IEC61850 STANDARD-BASED TRANSFORMER TAP CHANGER CONTROL FOR POWER SYSTEM STABILITY

by

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DECLARATION

I, Chadrack Lubamba Ntambwe, 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.

20th August 2022

Signed **Date**

ABSTRACT

Electrical transformers are one of the power system equipment widely used throughout the system. Generally, they alter voltage from one level to another as a function of turn ratio. In some cases, one of the windings is equipped with multiple taps for flexible output voltage. The tap changing mechanism is either an on-load or an off-load type. The on-load type is manually operated or automatically utilizing a designated device. Automated control of a group of transformers operating in parallel is more involved and requires more considerations to ensure power system integrity.

The research of this thesis presents the design and implementation of entirely decentralized and hierarchal transformer on-load tap changer controllers for a system of parallel transformers. The controllers are designed based on IEC61850 standards for communication. The design and implementation will be in the laboratory environment.

IEC61850 standards present an endless number of features. However, the Generic object-oriented substation event (GOOSE) messaging service is mainly the feature of interest in this research. Schweitzer Engineering Laboratories (SEL) products are the preferred choice of intelligent electronic devices (IED's). The controllers are designed and implanted in these IED's using the manufacturers' programming tool.

To achieve the aim of the research, a review of approaches for the design and execution of transformer tap changer controllers is conducted at first. Highlights of the applications of IEC 61850 standard for the implementation of the transformer tap changer controllers follows. An adjusted IEEE 12 Bus power system, allowing parallel operation of transformers, is then modelled in RTDS/RSCAD. The controllers are developed, implemented and hardware-in-the-loop (HIL) simulated under various conditions and disturbances. The simulation is carried out at the Centre for Substation Automation and Energy Management Systems (CSAEMS) at the Cape Peninsula University of Technology, Bellville campus.

Keywords: IEC 61850 Standards, transformer tap changer, Controller, Automatic, Power system, Voltage stability, Voltage Regulation.

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LIST OF ABBREVIATIONS

CSAEMS	Centre for Substation Automation and Energy Management Systems
CT	Current Transformer
EPRI	Electric Power research Institute
GOOSE	Generic Object oriented Substation event
GSSE	Generic Object-oriented Substation event
HIL	Hardware-in-the-loop
IEC	International Electronic communication
IED	Intelligent Electronic Divice
IEEE	Institute of Electrical and Electronics Engineers
LAN	Large Area Network
OLTTC	On Load Transformer Tap Changer
RTDS	Real time Digital Simulation
SCADA	Supervisor Control And Data Acquisition
SEL	Schweitzer Engineering Laboratories
VT	Voltage Transformer

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Modern days are characterised by tremendous technological breakthroughs and scientific discoveries of all history. With these new technologies and scientific discoveries come requirements of high reliability for the uninterrupted availability of electricity supply. Moreover, the ever-growing concerns over global warming resulting from burning fossils; rose urgent needs for clean energy generation and integration on the grid. Thus, reactive power, active power and voltage must be monitored and controlled at many points of the grid. Grid automation must be developed to face up to these challenges and enhance power system stability.

A combination of various methods and techniques is used in the power system to ensure that the electricity supply is delivered to the consumers' terminals at acceptable quality. Voltage regulation through on-load tap changing transformers is one of the methods used in grid automation for automatic voltage control. Controlled shunt capacitors banks can also be used for this purpose. However, they are more used for power factor correction than voltage regulation (James H Harlow, 2007). Owing to the presence of distributed generators and the dynamic nature of the current power system, the control of on-load tap changing transformers is much more complex than simply reacting to a voltage fluctuation at the controlled terminals of transformers.

For a stand-alone transformer, the control primarily requires 3 inputs: voltage, current and phase deviation between voltage and current. For a system with two or more transformers operating in parallel, additional inputs are required. the control of on-load tap changing transformers in parallel is achieved by using one of the three methods indicated below.

- **The mater-follower method, also known as the master-slave method**: One relay is chosen as master and the rest follow instructions issued by the master, hence the name. This method is effective for transformers presenting the same electrical properties

- **Circulating current method:** The circulating current method makes use of circulating current to make decisions to raise or lower the tap position
- **Negative reactance method**: This is the least used method. It makes use of line drop in the line due to line resistance and reactance and the pre-set voltage regulated value to evaluate the need to raise or lower the tap position.

The Master-follower method and circulating current method require communication between participating Controllers/ IED's. The negative reactance method does not necessarily require any sort of communication between participating controllers/IED's (ZIV Aplicaciones Y Tecnologia, 2019).

The communication between participating Controllers/IED's is achievable by using pilot cables or using an Ethernet cable for controllers manufactured with the communication feature. In the late '90s an international standard, IEC 61850 offering a unified resolution of the communication feature of substation automation was created. The standard offers endless benefits and applications in power system control, protection, automation, monitoring and management (MacKiewicz, 2006). The most used feature of the standard is GOOSE messaging services.

The development of on-load tap changer controllers based on the application of IEC 61850 standards for transformers operating in parallel is portraited in this research. The controllers are designed and implemented using equipment available in the Centre for Substation Automation and Energy Management

1.2 AWARENESS OF THE PROBLEM

Conventionally, the control of on-load tap changers is achieved by designated devices. These devices generally require quite a few amounts of pilot cables for communication for control of transformers operating in parallel. Moreover, there are other challenges associated with the traditional ways. To name a few

- Additional instruments transformers are required,
- Time-consuming troubleshooting because of cables involved,
- High cost of installation and maintenance,
- High cost of expansion,
- Lack of adaptability,
- Large space required.

In some cases, the control is achieved remotely via the SCADA system. Data are collected then sent to the master station for decisions. A typical SCADA system is illustrated in Figure 1-1 below.

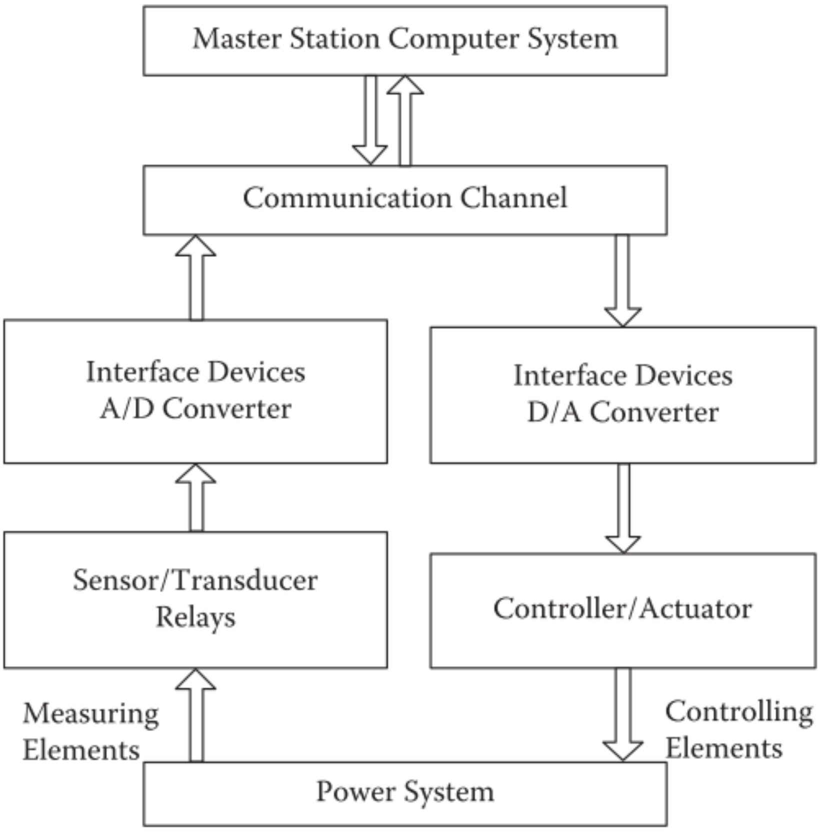


Figure 1-1: SCADA control process

As it can be seen from Figure 1-1 above, the dependability of the master station can be lessened by introducing more local and decentralised controls and automation.

This will release data traffic congestion as well as reduce the response time to only desired time delays.

1.3 PROJECT AIM AND OBJECTIVES

This project aims to elaborate procedures for the design of on-load tap changer controllers and to make use of analogue and digital GOOSE messages for the communication of data and command signals for transformers running in parallel.

To achieve the aim stated above, the objectives listed below must be reached:

- Review approaches for design and execution of transformer tap changer controllers
- Overview and application of the IEC61850 Standard for implementation of the transformer tap changer controllers
- Model a system of parallel transformers in the software environment of RSCAD and simulate the system behaviours under various disturbances and operational requirements.
- Design fully decentralised and hierarchal controllers for the tap changer of the system of the parallel transformers.
- To implement the developed controllers in the software environment of RSCAD and simulate the obtained control system under various operating conditions and disturbances
- Hardware-in-the-loop simulation of the parallel transformer tap changers controls system and investigation of behaviour for different operating conditions and disturbances.

1.4 HYPOTHESIS

There is a possibility to design and implement on-load tap changer controllers in modern substations without requiring additional equipment if any. Modern substations utilise IED's for protection automation and control. These devices are IEC 61850 standards enabled and are programmed to perform specific protection, automation, control scheme. For more flexibility, most of them possess room for custom schemes.

The successful implementation will result in the following advantages:

- Saving on copper as a result of reducing polite wires to a single Ethernet or fibre cable.
- No cost associated with additional equipment
- Reduced installation, maintenance and expansion cost.
- Easy adaptability and troubleshooting.

Moreover, the decentralisation of the controllers results in less congestion and fast response time.

