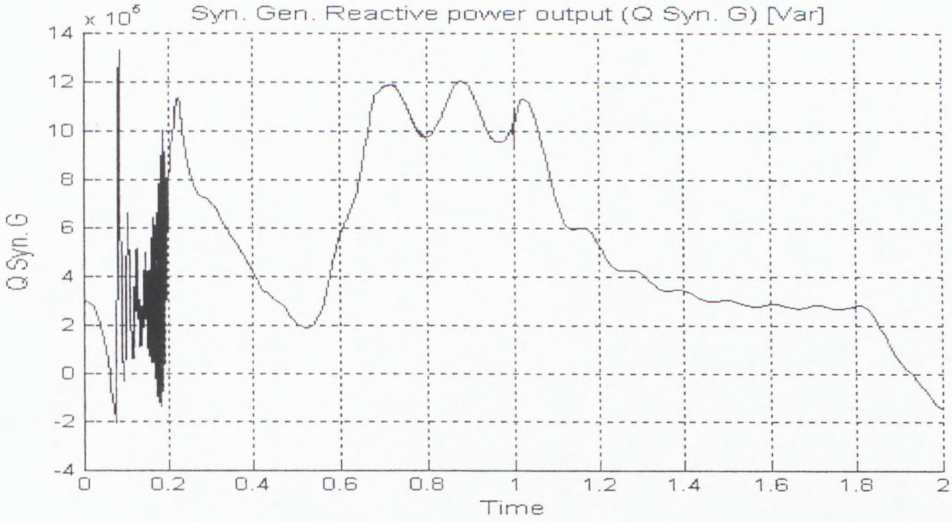


Figure 4.170: Synchronous Generator Reactive Power Output When Initial Slip Set at -0.0001

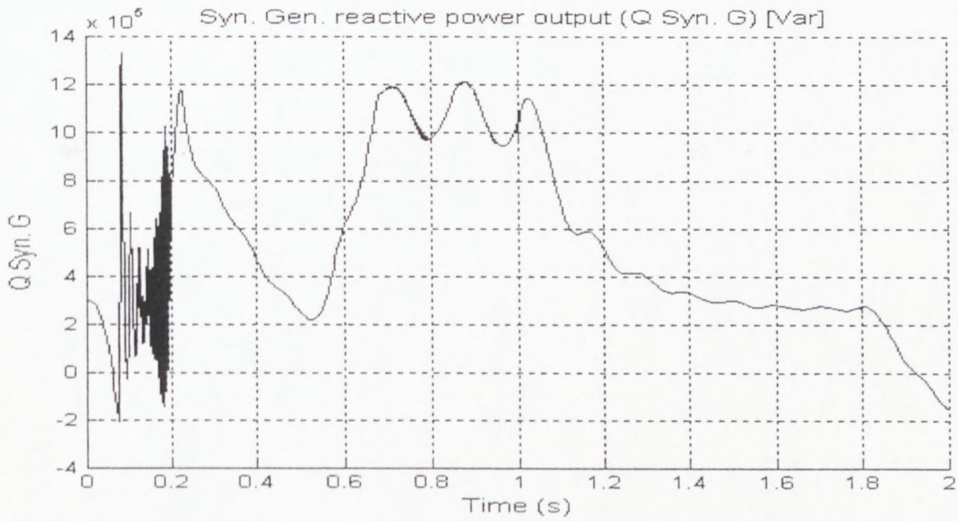


Figure 4.171: Synchronous Generator Reactive Power Output When Initial Slip Set at -0.01

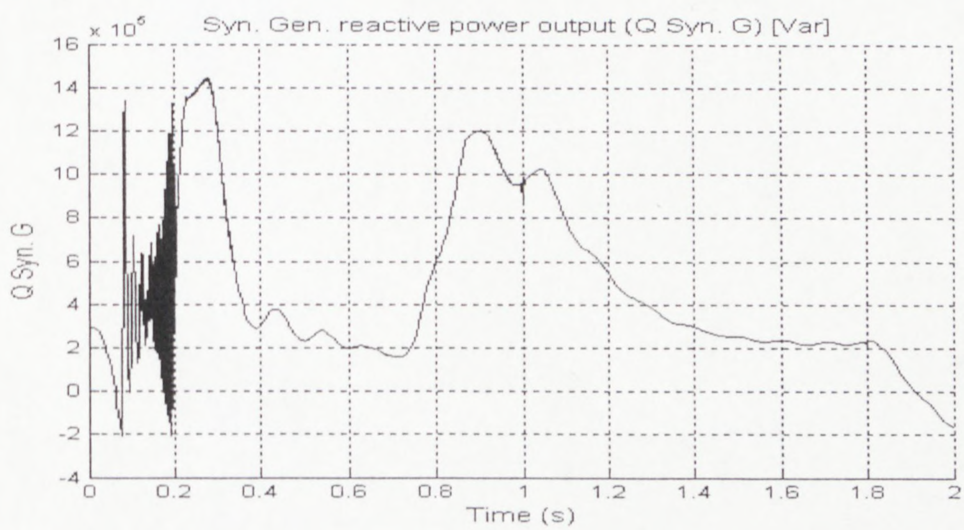


Figure 4.172: Synchronous Generator Reactive Power Output When Initial Slip Set at -0.1