1.5 DELIMITATION OF THE RESEARCH

This research focuses on the use of IEC 61850 standards for the development of the on-load tap changer controllers. The controllers are developed to operate with transformers in parallel. The limit to the number of transformers in parallel that this scheme is applicable is limitless. However, due to the limited number of equipment available in the laboratory, the scheme is only tested with three parallel transformers.

The research makes use of the 12 Bus IEEE power system, modified to accommodate transformers in parallel. The modelling of the system is given just as an overview. Moreover, the following items are not covered in this research:

- Protection scheme applicable to transformer or any other power system component.
- Modelling of the system in the software environment of DIgSILENT

Ideally, remote CT's and VT's would be used in accordance with part 9.2 of IEC 61850 over ISO/IEC 8802-3. Unfortunately, the ID's currently present in the laboratory do not support this feature. Thus, CT and VT's will be hardwired to the various IED's.

1.6 MOTIVATION FOR THIS RESEARCH PROJECT

This research project is motivated by the need for automation in the modern power system characterised by its diversity of generations and the complexity of electricity delivery requirements. With each technological breakthrough comes the need for a stable and reliable electricity supply. The prediction game does no longer work. Therefore, the control centre operator cannot cope with all the current control requirements. For this reason, the automation, protection, monitoring and control of the power system have no choice than being intelligently being programmed to operate based on predefined logic.

Should the control centre be the hub of data processing and decision making, delays in communication will occur. Moreover, a communication failure at the centre would create more replication effects of other substations and components of the power system. Therefore, most of the control and protection schemes will have to be decentralised.

1.7 ASSUMPTION

The power system being a vast field of study, each research is based on previously published work and assumptions to fairly define the scope of the research. For this research, the following assumptions have been made:

- The various protection schemes have been put into place and coordinated with the automation of the controllers designed.
- The voltage regulation employing tap changers is the last resort for improving voltage stability. Hence a higher time delay.
- Developed controllers are generic and able to operate with any type of transformer and power system. Hence the adjustable time delay and the time interval between tap actions.
- The generators in the test power system can supply the minimum and maximum load as required
- GOOSE messaging communication is faster than the traditional messaging system

1.8 RESEARCH METHODOLOGY

The development of this research project followed the months listed below:

1.8.1 Literature consultation and review

A study of various prior works on the technics employed in the automatic methods of controlling voltages in the power system is conducted. The study focuses on the voltage regulation utilizing on-load tap changers and various methods of controlling these transformers. Moreover, prior work on the implementation of the IEC 61850 and its benefits in the power system are reviewed.

1.8.2 Analysis of transformer design and theory

The design of the transformer is analysed as well as the operation of the transformer in parallel. Various transformer designs are analysed, and the applications are detailed. The concept of circulating current, the origin, its components, and calculation are analysed. Furthermore, the construction of various transformer tap changers is detailed and applications listed.

1.8.3 Analysis of communication in power system

The architecture of communication in the current power station is analysed. The various network topologies are analysed. The application of IEC 618500 is also analysed in detail.

1.8.4 Design of the proposed Controllers

The proposed controllers are designed using the hardware available in the CSAEMS. The controllers are designed using fundamentals of transformer circulating current and communication based on IEC 61850 standards.

1.8.5 Hardware-in-the-loop simulation

The developed controllers are hardware-in-the-loop simulated using RTDS/ RSCAD. The results are discussed and assessed for accuracy against expectations.

1.9 THESIS CHAPTERS

This document is divided into 10 chapters as follows:

Chapter 1: Introduction

This chapter portrays the overview of the research project. The aim and objects of the research are given. The chapter also lists the hypothesis and defines the scope of the project.

Chapter 2: Literature review

This chapter reviews previously conducted research on the application of IEC 61850 standards for automatic on-load tap changer controllers. Furthermore, a comprehensive analysis of published papers on Real-Time Digital Simulation is conducted as well as literature comparison and discussion.

Chapter 3: Transformer Theory & Power System Stability

This chapter gives an overview of the fundamentals and principles of transformers. The construction and calculations involved are also detailed. The different types of transformers are also listed, and applications are given. the chapter also focuses on listing all types of transformer on-load tap changers as well as their construction and operations. Furthermore, a brief overview of the power system stability, as well as the effects of the on-load tap changer on the power system, is given.

Chapter 4: Supervisory control and data acquisition (SCADA)

This chapter gives a comprehensive overview of the communication protocols in modern power systems. The chapter lists the components of the SCADA system, gives an overview of communication systems and network topologies. Furthermore, the chapter gives an overview of the IEC61850 Standards.

Chapter 5: Modelling and Simulation

This chapter describes the process of modelling and simulation used in this project. An overview of the simulation software used is given as well as the modelling of the major components of the power system. The modified IEEE 12-Bus test network is described, the initial load flow conducted, and the results are given. Furthermore, an overview of power flow methods for simulation is given. lastly, the various case studies are defined.

Chapter 6: Design of on-load tap changer controller for parallel transformers

This chapter deals with the development of the proposed controllers. All the major logic blocks are detailed, and an overview of all the software and hardware involved is given.

Chapter 7: Hardware-in-the-loop simulation

This chapter covers the simulations of all the scheduled case studies. The results of each case study are discussed under the case.

Chapter 8: Conclusion

This chapter gives a summary of the work completed in this research project. The chapter also confirms the achievement of the aim and objectives of the project. Furthermore, the chapter suggests future possible works relating to this research project.

Chapter 9: References

This chapter lists all references utilised in this research work

Chapter 10: Appendices

This chapter gives the documents relating to the work in this document but not necessary to be added to this work.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

In the past, electricity providers were only dealing with the demand to increase productivity and reduce costs. Power providers in present days are dealing with a new challenge to reduce the emission of carbon monoxide (CO), carbon dioxide (CO2), etc., resulting from burning fossil fuels. This has resulted in a rising number of distributed generations and renewable energy on the power system. Renewable energy generation is the future of energy production, it has a limitless number of ecological advantages. However, due to its intermittent nature and lack of huge power storage facilities, its effects on the power system remains a challenge (Dulău, Abrudean and Bică, 2014). Thus, the need for smarter, intelligent, faster devices and automation to tackle voltage profiles issues arising from the grid integration of renewable energy.

The power quality of a power system is generally determined by the system voltage. Thus, controlling the system voltage is essential for system stability (Mahmut Temel Özdemir, 2017). Automatic voltage regulation utilizing tap changing transformer is one of the methods used for ages in grid automation to control voltage at a given bus in the system.

This chapter deals with prior arts of accomplishing automatic voltage regulation using transformers equipped with tap changers. Control methods, as well as benefits of implementing IEC61850 standards for automatic voltage regulation using transformers equipped with tap changers, will be discussed. It is widely known that a transformer equipped with an on-load tap changer can present great advantages when controlled correctly. When not controlled correctly, the consequences can go as far as collapsing the power system (Mahendar and Yesuratnam, 2017). Moreover, this chapter will look at various issues associated with legacy methods to control on-load transformer tap changers. It will present new innovative methods used up to these days to tackle issues with old systems. Furthermore, the advantages of using IEC61850 standards for online transformer tap changers for transformers operating in parallel configuration will be portrayed.

2.2 POWER QUALITY IN POWER SYSTEM

The modern power system is characterised by a diversity of loads and integration of Distributed Generation (Wind energy, solar energy, biomass energy, etc.) connecting to the system via power electronics interfacings. Due to the intermittency, complexity and instability nature of renewable generation, the power system inevitably encounters serious challenges in maintaining the power quality required to supply its sensitive loads (Luo *et al.*, 2016). Figure 2-1 below illustrates a typical modern power system smart grid network.

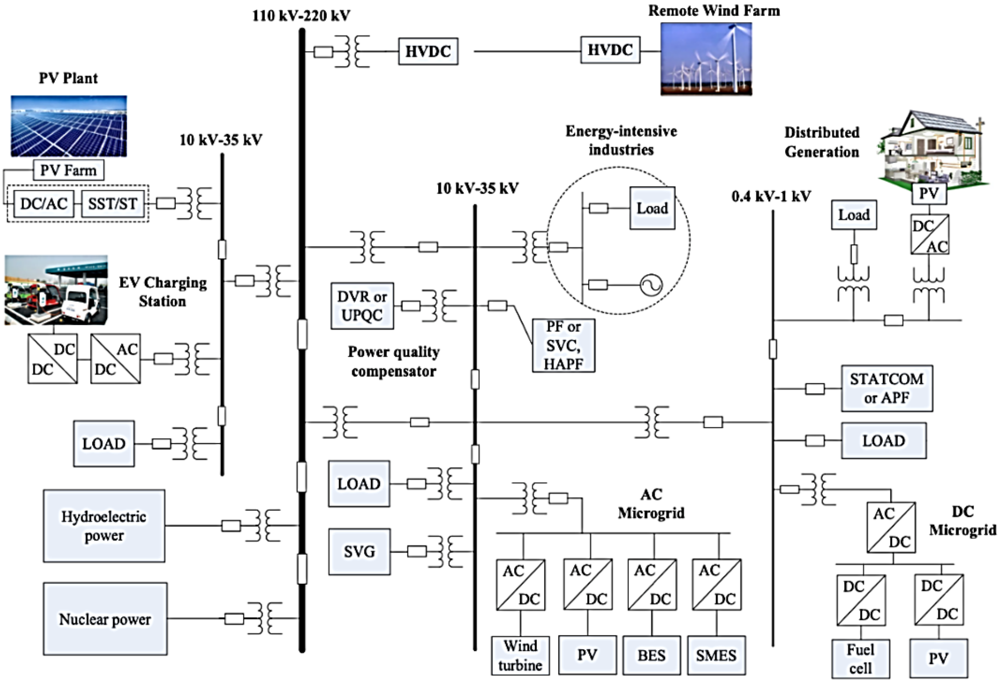


Figure 2-1: Modern Power System (Luo et al., 2016)

Power quality in a power system can be referred to as the perception of supplying electricity to equipment in a way that is acceptable for the functioning of the equipment (IEEE, 2000). Power system quality is determined by the quality of its parameters. i.e., voltage, frequency, current, power angle and power factor. To ensure power quality in the power system, all parameters will have to be monitored and controlled in a smarter and automated fashion. In the following paragraphs, some published papers related to power quality in power systems will be presented.

(Luo *et al.*, 2016) gave a compressive overview of power quality analysis in power systems. Furthermore, the authors introduce power quality compensators and control technologies to face up with challenges of modern smart grid and renewable energy power plants. The authors recommend the use of complementation devices to correct power quality issues. The classification of power system compensators is illustrated in the diagram below. Lastly, tendencies and predictions of power quality control technologies for secure and economic operation of the smart grid are presented.

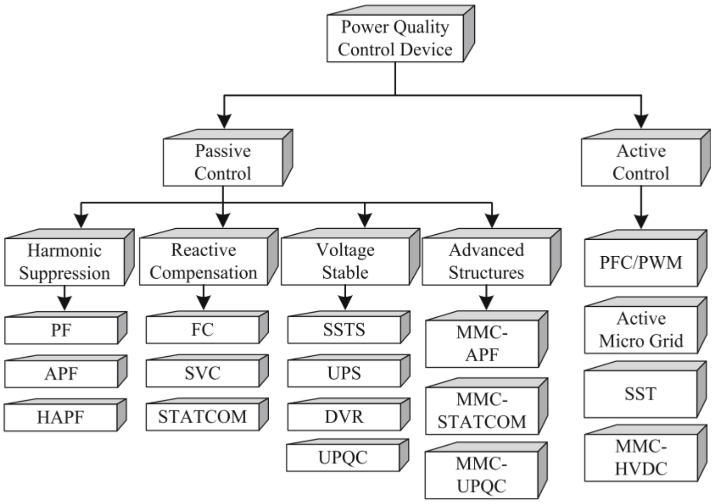


Figure 2-2: Classification of Power system compensators (Luo et al., 2016)

(Shah *et al.*, 2014) presented an overview of numerous factors affecting power system quality. The authors highlighted the definition of power as “the rate at which electrical energy is provided to the circuit or consumed by a load and it is proportional to the product of current and voltage”. From the given definition, voltage is the only helpful factor as it can be regulated.

The authors classify power quality issues as follows:

- **Transients:** they are defined as an ephemeral (typically one cycle) change in voltage and current. They are classified into two categories, namely: impulsive and oscillatory transients. They are generally triggered by a change in load, capacitor switching, climatic change, change in fault current, etc.
- **Voltage sag:** defined as an occurrence in which the RMS voltage experience a short depression or reduction ranging between 80-90% for a duration of 3 to 10 cycles. Voltage sags are generally triggered by errors (faults) in the power system.
- **Interruptions:** can be defined as a total absence of voltage. Interruptions are according to the duration for which the absence has been observed. Temporary interruption lasting for less than three minutes and permanent interruption lasting anything above three minutes.

- **Harmonics:** can be described as a distortion of the current and voltage waveform resulting from the presence of non-linear load in the power system. Transformers operating in low or high voltage states can be a source of harmonics.

Lastly, the authors propose the use of smart metering, Data Acquisition and Power Quality Analyzer to monitor power quality. The smart meter provides important information to both the power system provider and the user. Each user is a source of power system quality data. The Data Acquisition systems are coupled with the Power quality Analyzer to record power system quality data for use by engineers or research and development teams to investigate disturbances.

To improve power quality in power systems, many techniques are applied. These techniques depend on the targeted parameter, i.e.: voltage, power factor, harmonics, etc. For voltage quality improvement, (Quevedo *et al.*, 2016) propose the use of a smart distribution transformer equipped with an electronic on-load tap changer and communication facilities for automatic and remote voltage regulation. The electronic OLTC includes a communication system as well as a load identifier algorithm. The algorithm identifies the type of load connected to the transformer, tape changes are therefore based on the type of loads connected. (Mokkapaty *et al.*, 2017) proposes the use of a new generation voltage regulation distribution transformer equipped with an on-load tap changer. To validate the applicability of the proposed new generation voltage regulation distribution transformers, a series of tests are performed on two transformers based on IEC 60076-1 Standards. Both transformers are rated at 400kVA, 20/0.4kV. One transformer is equipped with OLTC and the other is not. The test result indicated that the on-load tap changer contributed to the improvement of voltage quality, thus improving power quality.

2.3 AUTOMATIC VOLTAGE REGULATION

Literature consultation indicates numerous definitions of voltage regulation. The conveying point of all the definitions is that it is the measure of the voltage deviation between two points. In the following texts, the term automatic voltage regulation refers to automated voltage control. The voltage at a controlled point (bus) is manipulated in such a manner that it remains within predetermined boundaries regardless of load fluctuation. An ideal power system would have constant voltage at its terminals. This is not the case because any changes in the power loading or generation do have a direct impact on the voltages at various terminals.

To maintain voltage constant at terminals, many techniques are used. To name a few, reactive power injection, the use of transformer equipped with tap changer, the use of designed circuit (power electronics), etc.

(Ghosh, Jindal and Joshi, 2004) Reviewed the performance and operation of a unified power quality conditioner (UPQC) functioning as a voltage regulator. The UPQS consists of two voltage source converters connected to the feeder one in series and the other in shunt and both have their DC-link connected to a common DC capacitor. The UPQC compensates for voltage flicker and imbalance present in a distribution network. In this paper, the performance of the UPQC competes against a dynamic voltage restorer (DVR). Single line diagrams of UPQC and DVR are indicated in Figures 2-3 and 2-4 below.

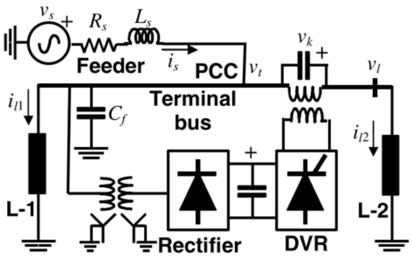


Figure 2-3: Single line diagram of a DVR (Ghosh, Jindal and Joshi, 2004

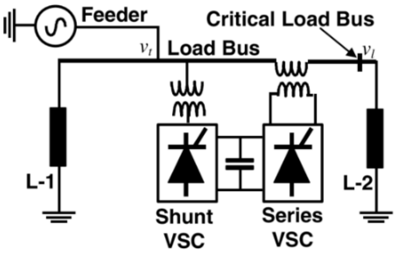


Figure 2-4: Single line diagram of a UPQC (Ghosh, Jindal and Joshi, 2004)

The DVR consists of three H-bridge inverters connected to a common dc storage capacitor. Simulations results using PSCAD/EMTDC, indicate that the UPQC performed well compared to the DVR.

The most common technique used to regulate voltage in distribution networks is the use of a transformer equipped with a tap changer. Literature indicates that the idea of using a transformer equipped with tap changer dates from ages. The focus of academics and research & development teams on this topic in recent years is finding innovative, smarter and optimal ways to control transformer tap changers satisfying the demanding requirements of the modern smart grid. There are two types of transformer tap changers, on-load tap changer and off-load tap changer namely. In the following paragraphs, the literature consultation will concentrate on the control of the on-load tap changer.

There are three methods of controlling transformer tap changer known to these days. The first is by using a designated device, the second is by an operator via SCADA (remote operation). Lastly by integrating customized control algorithms in Intelligent Electronic Devices (IED's).

(Sichwart, Nelli and Eltom, Ahmed and Kobet, 2013) presented a laboratory experiment of transformer tap changer based on GOOSE messaging service. In this experiment, a Transformer monitor relay (SEL-2414) was used to measure the voltage at the transformer and issue raise/fall commands. The controlling algorithm was incorporated in a programmable automation controller (SEL-2411) and an Omicron CMC device was used to simulate the assumed transformer voltage and current as seen from the secondary side of CT's and VT's. The communication between the transformer monitor relay (SEL-2414) and the programmable automation controller (SEL-2411) was purely through GOOSE services. The logic developed to control the tap position was based on voltage assumed to be balanced. In addition to logic to raise and lower the tap position, additional logic was created to keep track of the tape position. The experiment was conducted only for a single transformer and the results obtained from various test sets were satisfactory.

When two or more transformers are running in parallel, the control can be achieved in two ways. The first option is to dedicate an IED for the functionalities of all parallel transformers within a station. Such arrangement requires inputs from all transformers to the dedicated IED and eliminates the need for external communication. The second option is to use an IED for each transformer(Gajić and Aganović, 2016). The three most used methods to accomplish paralleling using a dedicated IED for each transformer are as follows:

- The Master-follower method also known as the master-slave method,
- The Circulating current method
- The Negative reactance method.

To achieve the master-follower method, one relay is designated as the master and the rest follow instructions issued by the master, hence the name. The Master-follower method is effective for transformers presenting the same electrical properties. The circulating current method makes use of circulating current to make decisions to raise or lower the tap position. The first two methods require communications between IED’s in parallel. The negative reactance method is the least used. It makes use of line drop in the line due to line resistance and reactance and the pre-set voltage regulated value to evaluate the need to raise or lower the tap position. It is important to note that this method is named **negative reactance** because it uses the negative value of the reactance portion. This method is achievable without any communication between IED’s (ZIV Aplicaciones Y Tecnologia, 2019).

(Yarza and Cimadevilla, 2014) presented in detail how the master-follow and the circulating current methods can be implemented based on IEC 61850 standards. The paper highlighted the advantages of using IEC 61850 standards. It describes the working principles as well as information required to be exchanged between the transformers. However, the paper does not indicate any experiment or simulation performed accordingly, nor does it show the results of such experimentation or simulation.