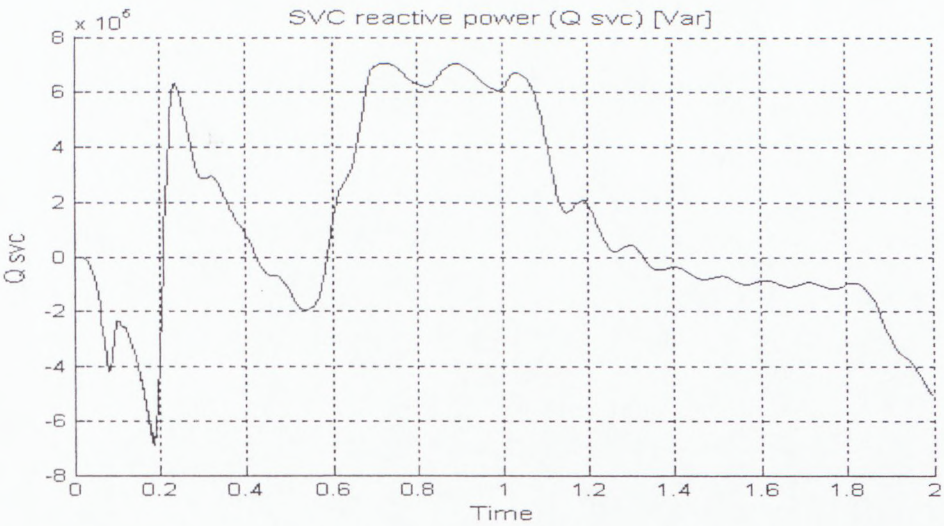


Figure 4.173: SVC Reactive Power Output When Initial Slip Set at -0.00001

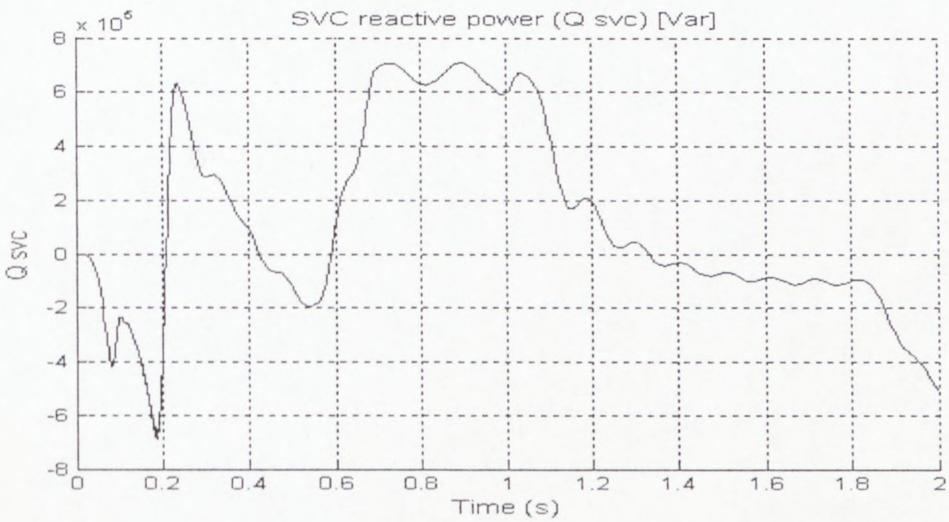


Figure 4.174: SVC Reactive Power Output When Initial Slip Set at -0.0001

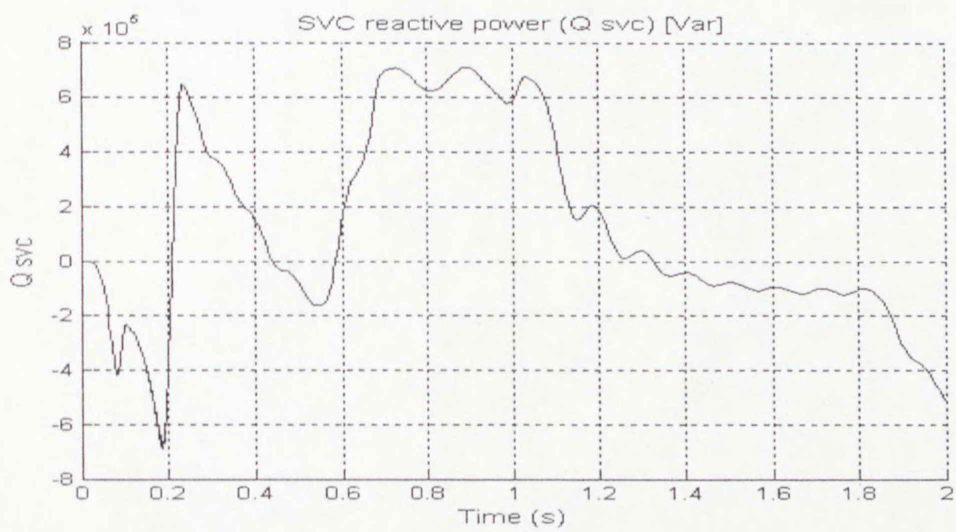


Figure 4.175: SVC Reactive Power Output When Initial Slip Set at -0.01

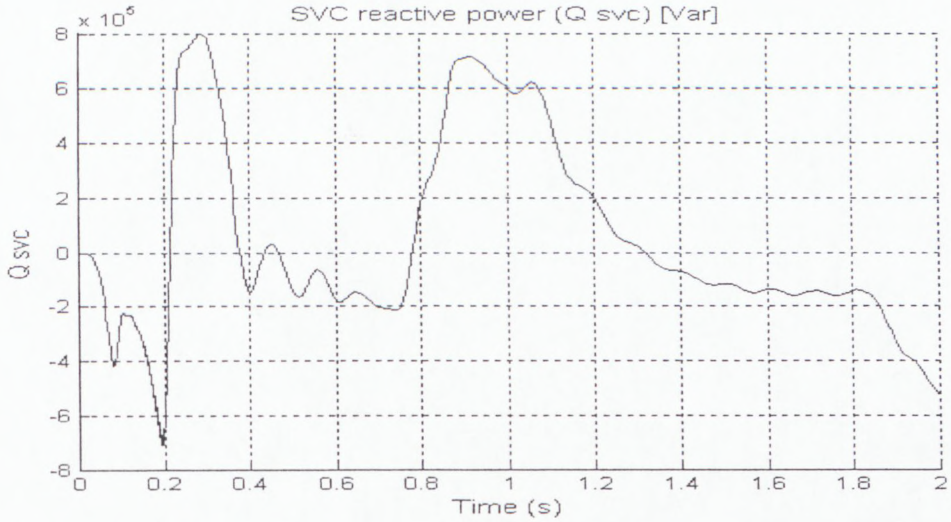


Figure 4.176: SVC Reactive Power Output When Initial Slip Set at -0.1

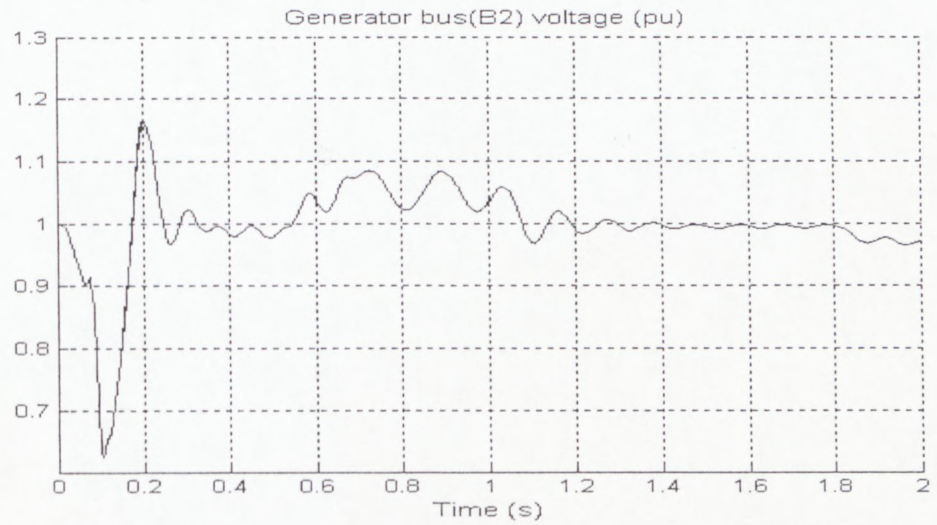


Figure 4.177: Generator Bus Voltage When Initial Slip Set at -0.00001

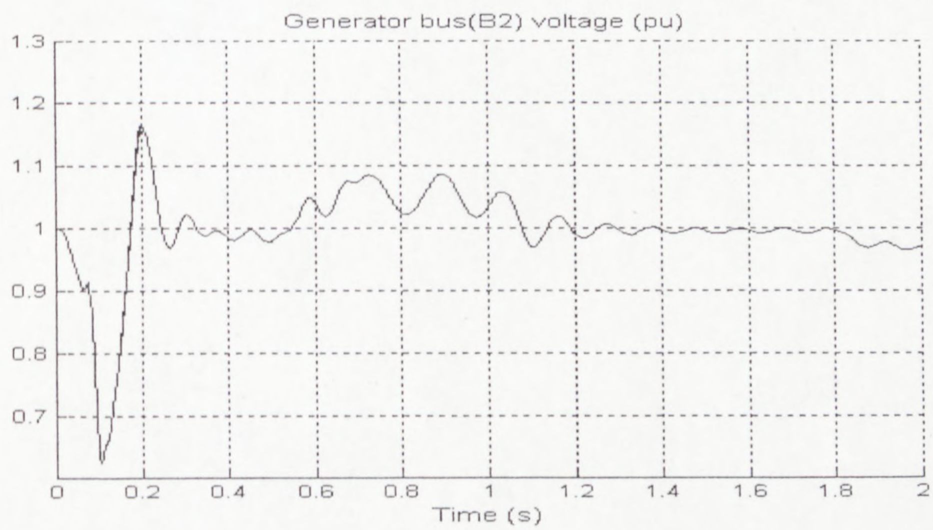


Figure 4.178: Generator Bus Voltage When Initial Slip Set at -0.0001

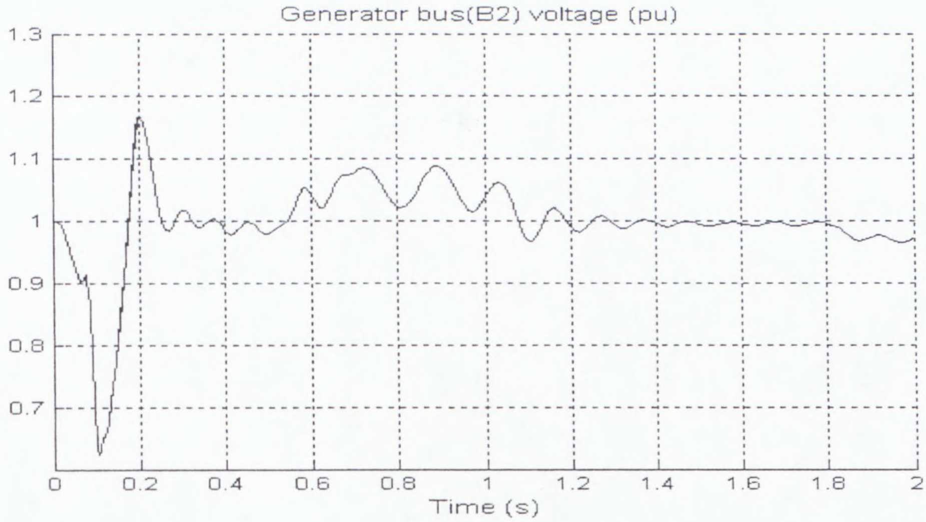


Figure 4.179: Generator Bus Voltage When Initial Slip Set at -0.01

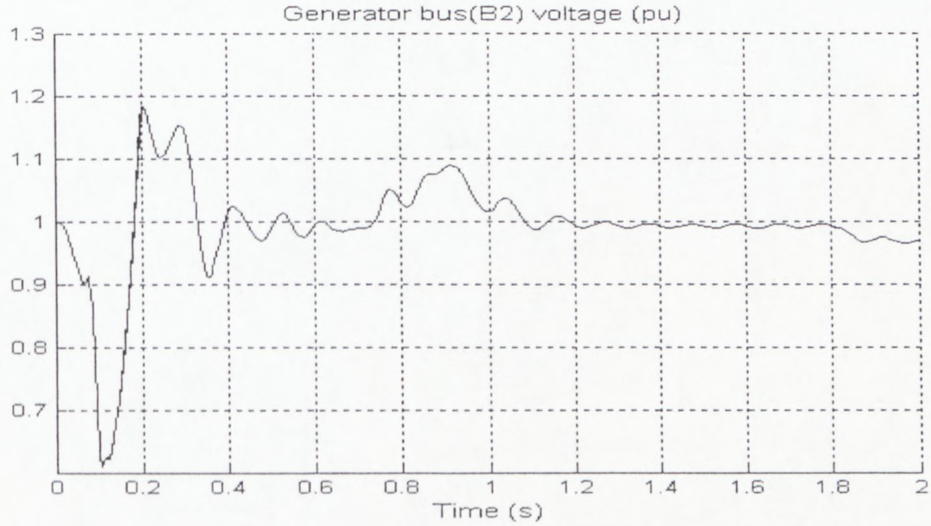


Figure 4.180: Generator Bus Voltage When Initial Slip Set at -0.1

Figure 4.181 to Figure 4.184 shows reactive power absorption induction generator when connected to the generator bus with different rotor speed. The graphs exhibit almost similar reactive power absorption behaviour regardless of the rotor speed at which the machine is connected into the system.

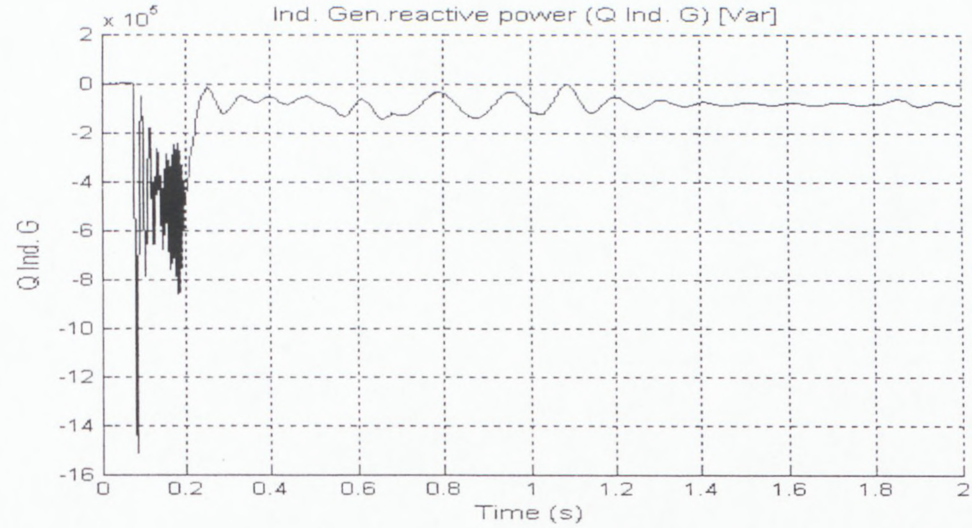


Figure 4.181: Induction Generator Reactive Power When Initial Slip Set at -0.00001