(Adam Patrick Taylor and Larry L. Wright, 2012) described in detail a field implementation of a transformer on-load tap changer (OLTC) controller based on IEC 61850 standards. The scheme was implemented at Santee Cooper substation in South Carolina. The scheme was implemented on three 230/115kV transformers in a parallel configuration. Previously, the OLTC control of these transformers was achieved utilizing a paralleling balancer. It uses circulating current and load current to decide on raising or lowering the tap position. The scheme is achieved through a complex configuration of auxiliary CT’s. Thus the installation is fairly costly (James H. Harlow, 2007). The operation of the paralleling balancer was unsatisfactory, therefore they launched themselves on a quest to find an alternative cost-effective solution. The proposed IEC61850 scheme consisting of the circulating current method was successfully implemented at the station. The challenge encountered during the installation was to strip redundant communication cables. The newly implemented scheme performed fairly well and met the utility’s goals (Adam Patrick Taylor and Larry L. Wright, 2012).

2.4 IEC COMMUNICATION STANDARDS

IEC61850 is the international standard offering a unified resolution of the communication feature of substation automation. The standard was created in the late ’90s as a result of the joint exertions of three organisations namely: Electric Power Research Institute (EPRI), Institute of Electrical and Electronics Engineers

(IEEE) and the Technical Committee 57 of the International Electronic Commission(MacKiewicz, 2006). To these days, IEC 61850 standards comprise 14 parts listed in table 2-1 below(IEC, 2011).]

Table 2-1: IEC 61850 Standards Series

Part #	Part code	Title
1	IEC61850-1	Introduction and overview
2	IEC61850-2	Glossary of terms
3	IEC61850-3	General requirements
4	IEC61850-4	System and project management
5	IEC61850-5	Communication requirements for functions and device models
6	IEC61850-6	Configuration description language for communication in power utility automation systems related to IEDs
7		Basic communication structure
7.1	IEC61850-7-1	Principles and models
7.2	IEC61850-7-2	Abstract communication service interface (ACSI)
7.3	IEC61850-7-3	Common data classes
7.4	IEC61850-7-4	Compatible logical node classes and data object classes
8	IEC61850-8	Specific communication service mapping (SCSM)
8.1	IEC61850-8-1	Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3
8.2	IEC61850-8-2	Mapping to Extensible Messaging Presence Protocol (XMPP)
9		Specific communication service mapping (SCSM)
9.1	IEC61850-9-1	Sampled values over serial unidirectional multidrop point to point link
9.2	IEC61850-9-2	Sampled values over ISO/IEC 8802-3
9.3	IEC/IEEE61850-9-3	Precision time protocol profile for power utility automation
10	IEC61850-10	Conformance testing

IEC61850 present heaps of benefits and features such as a standardised configuration language, reducing the cost associated with installation and operation(MacKiewicz, 2006).

Below listed are some of the key features of IEC61850:

- Standardised configuration language
- High-level services
- Self-describing devices
- All objects identification is standardised and well-defined in a power system context
- Using of virtual model and naming of all data.

As a conveyance of the above key features, some befits are listed below.

- **Eradicate Procurement Vagueness**
- **Minor Installation Fee**. IEC 61850 allows devices to rapidly exchange data and commend through GOOSE and GSSE thru the station LAN without copper links between relays. This meaningfully decreases wiring charges by further completely using the station LAN bandwidth for these signals and structure costs by decreasing the necessity for wireways(MacKiewicz, 2006).

- **Decreases expansion cost**. A device added to IEC based substation has only minimal impacts or none on the existing apparatus.
- **Implement New Capabilities**. The cutting-edge services and unique structures of IEC 61850 allow innovative capabilities that are not probable with legacy protocols. A wide area protection scheme is much more feasible because devices are already connected to the substation LAN.

2.5 APPLICATION OF IEC 61850 FOR TRANSFORMER TAP CHANGER

IEC 61850 standard has many benefits and features. Among them, the key ones are indicated in the previous sections. GOOSE messaging is the main feature of the IEC 61850 standard used for application in an on-load tap changer controller. It enables the reduction of pilot wiring between relays to a single data cable (fibre cable). The 3 basic inputs for transformer tap changing control - i.e. voltage, current and phase voltage - can be transferred from one IED to another via the fibre connection(James H. Harlow, 2007). In addition to that, information such as tap position of transformers in the same parallel configuration, substation configuration, the status of other IED, etc. can be communicated through the same cable(Hossenlopp, 2007).

To illustrate the section above, 4 transformers are assumed as indicated in Figure 2-3 below.

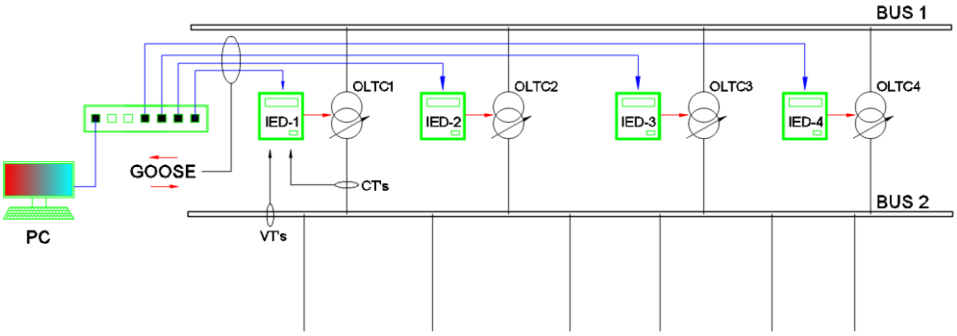


Figure 2-5: Example of IED's Connection

Regarding the system illustrated in Figure 2-3 above, all IEDs will be able to have at their disposition information listed below through IEC61850 Standards:

- **Voltage**s: Magnitudes and amplitudes will be known to all IED’s
- **Currents:** Current flowing in each transformer will be known to all IED’s in the system

- **Tap position:** Each IED can communicate its transformer tap position to others in the system.
- **Commends signal:** Depending on the method of control selected raise/lower commend can be issued.

The above list is not definite, there is more information that is communicated via the IEC61850 messaging services.

2.6 COMPARISON OF RESEARCH ON TRANSFORMER ON-LOAD TAP CHANGER CONTROLLERS

Various academics, research and development teams of power system providers have identified and developed solutions for automatic voltage regulation. Among the solutions, automatic transformer on-load tap changer controllers are the most common. The development and implementation are analysed. The IEC 61850 standards outlining communication protocols between various IED's are used to implement complex controllers and large area monitoring.

2.6.1 Overview of Literature

There are two main groups of transformer tap changers, off-load tap changer and on-load tap-changer. Off-load tap changer requires the load to be disconnected before taps can be changed. On the other hand, on-load tap-changer allows for tap changing under load conditions. The reactor on-load tap-changer was invented in 1926, the first of its kind. This leads to the invention of the resister type then the hybrid type. In 1973 the idea of a fully electronic tap changer was proposed. However, its uses were limited to special applications. Two decades later, the first comprehensive academic investigation of the system was conducted, then the research continued (Jawad and Siahkolah, 2011).

Later in the 90s decades, the IEC61850 standard was created as a result of the joint exertions of three organisations namely: Electric Power Research Institute (EPRI), Institute of Electrical and Electronics Engineers (IEEE) and the Technical Committee 57 of the International Electronic Commission (MacKiewicz, 2006). The standards offer a limitless number of advantages. Thus, enhancing power system protection, control and monitoring.

Gajić and Aganović, 2016 presented the advantages of fusing IEC61850 for voltage regulation. In this paper, the authors indicated required information to be shared between IED’s to achieve master-follower method or circulating current method for transformer equipped with on-load tap changer and operating in parallel.

2.6.2 Description of the criteria used for comparison of the papers

Table 2-2 further presents a comparison of published academic papers relating to the application of IEC 61850 standards for transformer on-load tap changers. Their aim, the method used, achievement and limitations are compared. Table 2-3 presents a similar comparison. However, the papers compared in this table relate to real-time digital simulation.

2.7 COMPARISON OF PUBLISHED PAPERS ON THE APPLICATION OF IEC 61850 STANDARDS FOR TRANSFORMER ON LOAD TAP CHANGER.

Table 2-2: Literature review on the application of IEC 61850 standards for transformer on-load tap changer

Item	Title	Aim	Method & model used	Limitation	Achievement
1	**Transformer Load Tap Changer Control Using IEC 61850 GOOSE Messaging** (Sichwart, Nelli and Eltom, Ahmed and Kobet, 2013)	To implement. On-load tap changer control using key elements of IEC 61850 Standards	The project was implemented in the laboratory using SEL IED's and CMC device.	Limited to the implementation of the control scheme for a single transformer. The scheme designed uses inputs from only the secondary side of the transformer. Thus, it would work for reverse power flow.	The paper has indicated how copper wiring used as pilot cable in substation can be reduced by using very reliable IEC Standards for communication between IED's.
2	**Advanced Tap Changer Control of Parallel Transformers based on IEC 61850 GOOSE Service** (Yarza and Cimadevilla, 2014)	To implement two most used voltage regulation schemes for transformers running in parallel can be implemented using EIC61850 Standards	Review and analysis of Mathematical expressions required to achieve each scheme	The paper does not indicate if any implementation was done successfully to support the theory detailed. Nor such results are given in the texts.	This paper highlighted various advantages of fusing IEC61850 for voltage regulation. It has shown required information to be shared between IED's to achieve master-follower method or circulating current method.
3	**Innovative Transformer Load Tap Changer Control Using Ethernet-Based Communications** (Adam Patrick Taylor and Larry L. Wright, 2012)	To implement an on-load tap changer for parallel using Ethernet-based communication.	Design, implementation and field testing of the developed control scheme	The modified circulating current approach used in this project can only work for up to 4 transformers in parallel. The scheme is designed only for mono-directional power flow.	Successfully developed on-load tap changer controllers for transformers in parallel based on IEC 61850 goose messaging for data communication. The developed scheme was successfully field-tested on a utility substation.
4	**Smart Monitoring and Control of Tap Changer Using Intelligent Electronic Device** (Babu *et al.*, 2015)	To implement an on-load tap changer in EID's and eliminate the need for separate equipment required to	Development and implementation of on-load transformer tap changer.	Briefly discuss the parallel operation of the on-load tap changer. It is limited to the master-follower method.	Successfully implemented tap changer in IED's already designed to other protection schemes. Thus, eliminating the need for a separate panel for this task.