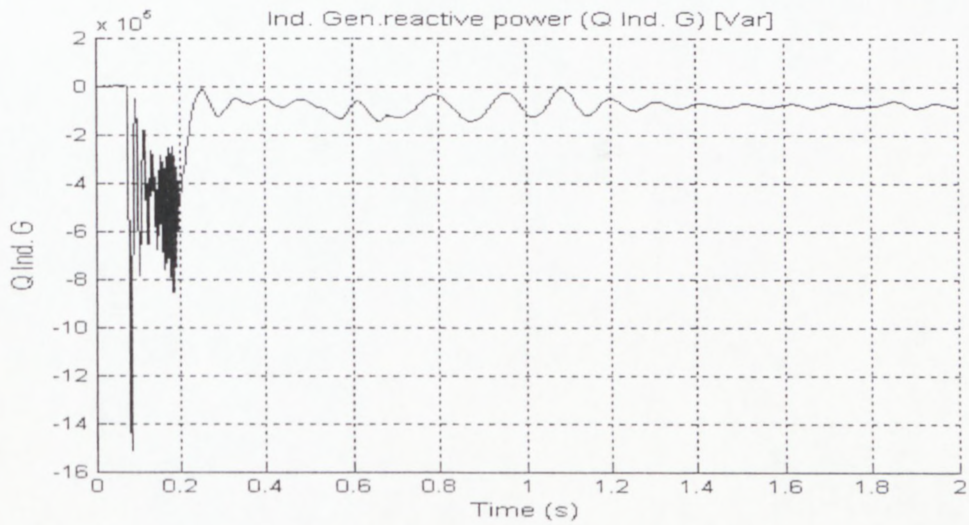


Figure 4.182: Induction Generator Reactive Power When Initial Slip Set at -0.0001

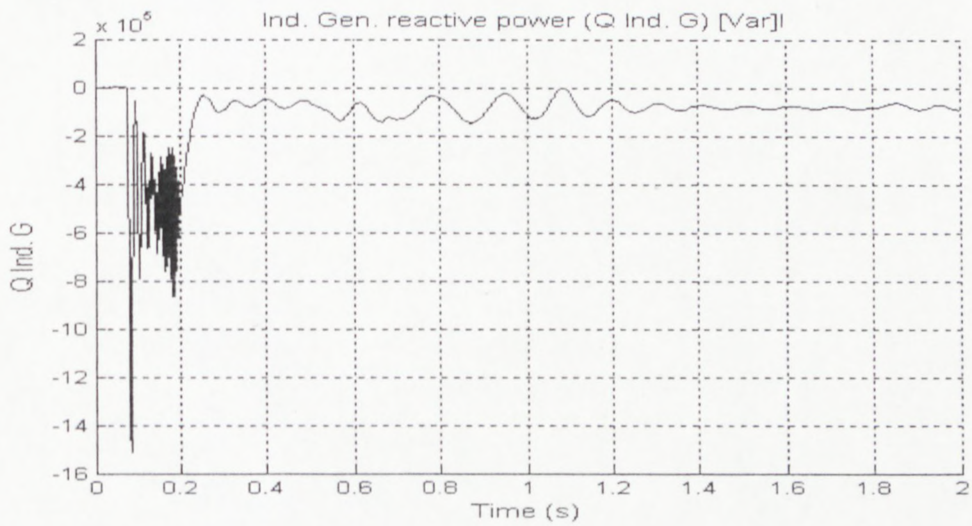


Figure 4.183: Induction Generator Reactive Power When Initial Slip Set at -0.01

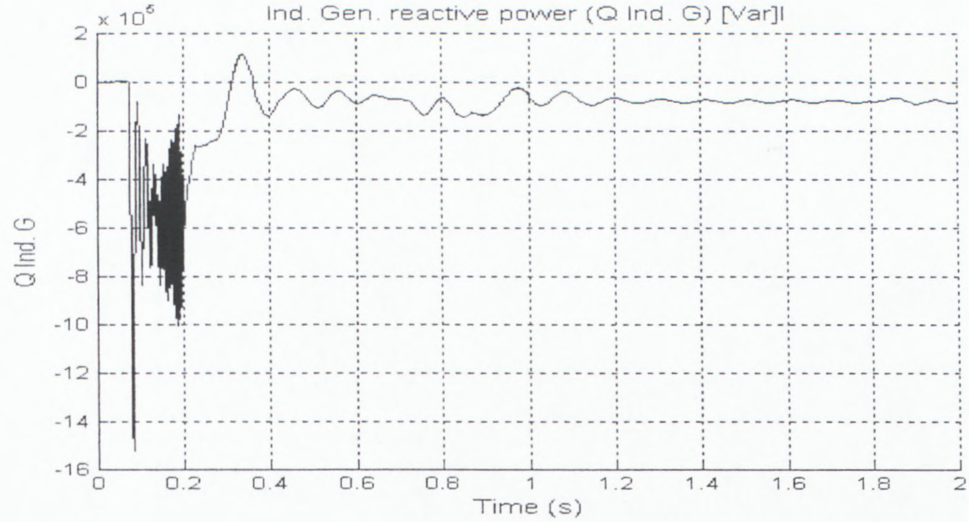


Figure 4.184: Induction Generator Reactive Power When Initial Slip Set at -0.1

Speed oscillations of the rotor of synchronous generator as depicted in Figure 4.185 to Figure 4.188 indicate increase of peak value as the speed of the induction generator at the moment of connection of induction generator into the system. This is attributed to the fact that when induction generator rotor loses its speed as an effect of connection, it also inject power into the system proportional to rate the speed reduction (rate of change of rotor kinetic energy) resulting to reduction of load to synchronous generator due power balance principle. Reduction of load to synchronous generator led to acceleration of the synchronous generator rotor until torques acting on the rotor balances then it starts to decelerate. These processes continue until steady state speed which is also the generation frequency is reached.

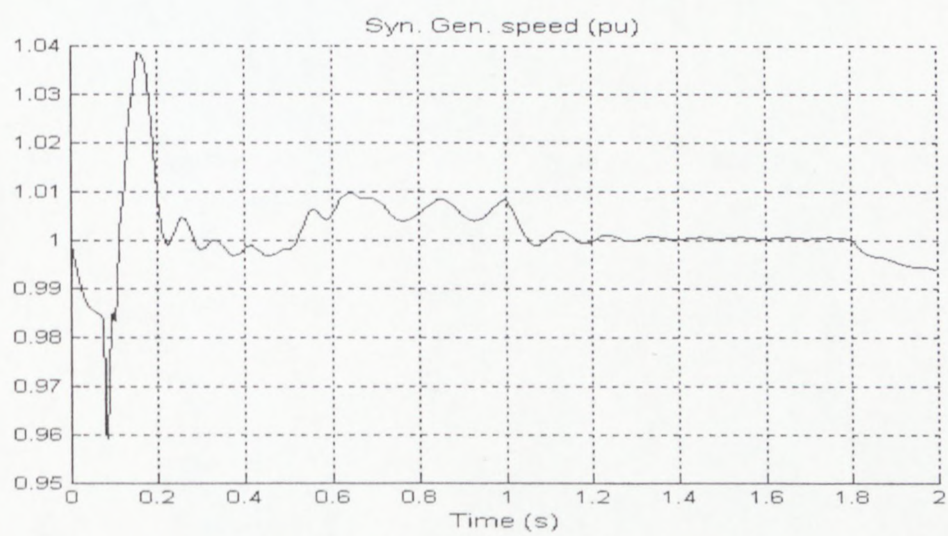


Figure 4.185: Synchronous Generator Rotor Speed When Initial Slip Set at -0.00001

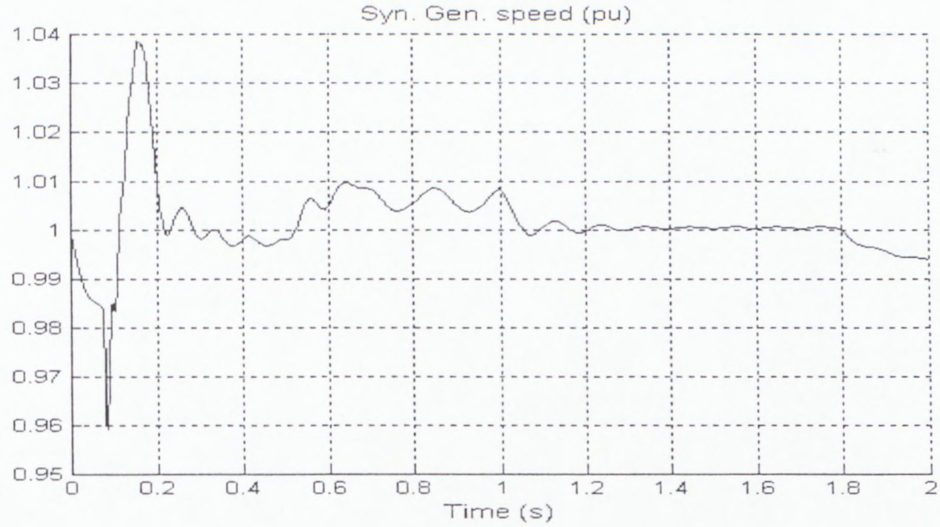


Figure 4.186: Synchronous Generator Rotor Speed When Initial Slip Set at -0.0001

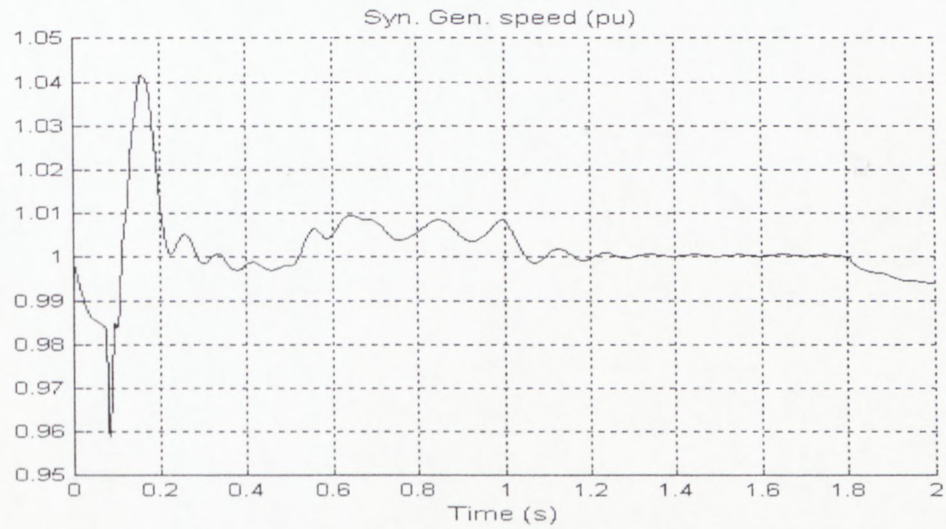


Figure 4.187: Synchronous Generator Rotor Speed When Initial Slip Set at -0.01

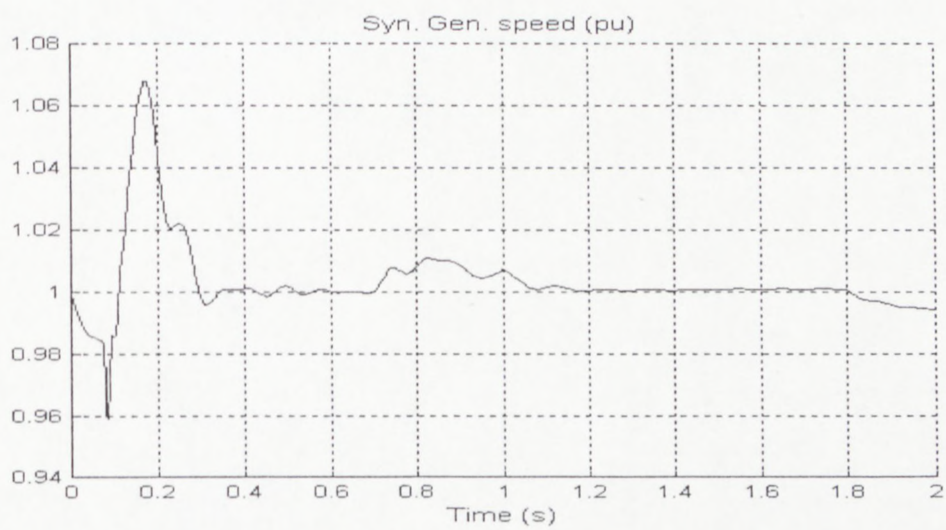


Figure 4.188: Synchronous Generator Rotor Speed When Initial Slip Set at -0.1

4.4 Conclusions

Hydropower plants including small ones employ hydraulic turbines as prime movers whose selection in type and capacity is dictated by conditions of the site where they are to be installed. Nevertheless, their function as sources of mechanical power/torque for driving electric generators even their control strategies can be treated in a generic manner.

In the proposed SHP, control strategy for the turbine which drives synchronous generator is to regulate the rotor speed/frequency and the power output. The turbine model available in MATLAB/Simulink software is capable of performing both functions needed to satisfy the control strategy. On the other hand, for the turbine driving induction generator the control strategy is to step-wise regulate its mechanical power output or mechanical torque which is driving the coupled induction generator. Therefore, for this purpose switching mechanism that switches the driving torque from one value to the other was used to simulate change of turbine's mechanical power output/driving torque.

The proposed SHP has two generating units installed; one consists of a hydraulic turbine and synchronous generator while the second one is composed of a hydraulic turbine coupled to an induction generator. Each turbine is interfaced with applicable control system. Incorporated with, for reactive power generation is a Static Var Compensator whose reactive power generated supplements that generated by synchronous generator in meeting the reactive power requirements of the induction generator and that of the load connected to the power plant.

Using the physical modelling option available in MATLAB/Simulink software, the proposed small hydropower plant modelled and simulated. The conducted simulations were aimed to establish the technical viability of the plant which mainly entails interactions between the synchronous and induction generator installed in the plant during operation of the power plant, small signal and transient stability of the synchronous generator and speed stability of the induction generator installed.

Simulation of the proposed power plant supplying a constant load with initially only synchronous generator in operation then joined by induction generator later has shown, that after transient period the power output of the synchronous generator dropped by amount of power equivalent to output of the induction generator i.e. the induction generator relieved the synchronous generator from load by the amount of power it injected into the system. It was observed, that further increase in induction generator power output, brought about reduction in the loading of synchronous generator. At the same time frequency of power generated and voltage at the generator bus was maintained within permissible values. Therefore, when supplied with sufficient reactive power for its excitation, induction generator can effectively generate active power proportional to driving mechanical power delivered by the coupled prime mover hence taking load from the parallel operating synchronous generator without affecting the supply to load connected to the plant.