Item	Title	Aim	Method & model used	Limitation	Achievement
		achieve n-load tap changer			
5	**An Approach to Identify Critical On-Load Tap Changing (OLTC) Transformers under Network Contingencies** (Mahendar and Yesuratnam, 2017)	To identify critical On-load tap changer transformers under network contingencies.	Simulation & Investigation of the operations of on-load tap changer transformers under network contingencies.	Limited to the identification of critical on-load tap changer transformer. Blocking the operation of these under network contingencies remains a task for the operator in the control centre.	Successfully developed an approach to identify critical on-load tap changer transformers under network contingency.
6	**Advanced tap changer control to counteract power system voltage instability** (Gajić and Aganović, 2016)	Develop an on-load tap changer scheme that takes into consideration of voltage fluctuation on the primary side of the transformer.	Development of an approach to control on-load tap changer using IED's	Limited to the principles of the developed control scheme.	Successfully developed an approach to control on-load tap changer taking into consideration the primary voltage of the transformer. By doing so, the likelihood of voltage collapse resulting from the operation of the on-load tap changer is reduced.
7	**Implementation of LCC HVDC Converter Transformer Tap Changer Controller, H-I-L validation Using Real-Time Digital Simulator** (Nasika, Yuvaraju and Vishnuvardhan Reddy, 2016)	To implement converter transformer tap changer controller in IED and to test the controller using real-time digital simulation.	Development, design, implementation and hardware in the loop simulation of the developed controller.	Limited to a single controller.	Successfully developed, design, implemented and hardware in the loop simulated converter transformer on-load trap changer controller
8	**Intelligent Control of On-Load Tap Changer of Transformer** (Wang *et al.*, 2011)	Investigate the operation of Vacuum On-load transformer tap changer & Implementation of On-load tap changer controller in Programable logic controller to operate	Investigation of Vacuum On-load transformer tap changer & Design and implementation of control scheme in Programmable logic controllers.	Limited to the operation of a transformer operating in solo mode.	Demonstrated advantages of Vacuum On-load tap changer compared to traditional on-load tap changer. Successfully developed on-load tap changer controller using programmable logic controllers.

Item	Title	Aim	Method & model used	Limitation	Achievement
9	**A detailed analysis of the GOOSE message structure in an IEC 61850 standard-based substation automation system** (Kriger, Behardien and Retonda-Modiya, 2013)	Investigate the structure of IEC 61850 GOOSE messages service and its data content	Investigation of GOOSE message services by means of simulation and experimentation	Limited to the confirmation of IEC 61850 GOOSE message services and its data content.	Successfully discussed an investigation and confirmed the structure and data content of IEC 61850 GOOSE messages services
10	**Overview of IEC 61850 and Benefits** (Mackiewicz, 2006)	Highlight benefits of using IEC 61850 in substation automation.	Presentation of key benefits and concepts of the IEC61850 Standard	Limited to benefit of IEC 61850 standard as known in 2006.	Presented the overview of IEC 61850 as well as the most important features and their benefits. Also give power system related examples.
11	**Real-time under-load tap-changer control based on Synchrophasor measurements** (Adewole, Tzoneva and Apostolov, 2016)	Make use of IEC 61850 and synchrophasor measurements to develop and implement an on-load transformer tap changer system integrity protection scheme.	Develop, implement, test and validate proposed scheme using real-time digital simulation	Limited to real-time and Hardware-in-the-loop simulation	Successfully Designed, implemented, tested and validated a proposed system integrity protection scheme-based o On-load transformer tap changer blocking an unblocking algorithm and synchrophasor measurement.
12	**A review on voltage control methods using on-load tap changer transformers for networks with renewable energy sources** (Sarimuthu *et al.*, 2016)	Highlight the need for an innovative on-load transformer tap changer scheme to face up challenges arising from penetration of renewable energy	Investigation and comparison of traditional ways of controlling OLTC and newly available technologies.	Limited to the theoretical aspect	Reviewed techniques of controlling OLTC. Also highlighted the need for special care for a network with renewable energy penetration.
13	**Transformer Tap-Changer Algorithm for Meshed Power Networks** (Hanser and Mueller, 2015)	To develop an on-load changer algorithm for bidirectional power flow and reduce on-load tap changing action.	Development and simulation on the IEEE 30 bus and 57 bus network system	Could not calculate real-time line impedances. They are calculated manually thus, challenging real-time implementation of the proposed algorithm.	Successfully developed a modified approach to control on-load tap changer applicable for both radial network and meshed network. The proposed algorithm optimises the tap changer action. Thus, enhancing reliability.

Item	Title	Aim	Method & model used	Limitation	Achievement
14	**Investigation of on Load Tap Changer Control in Smart Distribution Network** (Bangash, Farrag and Osman, 2016)	To evaluate the operation of on-load tap changer with smart conditional controller under high penetration of distributed generation.	Modelling simulation and investigation of the operation of a smart conditional controller on UK network	Limited to MATLAB/Simulation.	Presented the investigation of the operation of on-load tap changer with smart conditional control on UK network with high penetration of Distributed Generation.

2.8 ANALYSIS OF PUBLISHED PAPERS ON REAL-TIME DIGITAL SIMULATION IN POWER SYSTEM FOR PROTECTION AND AUTOMATION.

Table 2-3: Literature review on Real-time digital simulation in power system for protection and automation

Item	Title	Aim	Method & model used	Limitation	Achievement
1	**Design, implementation and validation of a real-time digital simulator for protection relay testing** (Kezunovic, 1996)	To design and implement a new real-time digital simulator to run using low-cost commercial computers. To improve the time step up to 50μS	Design and implementation	The time step is limited to 50μS and the system was bulky.	Successfully designed and implemented a real-time digital simulator for protection relays. Developed simulator adhered to all design requirements.
2	**An advanced real-time digital simulator-based test system for protection relays** (Du *et al.*, 2006)	To Provide details regarding the improvements of Real-Time Digital Simulator based test system for Protection relays.	Analyse and investigate and simulation	Limited to the presentation of features.	Presented advantages of Real-time digital simulation over conventional testing techniques.
3	**The What, Where and Why of Real-Time Simulation** (J. Bélanger, 2014)	To give an overview of Real-time digital simulation.	Real-time digital simulation is discussed and reviewed in this paper.	Limited to fixed time-step simulation.	Successfully give a comprehensive overview of Real-Time simulation, indicated why is it needed and where it fits best.

Item	Title	Aim	Method & model used	Limitation	Achievement
5	**Real-Time Digital Simulations: A Comprehensive study on System Overview, Application, and Importance** (Noureen *et al.*, 2017)	To present technological aspects and concepts of modern real-time digital simulation tools.	Overview and review of popular real-time digital simulators listed below based on the accessibility of information: • Real-Time Digital Simulators (RTDS), • OPAL-RT, • Network Torsion Machine Control (NETOMAC), • dSPACE, • Real-Time solution by MathWorks (xPC target, Real-Time Windows target), • Power system Online simulation Unveil Your Analysis (POUYA) Simulator and • Typhoon HIL Simulator	The review and comparison of capabilities are based only on the accessibility of information.	This paper reviewed keys features of most populator real-time simulator and highlights their applications in diverse industries
6	**Real-Time Hardware and software-in-the-loop simulation of decentralised distribution network control architecture.** (Tuominen *et al.*, 2017)	This paper aims to: • Introduce a laboratory test set-up established to assess the functionality of an innovative decentralised distribution automation architecture. • Track out any potential interfacing issues of the automation system before implementing	simulation of a distribution network in a real-time simulation environment comprising monitoring and control devices as well as physical devices interfaced with the simulator as hardware-in-the-loop test devices. The system involves also substation automation units for real-time monitoring and control that are interfaced with the simulator and physical devices. The operating principle of the	This is limited to Integrated hardware-in-the-loop (HIL) and software-in-the-loop (SIL) testing of distribution network hardware and architecture only	The system presented in this paper was developed and successfully used to perform testing of the automation architecture concept before deploying the system for field testing.

Item	Title	Aim	Method & model used	Limitation	Achievement
		the concept to actual field demonstrations	system is demonstrated with an example simulation case		
7	**Hardware and software integration as realist SCADA environment to test protective relaying control** (de Souza *et al.*, 2014)	To present an innovative hardware and software integration to reproduce a real-time performance environment of power system simulations, focusing on protective relaying control adjustments and training tools.	Implementation and reproduction of the IEEE-9 bus system and the Colombian transmission system's section in the real-time platform to assess their performance. Protective relaying control applications are verified on the platform via Hardware-in-the loop techniques	Limited only to the use of Hardware-in-the-loop testing.	Successfully presented a full framework to simulate power systems in real-time with Hardware-in-the-loop simulation. The presented framework is a modern solution with low-cost hardware/software integration that successfully linked Power Factory with National Instrument Tools. The platform presents the feature of simulating an unlimited number of nodes depending on the power factory license and the computational performance.
8	**Automatic Pre-processing Scheme for Real-Time Digital Simulation** (Noh *et al.*, 2018)	To present the data pre-processing algorithm for real-time digital simulation of enormous power systems grounded on energy management system data.	Developed and implemented the data pre-processing scheme. The Energy Management System at a peak time of the Korea Power Exchange is used to apply the scheme. The RTDS of Korea Electric Power Research Institute comprising up to 34 racks were used to simulate the power system.	The proposed pre-processing scheme is only designed for RTDS	This paper presents a handful number of pre-processing methods automatically processed in using Python programming language. The process duration ranges between 2 and 3 minutes. Furthermore, the proposed scheme enables reporting on reporting deleted and converted substation data.