Adding on load to the proposed plant with both synchronous and induction generators in operation has been found not to cause any operational problems. Simulations of the model revealed, that the proposed small hydropower plant is stable to small signal disturbance. In its operation, power relay monitored power supplied to the connected load and it reached a value that warrant increase in induction generator contribution to active power supplied to the load, the servomotor control system activated further opening of the gate to the respective turbine resulting to the required change in induction generator's power output. Hence induction generator action allows the synchronous generator to have capability of meeting any further load demand that might occur. So when additional load was switched on synchronous generator increased its output then as the power detects the power supplied to the load required increase of induction generator it instruct so as a result load to synchronous generator falls and the process continues until the plant is loaded to its capacity. Again simulations showed, that system frequency and generator bus voltage were kept with acceptable limits. In this way the propose power plant is capable of successfully responding to normal load changes.

Simulation of a three-phase fault at the generator bus showed that in occurrence of the fault there is momentarily drop of generator bus voltage, speed of synchronous generator rotor which is also power frequency in the system, speed of the induction generator rotor and the power output of the plant but then rotors of both generators started to accelerate. The fault was cleared two cycles after its occurrence yet the generators' rotors continued to accelerate for a while and then decelerated after some oscillations both rotors attained steady state speed. It was observed that immediately after the fault occurrence rotor of the induction generator followed that of the synchronous generator but thereafter behaved independently for some time even after fault clearance then again it followed the synchronous generator rotor until both reached their steady state speeds. The generator bus voltage went through fluctuations after the clearance of the fault before reaching a steady state value as well. Power supplied to the connected load was restored after the fault had been cleared. However, it was also observed that the moment the fault had occurred mechanical power output of the turbine driving induction generator dropped to its set minimum value i.e. 0.6 of full load value as power relay responded to the drop of power output of the plant caused by the fault. Therefore, it is obvious that with appropriate settings power relay can be used for protection of the induction generator by shutting down the turbine to which is coupled in case of fault on the generator bus. The simulation showed the generators in the proposed power plant can maintain steady operation conditions if a fault on the system is cleared before critical clearing time for the synchronous generator and before critical speed for the induction generator. But since the generators in the plant operate in parallel, the critical clearing time of fault in the plant should be whichever is smaller between that for synchronous generator and the one for induction generator.

Simulation of the plant operation with different initial negative slip of the induction generator's rotor was intended to establish effects of the rotor speed at the moment the induction generator is connected to the system. It was observed that as connection of induction generator into the system takes place when speed of rotor of the generator is much higher than synchronous speed and it has to drop to a level that corresponds to power output of the generator which is also proportional to the power supplied by the prime mover. In the process the rotor gives up its kinetic energy to the system and cause power surges whose peak show direct proportional characteristic to the rotor speed at the moment of connection. However, the steady state behaviour of the plant power output seemed not to be affected by the initial rotor speed provided it is lower than critical speed. Therefore for minimisation of power surges in the system it is recommended to connect the induction generator into the system when magnitude of native slip of its rotor is as small as permissible.

CHAPTER FIVE

Conclusions and Recommendations

5.1 Conclusions

Small hydro potential in Tanzania is estimated to be around 314 MW spread in different parts of the country mainly in remote rural areas which are yet to be electrified. Employing small hydro in distributed electricity generation can facilitate electrification of rural communities surrounding small hydro potentials at a far less cost than by using a traditional approach of extending the existing grid. On contrary to this, small hydropower was partially abandoned not only in Tanzania but all over the world despite of being most clean and reliable among renewable energy sources. This was due to availability of more competitive large hydro schemes and the then cheap fossil fuel powered power plants. However, the ever escalating oil prices and environmental concerns have made small hydro to become an attractive energy source again hence researches on their effective development are being carried including this one.

Amongst the aspects of small hydropower that are being researched upon is cost reduction in up-front capital investment and small hydropower plant operation. Looking at capital investment in small hydropower plants electro-mechanical equipment constitutes between 30 to 40 percent of the total investment while the remaining part is investment on civil engineering works. But on maintenance costs, civil engineering works have negligible contribution meaning the costs are mainly for maintenance of electro-mechanical equipment. In this regard, selection of type of electromechanical equipment for a particular site has a bearing on both up-front capital investment and maintenance costs of a respective plant.

This research proposed a novel small hydropower plant that employs two generating units of which, one consists of a hydraulic turbine and synchronous generator and the other consists of a hydraulic turbine coupled to an induction generator. In addition, conventional governors for regulating the turbines are replaced with electric servomotors with their applicable control systems. Due to its simplicity and rugged construction induction generator is cheaper than synchronous generator. Also currently in the market, electric servomotors and their control systems are available for all range of power and they have shown that they can effectively replace the much expensive and sophisticated conventional governors. These measures were implemented in this research work and showed the potential of reducing both capital investment and maintenance costs of electro-mechanical equipment without much effect normal performance of the small hydropower plant.

In principle, for the induction generator machine to operate as a generator, one of its requirements is to be supplied with reactive power that is capable of varying with the loading of the generator for excitation purposes, in this study supply of that reactive power is effected by FACTS element namely Static Var Compensator connected to the generator bus. Other shortcomings inherent to induction generators are difficulty in controlling their terminal voltage and frequency of the generated power. In the proposed small hydropower plant, generator bus voltage is determined by the synchronous generator operating in parallel to the induction generator through its field excitation system incorporated in automatic voltage regulator (AVR), however, its regulation involves the action of SVC connected to the generator bus at the same time the frequency of power generated is determined by the synchronous generator and its regulation depends on the action of load-frequency control system of the synchronous generator.

Application of conventional governor for load-frequency control in small hydropower plants had been proved to contribute in making generation cost of small hydropower plants comparatively higher because its cost do not decrease proportionally with the size of the to which it is applied. Main reasons for the observation are sophistication and complexity of conventional governors. Electronic load controller (ELC) was developed as an attempt of replacing conventional governor in small hydropower plant, but limitation of used dump load capacity in terms of amount of excess energy that can be dissipated and method of dissipation made ELCs to be used only in micro hydro power plants.

In the proposed small hydropower plant, power output of induction generator was regulated by using new approach by employing power relay which monitors the power output of the plant and activates action of servo control system that actuates the interfaced servomotor to regulate gate opening of the respective turbine. Load-frequency control system for the synchronous generator involved tacho-generator as transducer that translate speed of the generator rotor into electric signal which was then compared to reference signal based on the error signal servo control system actuated servomotor to make corresponding adjustment of gate opening of the turbine coupled to the synchronous generator. Therefore, the proposed power plant without employing conventional governor could still cope effectively with load connected to it provided the changes of the said load were small and also the ultimate load had not exceeded the capacity of the power plant. Novelty of the proposed SHP bases on possibilities of implementing low cost plant in terms of both investment and operation costs.

Model of the proposed small hydropower plant was implemented on MATLAB/Simulink using physical modelling approach. The approach enabled assembling of the plant using the available models of machines, switchgears and electric elements in Simulink. The modelled plant included a normal hydraulic turbine coupled to synchronous generator, the turbine driving induction generator was represented by a system that give step changing mechanical power/torque output. An SVC was included as source of reactive power needed by the induction generator as well as by inductive loads connected to the plant modelled in load blocks. Switching of generator and loads into the electrical system of the proposed small hydropower plant model was done through circuit breaker blocks. Measurements of all quantities were sent to scopes to plot characteristic graphs. The power plant model has been able to simulate operational behaviour of the proposed power plant.

Simulations of the proposed power plant were conducted in order to establish technical viability of the new type of small hydropower plant which is anticipated to be of low cost as compared to the ones implemented using the current existing practices. The simulations were classified as to:

- Demonstrate interaction between the parallel operated synchronous generator and induction generator during operation of the power plant.
- Prove stability of the plant to changes of load that normally take place in operation of any power system. In other words, to verify small signal stability of the plant.
- Determine whether the plant can sustain fault and continue with normal operation after the fault has been cleared or transient stability of the synchronous generator and speed stability of the induction generator.
- Find out effects of speed induction generator rotor at the moment of connecting the generator into the system to performance of the power plant.

Simulation of the plants started at a steady state condition whereby in the power plant only synchronous generator was operating supplying a fixed inductive load with both active and reactive power. Connected to the generator bus also was SVC which contributed to reactive power generation so as to maintain voltage at the bus. Initial slip of induction generator rotor was -0.001 while the induction generator was connected into the system two cycles after simulation had started implying connection of induction generator when the system is at steady state. For demonstration of interaction between the generators in the power plant, two situations were simulated first when the power output of induction generator was maintained at 0.6 of its full load capacity and in the second case the output of the induction generator was initially made to be 0.6 then increased to its full load capacity. It was observed, that as the induction generator was brought into the system supplying 0.6 of its full load power output, while the power delivered to the connected load almost remained constant the active power output of the synchronous generator dropped in magnitude equal to that supplied by the induction generator. When power output of induction generator was increased by increasing the driving torque to its full load capacity, the active power output of the synchronous generator dropped further in magnitude equal to the increment of induction generator's power output. This showed that when both generators are in operation, change of induction generator power output leads to change of active power output of synchronous generator without affecting output of the plant that is supplied to the load connected to the plant. This feature was successfully used to manage the load sharing between the generators through which power relay monitoring the output of the plant was set to detect the magnitude of power when contribution of induction generator should be adjusted.

The proposed small hydropower plant was verified whether it could cope with changes in power demanded by the connected load. Like in the previous cases, for this purpose simulation was initialised at steady state condition and the induction generator was connected into the system two cycles after the start supplying 0.6 of its full load power output. Then load to the plant was increased first by 50 kW and after a while it was increased further by 40 kW. As the load to the plant was increased, when active power supplied to the load reached 530 kW, power relay activated the increase of power output of induction generator to its full load output capacity according to the settings of the power relay. All the time when there was changes in load change of induction generator power output, they were accompanied by transients before a new steady state condition was reached. The plant demonstrated stability to normal changes in loading.

Ascertaining that the proposed power plant would continue with normal operation after fault clearance required simulation of most severe fault the plant could sustain. For this, a three-phase fault at generator bus was simulated in order to assess transient stability of the synchronous generator and speed stability of the induction generator. The fault was simulated to occur and being cleared within a two cycles duration. It was observed, that at the moment when the fault was sustained, power output of the plant dipped to zero and speed of rotors of the generators, synchronous generator rotor and induction generator rotor dropped instantly and then each rotor started to accelerate independently for some time even after the fault had been cleared. But afterwards the rotor of induction generator followed that of synchronous generator with its speed slightly higher than that of the synchronous generator rotor. The rotors reached their respective peak speed then decelerated. After some oscillations each rotor reached a new steady state speed. The new steady state speed reached by synchronous generator rotor which also determines frequency of power generated in the plant, was about 0.98 pu.

After the fault had been cleared, the power from the plant was observed to be restored and plant resumed supplying power to the connected load, however, the contribution of induction generator to the active power supplied dropped to the minimum value set from the full load capacity. The power relay had actuated reduction of induction generator's power output at occurrence of the fault. The plant has therefore demonstrated stability to fault conditions provided the clearance of the fault take place before critical fault clearing time for the plant which has to be determined after assessing the critical clearing angle for synchronous generator and the critical speed for induction generator. Simulation has also shown that in case of a fault, the action of power relay can be used to shut off the turbine coupled to induction generator as well as its isolation from the power system hence simplifying protection of the generator.

Impact of induction generator rotor speed at the moment the generator is to be connected into the system to the performance of the proposed power plant, was investigated by simulating operation of the plant with initial conditions of the induction generator set at different slip magnitude to imply different rotor speed at the moment the generator is brought in. In all cases simulated, the rotor speed dropped with oscillations immediately after the induction generator was connected into the system, then afterwards a steady state speed was reached. But during the time when the rotor speed was dropping, rotor released some of its kinetic energy into the power system as active power and cause power surges in the system as a consequence. However, surges of reactive power supplied to the load were also observed and surge peak of both active power and reactive power surges showed direct proportionality with the rotor speed at the moment when induction generator was connected into the system. Therefore, to minimise power surges caused by connection of induction generator into the power system, it is recommended that the magnitude negative of induction generator rotor at the moment of connection to be as small as applicable. But this should not be a strict condition because simulations showed apart from consequences of power surges no other impairments could be caused.

Simulations of the model of the small hydropower plant implemented through newly proposed approach have sufficiently shown that combination of synchronous generators and induction generators in a multi-generator installation is technically viable under condition that proper mechanism of generating controlled reactive power to supplement that generated by synchronous generators so as to meet instantaneous requirements of the connected load and excitation systems of the induction generators.

Looking at the functions of the generators in the installation, induction generators contribute only to the supply of active power to the system while synchronous generators, apart from supplying active power to the system, they also have the role of determining system frequency and maintaining the generator bus voltage. Therefore control strategies for the two types of generators differ hence application of tacho-generators in the case of synchronous generators' and power relays for induction generators' control systems interfaced with electric servo motors through servo control systems.

5.2 Recommendations and Further Research Works

- The research has shown that combination of synchronous and induction generators can be installed in small hydropower plant as cost reduction measure to improve competitiveness of the plants. But whether two generator of equal capacity can successfully operate in parallel has to be verified.
- Major challenge of parallel operation of induction and synchronous generator lies in generation of reactive power to meet excitation requirements of the induction generator and supply load connected to system sufficient reactive power according to its operational requirements. In this research project, SVC connected at generator bus was used to generate reactive power in order to supplement the reactive power generated by the synchronous generator. Other methods of reactive power generation need to be tested and compared to determine better option.
- In implementing the proposed power selection of electrical main connection has to put into consideration the fact that in fault conditions, induction machines' contribution to short circuit current is normally limited to initial moment after occurrence. Therefore in the proposed small hydropower plant less expensive switchgears and other conducting equipment can be applied.
- The research has not looked upon protection systems for equipment in the proposed plant, therefore a study on effective protection scheme that ensures smooth operation of the plant has to be conducted. However, power relay incorporated in regulation of mechanical power output of the turbine coupled to induction generator can also play part in control scheme for the induction generator.
- The small hydropower plant investigated operates in autonomous condition so the control of turbine coupled to synchronous generator can be implemented even without considering droop characteristic but if interconnection with another plant is envisaged droop characteristic operation has to be effected and measures for parallel operation of synchronous generators put in place.