2.9 LITERATURE COMPARISON AND DISCUSSION

2.9.1 New development

(Grondin, 1981) presented a computer-aided based voltage control method for substation equipped with transformer on-load tap changers. The author indicated that the proposed Scheme was successfully simulated, a prototype was to be built afterwards. The author mentioned the use of approximated values in the algorithm due to the unavailability of certain information. (Bornard, 1988) indicted that with development in integrated substation controls and substation protection schemes, relaying engineering is likewise on its approach to completely integrate local area network. Thus, enhancing real-time data distribution and management.

Moreover, (Kezunovic, 2002) indicated the prediction of two main trends regarding substation automation, these are: Relays are getting progressively flexible as far as capacities and abilities are concerned, and, New algorithms are being introduced. These are based on unconventional approaches such as Neural networks and Fuzzy logic. Furthermore, integration of relays and other IEDs' into all digital substation systems and the use of substation automation systems as remote terminal units of SCADA for the energy management system. Lastly, the development and utilization of digital simulators for relay testing.

(Gibadullin, Pulyaeva and Yerygin, 2018) demonstrated the need for smart and digital substations to accomplish digitalization of energy and tackle the demanding requirement of modern power systems. Smart substations are basically implemented with a sophisticated mixture of intelligent high-voltage equipment and hierarchically networked secondary devices. IEC61850 communication protocol, the functionalities, such as the information sharing and interoperability among smart electric equipment, are realized in smart substations. Smart substations are regarded as the basis for the development of smart grids and the digitalization of power systems (Gibadullin, Pulyaeva and Yerygin, 2018).

2.9.2 Communication

Intelligent electronic devices are widely used in modern and legacy substations for data acquisition, protection, metering, control and automation. Over the past few years, they have been recognised as crucial for optimised operation and management of modern substations. Their integration in substation protection systems and/or control systems is achieved over a substation LAN network using

IEC 61850 as the communications protocol. The integration results enhance the functionality of the system with keeping the cost unchanged (Haffar, Thiriet and Savary, 2007).

IEC 61850 substations architecture presents three levels: Substation level, bay/unit level and process level as illustrated in figure 2-4 below.

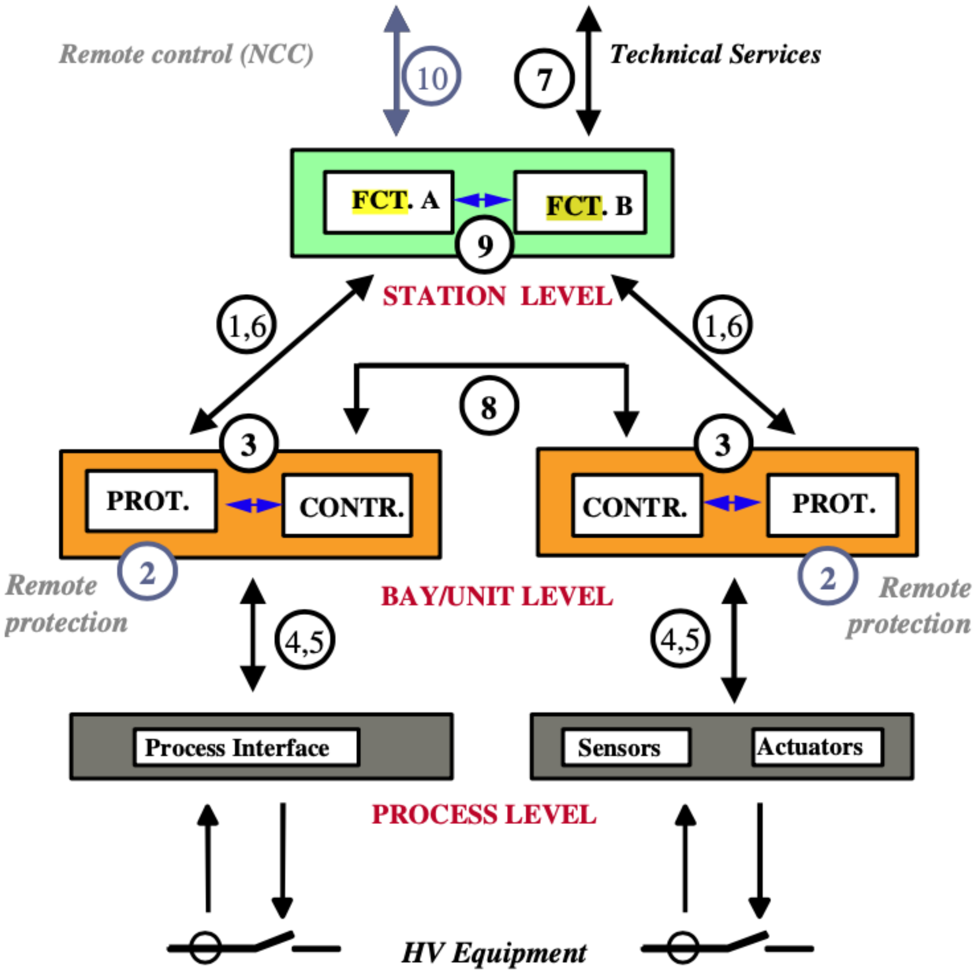


Figure 2-6: Logical interfaces in substation automation (Apostolov, 2005).

In recent years great concerns have arisen regarding the security of communication in substations. According to (Duman *et al.*, 2018), IEC substations are designed with redundancy in the form of multiple subsystems. To ensure continuity of supply in the case a subsystem fails, multiple subsystems are assigned identical tasks. Figure 2-5 below illustrates an IEC 61850 substation with two subsystems.

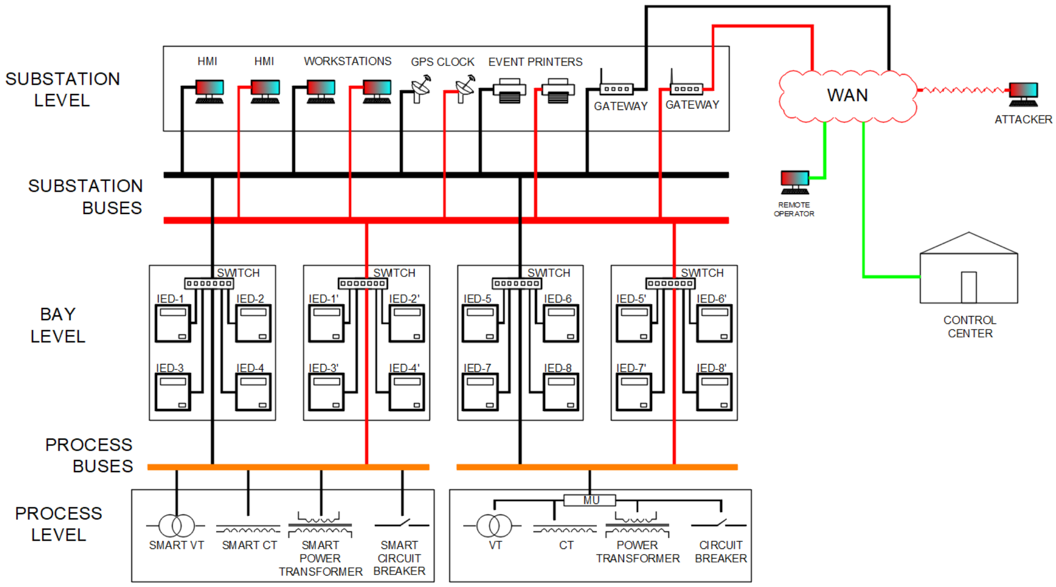


Figure 2-7: IEC 61850 Substation with two subsystems

It can be seen from the illustration above that if a subsystem fails, the 2nd identical will carry on with the normal operation. However, this technic is only effective for natural faults. Malicious attacks deliberately target the weakest link i.e. common vulnerability found in the subsystems (Duman *et al.*, 2018).

2.9.3 Control and automation

Historically, power system optimization, control and automation have been achieved by the use of centrally computed algorithms (Molzahn *et al.*, 2017). This is no longer the case with modern power systems due to their complexity and demanding requirements.

(Molzahn *et al.*, 2017) indicated that the power system has adopted the definition of being "A set of technologies that enable an electric utility to remotely monitor, coordinate and operate distribution components in a real-time mode from remote locations". According to the author, there are three of visualising automation:

- Local automation (Decentralised): This comprises any switch operation by protection or any logic-based decision-making operation
- SCADA (Remote control): This is any manually initiated switch operation via remote control based on remote monitoring of status, indications, alarms and measurements

- Centralised automation: This is any automatic switch operation via remote control from the central decision-making for fault isolation, network reconfiguration, service restoration, etc.

Any automation implementation is mandated to include a minimum of two of the option above. This is because communication is compulsory for implementation (Molzahn *et al.*, 2017).

2.9.4 OLTC control

Generally, controlling a single transformer equipped with OLTC is just a response to a voltage change. Although the control can be achieved with the use of a single controller/ IED, the IEC 61850 standard can still be used for the communication between the actuator and the merging unit. The standard can also be used for the communication between the control centre and the controller (Sichwart, Nelli and Eltom, Ahmed and Kobet, 2013).

The control of a parallel group of transformers requires information sharing between the transformers. Depending on the controlling method employed, the communication between controllers ranges from just a dozen to several hundred signals. The smarter the controller, the more data will need to be shared amount participating controllers (Sichwart, Nelli and Eltom, Ahmed and Kobet, 2013).