5.3 Publications

The study outcomes were presented in the following publications:

- Kilimo, A.S.G. and Kahn, M.T.E. 2009. Prospective Small Hydropower Plant for Electrification of Rural Tanzania. Proceedings of the 25th National conference on Global Economic Crisis: Challenges and Opportunities to Engineers in lesser Developed Economies, 7-8 December, 2009 Arusha, Tanzania. pp. 146 – 151.
- Kilimo, A.S.G. and Kahn, M.T.E. 2011. Small Hydropower Plant for Rural Electrification. Proceedings of the International Conference on Domestic use of Energy, 12-13 April, 2011 Cape Town, South Africa. pp. 189 – 192.
- Kilimo, A.S.G. and Kahn, M.T.E. 2011. Small Hydro for Electrification of Rural Sub-Sahara Africa. Under review by Journal for New Generation Sciences.

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APPENDICES

APPENDIX A: Fundamentals of Hydropower

Basic hydraulic theory of hydropower engineering is based on Bernoulli's theorem by which ordinary turbines and waterwheels are said to use energy that can be evaluated as the sum of the three forms of energy: kinetic energy, potential energy and pressure energy. The Bernoulli equation remains constant for a given cross section and position in a channel:

$$\frac{v^2}{2g} + h + \frac{p}{\rho g} = \frac{P}{\rho g Q}$$

Where

v = water flow speed [m/s]

g = acceleration due to gravity [m/s^2]

h = height of water [m]

p = pressure of the water [N/m^2]

ρ = density of the water [kg/m^3]

P = power [W]

Q = flow of the watercourse [m^3/s]

For modern turbines, the effective power at their input may be estimated by neglecting terms accounting for water flow speed and pressure of the water and therefore considering the potential energy in the watercourse. Then at a given site with water head H and hydraulic efficiency η mechanical power output can be estimated to be:

$$P = \eta \rho g Q H$$

APPENDIX B: Small Hydro Potential Sites in Tanzania

S. No.	River Name	Location (Region)	Head [m]	Capacity [kW]	Average flow rate [m^3/sec]
1	Kasongenye	Biharamulo (Kagera)		420	1
2	Kamwana	Muleba (Kagera)	90	800	1.2
3	Yungu	Mbinga (Ruvuma)	20	90	0.5
4	Mbawa	Mbinga (Ruvuma)	200	1800	1
5	Luwika	Mbinga (Ruvuma)	200	1400	0.8
6	Luaita	Mbinga (Ruvuma)	30	190	0.6
7	Upper Ruvuma	(Ruvuma)	20	15000	6
8	Hanga	Songea (Ruvma)	40	550	5.2
9	Lilondo	Lingatinda (Ruvuma)	150	1400	0.75
10	Kibwaka	Njombe (Iringa)	50	5100	35
11	Malisa	Njombe (Iringa)	75	1250	6
12	Mbaka	Kyela (Mbeya)	200-300	8000	2.5
13	Kiwira	Kyela (Mbeya)	285	25000	15.7
14	Songwe	(Rukwa)	20	1000	10.6
15	Lupa	Chunya (Mbeya)	50	2800	15.7
16	Lkwate	Chunya (Mbeya)	60	900	1.8
17	Wuku	Chunya (Mbeya)	80	2500	3
18	Yeye		90	2500	2.5
19	Rungwa		108		35
20	Lukima		120	4000	4
21	Msadia/Mfwizi		120	25000	18
22	Mtozi		40	2400	12
23	Mbede		50	1240	0.3
24	Mamba		50	155	0.1
25	Filongo		150	415	0.3
26	Mpete		200	5500	0.03
27	Chulu	(Rukwa)	300	850	0.3
28	Kirambo		300	280	0.1
29	Muse	(Rukwa)	200	520	0.2
30	Luiche	(Rukwa)	200	1100	0.5
31	Msofwe		500	4500	0.95

32	Milepa	(Rukwa)	450		0.2
33	Mba	(Rukwa)	300	1000	0.55
34	Kilemba	Sumbawanga (Rukwa)	300	270	0.95
35	Kalambo	Sumbawanga (Rukwa)	430	80000	30
36	Kawa	(Rukwa)	200	2000	2.7
37	Luamfi	(Rukwa)	40	1200	9
38	Mtambo	Mpanda (Rukwa)	40	2400	8
39	Luegele	Mpanda (Rukwa)	175	15000	15
40	Ruguchi	(Kigoma)	20	1000	30
41	mkuti	(Kigoma)	23	630	3.3
42	Himo	Moshi (Kilimanjaro)		945	3.3
43	Seseni	Kihurio (Kilimanjaro)		1740	3.3
44	Goma	Ndungu (Kilimanjaro)		1740	3.3
45	Higilili	Bombo/Gonja (Tanga)			0.64
46	Mto wa Simba	Mto wa Mbu (Arusha)	210		2.4
47	Mbulu	Mbulu (Arusha)	450	8100	1.75
48	Pinying	Loliondo (Arusha)		450	0.9
49	Njombe	Njombe (Iringa)		2000	5.6
50	Kifunga	Njombe (Iringa)		3600	16
51	Hagafiro	Njombe (Iringa)		5000	
52	Malagarasi	(Kigoma)	80		16
53	Ruguchi	Uvinza (Kigoma)		1000	30
54	Nzowe	Sumbawanga (Rukwa)		3000	0.33
55	Nakatuta	Songea (Ruvuma)	30	9000	61
56	Hainu	Babati (Arusha)	100	3520	0.48

APPENDIX C: List of Existing Small Hydropower Plants in Tanzania

S. No.	Location	Installed capacity [kW]
1	Tosamaganga (Iringa)	1220
2	Kikuletwa (Moshi)	1160
3	Mbalizi	340
4	Kitai (Songea)	45
5	Nyagao (Lindi)	15.8
6	Isoko (Tukuyu)	15.5
7	Uwemba (Njombe)	800
8	Bulongwa (Njombe)	180
9	Kaengesa (Sumbawanga)	44
10	Rungwe (Tukuyu)	21.2
11	Nyangao (Lindi)	38.8
12	Peramiho (Songea)	34.6
13	Isoko (Tukuyu)	7.3
14	Ndanda (Lindi)	14.4
15	Ngaresero (Arusha)	15
16	Sakare (Soni)	6.3
17	Mbarari (Mbeya)	700
18	Ndolage (Bukoba)	55
19	Ikonda (Njombe)	40
	TOTAL	47000

Source: http://www.waterpowermagazine.com 2011/05/26