In the last decade, the trend shifted to the below-listed aspects of the controllers:

- Bi-directional power flow,
- Adaptative controller,
- Optimisation of tap changer operations,
- Synchrophasor measurement,
- Automatic tap changer blocking

2.10 CONCLUSION

To conclude, this chapter gave an overview of various recorded literature related to the topic under investigation. Literature records on the application of IEC 61850 standards for automated on-load transformer tap changers were consulted and discussed. Furthermore, prior arts on automation, control, as well as hardware-in-the-loop simulation, are summarised and discussed.

In the following two chapters (chapters 3 & 4), theoretical aspects of the topics discussed hereabove will be analysed. Chapter 3 will mainly focus on the construction and working principle of the power transformer and its tap changer. Chapter 4 will deal with the control of the transformer in parallel for voltage regulation.

3.1 INTRODUCTION

Electrical energy is generated at generating plants generally located closer to the energy source such as fossil (gas, coal and uranium), water, wind and concentrated sunlight (solar). Generated electricity has then to be transmitted to the consumption centre generally located in the city centre. From the generation site to the end-user point, generated electricity must undergo a set of alterations and control to achieve optimal transmission and ensure power quality at delivery as illustrated in figure 8 below. Transformers are essential tools in the power system. They are found at the generation site stepping up the generated voltage to a transmission level; in distribution networks stepping down the voltage to the distribution level. Transformers convert voltage from one level to another as a function of the turn's ratio. For more flexibility, some transformers are designed in such a way that the turns ratio can be altered to adjust output voltage for a given constant input voltage.

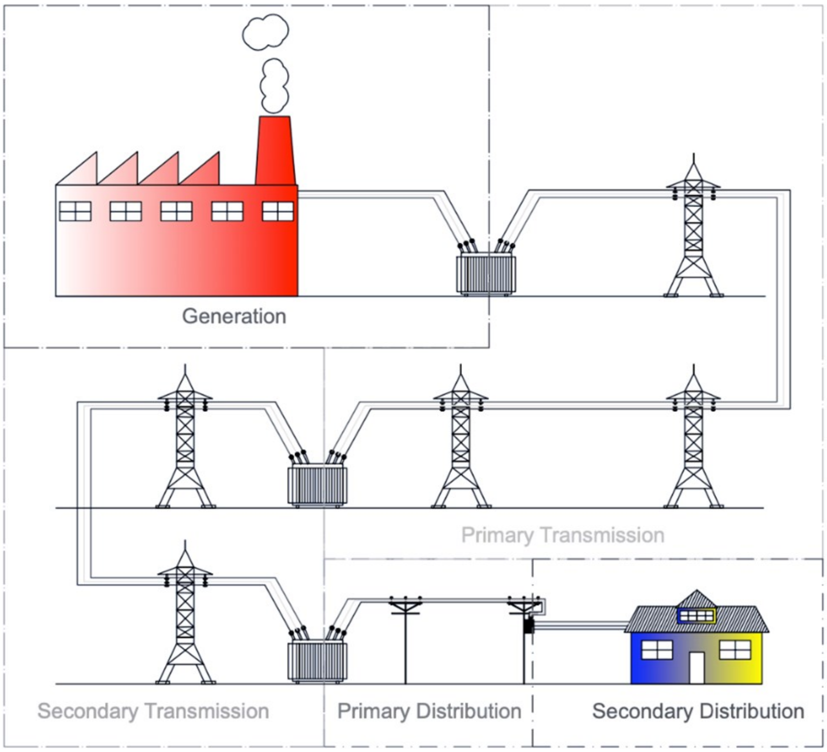


Figure 3-1: Typical power system

Transformers equipped with an on-load tap-changer can adjust the turn ratio while carrying its loads. This chapter deals with theoretical aspects of transformer tap changer and voltage control. The construction of transformers and the tap changers will be discussed.

3.2 OVERVIEW OF TRANSFORMER

Transformers are defined as devices that bridge electrical energy from one circuit to another through a magnetic field. Transformers offer electrical isolation between the two circuits except for some special transformers where the same winding is used for both the primary and secondary circuits (Harlow, 2004).

When a conductor is carrying an alternating current, a magnetic field is created around that conductor. If another conductor is present in the vicinity of the magnetic field created, a voltage will be induced across the second conductor. This is the principle used by electric transformers to transfer electrical energy from the primary circuit to the secondary (Harlow, 2004).

3.2.1 Construction

An electric transformer comprises a primary coil, a secondary coil and a magnetic core. Transformers can be classified into two categories based on their core construction. These are Air-Core transformers and Iron or steel core transformers. The construction of both is illustrated in the figure 3-2 and figure 3-3 below.

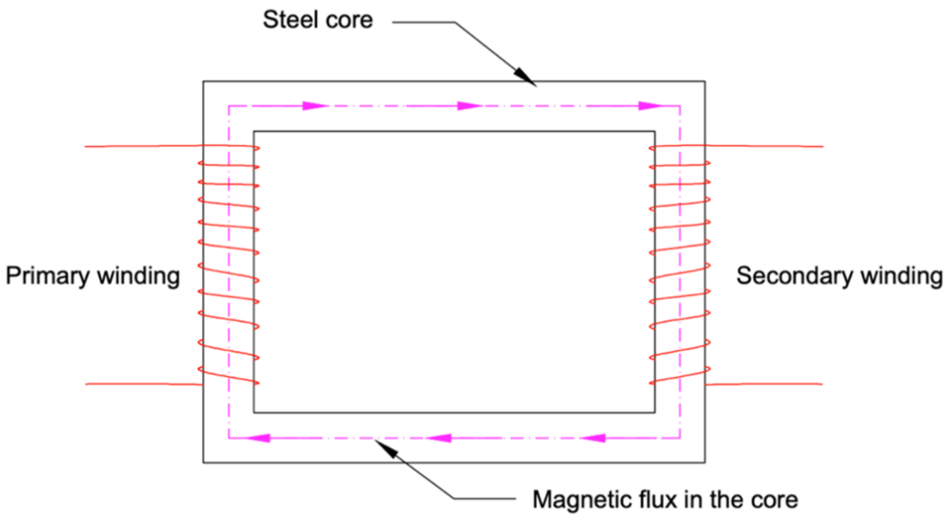


Figure 3-2: Air core transformer type

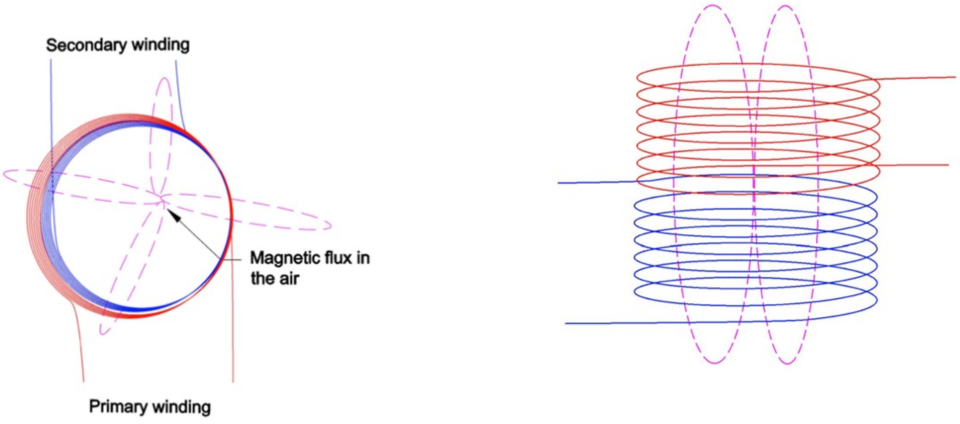


Figure 3-3: Iron or steel core transformer

The iron/steel core type transformer illustrated in Figure 3-2 above uses iron or steel to facilitate the circulation of magnetic flux. Steel or iron are chosen due to their capability to carry magnetic flux with negligible to no losses. The shape of the core depends on the application. Various shapes are used to construct the core. i.e.: round, oblong, square, ferrite, etc…

The air core type transformer used air to circulate magnetic flux. It is important to note that the ability of the air to carry magnetic flux is 1500 times less than that of iron/steel. Thus, air-core transformers are usually used in low power applications (Harlow, 2004).

3.2.2 Ideal transformer

The ideal transformer has no losses. The equivalent circuit of an ideal transformer is given in Figure 3-4 below. This is the simplified version of the transformer to illustrate basic principles.

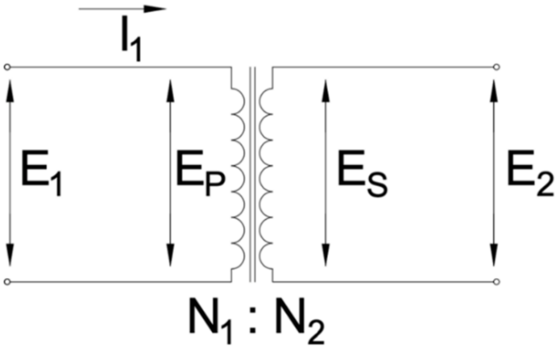


Figure 3-4: Ideal transformer Equivalent circuit

When a voltage E_1 is applied to the primary coil of the transformer as illustrated in figure 8 above, a current I_m will flow in the coil. Neglecting the resistance of the coil, the current flowing in the coil is given by:

$$I_m = \frac{E_1}{X_m} \qquad \text{Equation 3-1}$$

Where X_m is the reactance of the coil.

Voltage E_p is the voltage induced in the primary coil and s equal E_1, the same applies to E_s and E_2

The magnetizing current I_m produces a magnetic flux Φ_1 given by the formula below.

$$\boldsymbol{\Phi_1} = \frac{\mathbf{E_1}}{\mathbf{4{,}44\ fN_1}} \qquad \text{Equation 3-2}$$

Where N_1 is the number of turns of the primary coil.

The magnetic flux Φ_1 created will travel through the magnetic core then induce a voltage E_2 in the secondary coil. The induced voltage is expressed as follows:

$$E_2 = 4{,}44\ fN_2\Phi_1 \qquad \text{Equation 3-3}$$

By substituting equation 3-2 in 3-3, the following is obtained

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \mathrm{c} \qquad \text{Equation 3-4}$$

Where

E_1 is the voltage at the primary terminal of the transformer

E_2 is the voltage at the secondary terminals of the transformer

N_1 is the number of turns on the primary side

N_2 is the number of turns on the secondary side

C is the turns ratio

If a load z is connected to the secondary terminals of the transformer, a current will subsequently flow in the secondary coil.

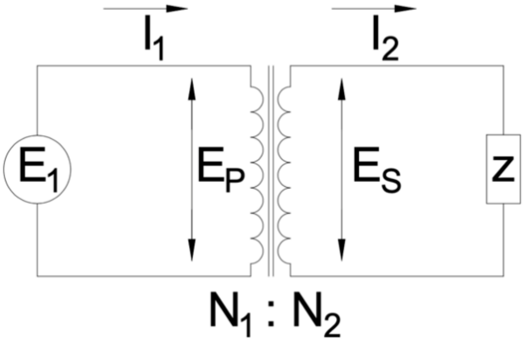


Figure 3-5: Ideal transformer under load

The current I_2 flowing in the secondary winding will be given by the expression below

$$I_2 = \frac{E_S}{Z} \quad \text{Equation 3-5}$$

Since the ideal transformer ignores losses in the transformer, the voltage at the secondary terminals will remain the same with or without a load connected. Figure 3-6 below shows the phasor relationships under load conditions.

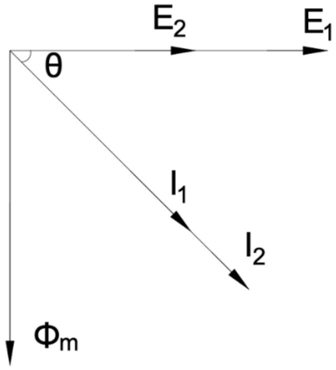


Figure 3-6: Phasor diagram

An expression summarizing the relationship between secondary and primary quantities is given below:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = C \quad \text{Equation 3-6}$$

Where,

E_1 is the primary voltage

E_2 is the secondary voltage

N_1 is the number of turns of the primary coil

N_2 is the number of turns of the secondary coil

I_1 is the primary current

I_2 is the secondary current

C is a constant.

The above equation indicates the input put power of the ideal transformer is equal to its output.

3.2.3 Practical transformer

In previous sections we have discussed the ideal transformer its basic properties were highlighted. However, in real life, the ideal transformer does not exist. For each conversion of power from one form to another, there are always losses. The simple analysis done in the previous section will have to be modified to take into consideration transformer losses. The following process chart indicates various conversion steps in a transformer.

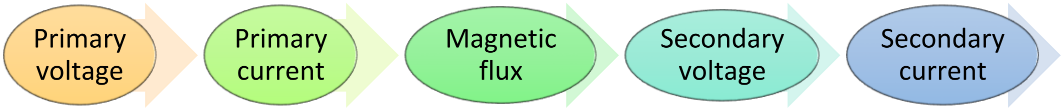


Figure 3-7: Transformer process chart

The conversion at each step of the process chart illustrated above presents some losses. These losses can be classified into two groups namely: Copper losses and core losses. The copper losses occur during the voltage ➔ current process. The core losses occur during the current ➔ magnetic flux or magnetic flux ➔ voltage process. The core losses comprise “eddy current loss” and “hysteresis loss”. Both losses are depending on the magnetic properties of the core material as well as its construction

To reduce the loss created from eddy current, the core is laminated from very thin sheets. Each sheet is coated with a very thin insulation material to prevent shorts between the laminations.

When AC voltage is applied to the primary winding of a transformer, the flux density alternates between $-B_m$ and $+B_m$ at a frequency equal to the voltage frequency

(50Hz). During each cycle, the magnetic material absorbs energy. This energy is dissipated as heat and is known as Hysteresis loss (Wildi, 2006). To determine losses in a transformer, No-load and Full-load tests are performed. The equivalent circuit of a two windings transformer is illustrated in Figure 3-8 below. The circuit comprises inductive and resistive elements (R_1, R_2, R_m, X_1, X_2, X_m, Z). coupled together by a mutual flux Φ_m.

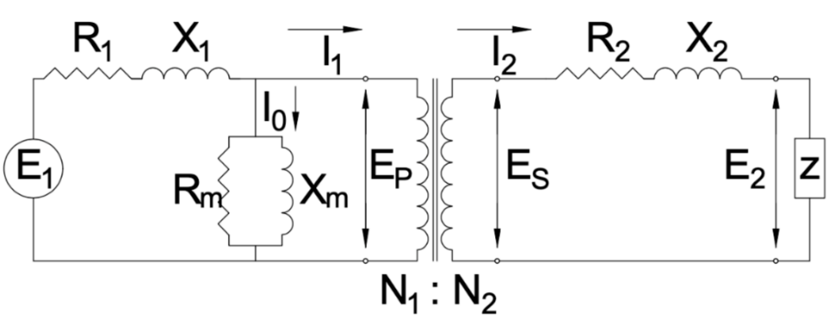


Figure 3-8: Transformer equivalent circuit for two windings transformer

Where:

E_1 is the input voltage on the primary terminals of the transformer

R_1 is the ohmic resistance of the primary windings

X_1 is the reactance of the primary windings

R_m is the magnetizing resistance

X_m is the magnetizing reactance

I_0 is the exciting current

I_1 is the primary current

E_p is the primary voltage

N_1 is the number of turns of primary coil

N_2 is the number of turs of secondary coil

E_s is the secondary voltage

I_2 is the Secondary current

R_2 is the ohmic resistance of the Secondary windings

X_2 is the reactance of the Secondary windings

E_2 is the voltage on the secondary terminals of the transformer

Z is the impedance of the load connected to the transformer.

X_m and R_m are determined by performing the **no-load test**. In this test, the rated voltage is applied to the primary terminals of the transformer. Since there is no load connected to the secondary side, the secondary current I_2 is zero. Consequently, the current I_1 is also equal to zero. Only I_0 will flow in the primary winding creating a voltage drop across X_1 and R_1. This voltage drop is very small and can be neglected resulting in a simplified equivalent circuit given in Figure 3-9 below.

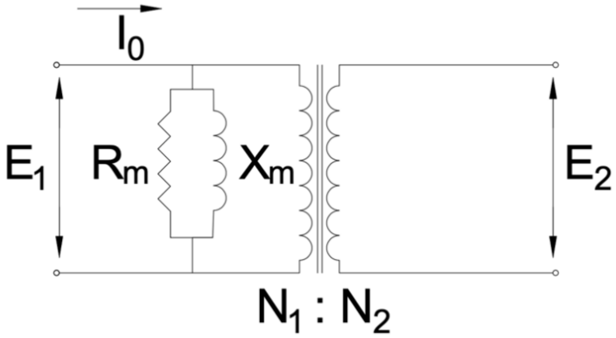


Figure 3-9: Simplified equivalent circuit at no load

Power absorbed can then be measured and applied in the below equations to calculate X_m and R_m

$$R_m = \frac{E_1^2}{P_m}$$ Equation 3-7

$$X_m = \frac{E_1^2}{Q_m}$$ Equation 3-8

Where,

R_m is resistance expressed in Ω representing the iron losses

X_m is the magnetizing reactance of the primary winding expressed in Ω

E_1 is the primary voltage in V

Q_m is the iron losses expressed in W

P_m is the reactive power required to set up the mutual flux Φ_m expressed in var

During the full load test, the primary voltage of the transformer is gradually increased with the secondary of the transformer short-circuited. The primary voltage will be increased until the rated primary current is reached. At this point, the primary current I_1 will be about 20 times greater than the exciting current I_0. For this reason, the power losses in the iron core and the power required to set up mutual magnetic flux is very small and will be neglected in the calculation (Wildi, 2006). The simplified full load circuit is given in Figure 3-10 below.

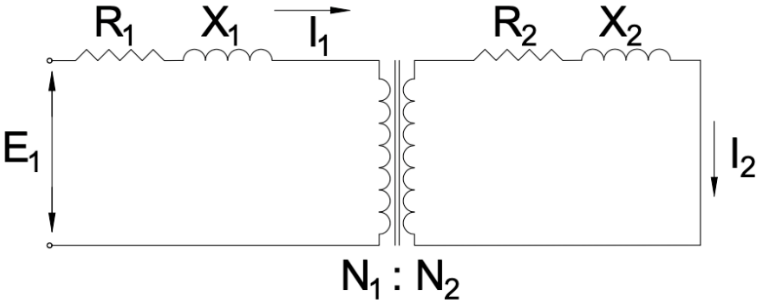


Figure 3-10: Simplified equivalent transformer full load circuit

For ease of calculation, the secondary impedances can be shifted to the primary side by multiplying their values by $(\frac{N_1}{N_2})^2$. Thus, the equations below apply:

$$\mathrm{R_p = R_1 + c^2R_2} \quad \text{Equation 3-9}$$

$$\mathrm{X_p = X_1 + c^2X_2} \quad \text{Equation 3-10}$$

$$\mathrm{R_p = \frac{P_1}{I_1^2}} \quad \text{Equation 3-11}$$

$$\mathrm{X_p = \frac{Q_1}{I_1^2}} \quad \text{Equation 3-12}$$

Where,

R_p is the total resistance of the transformer as seen from the primary [Ω]

X_p is the total reactance of the transformer as seen from the primary [Ω]

I_1 is the primary full load current (rated current) [A]

Q_1 is the total full load reactive power losses [var]

P_m is the total full load active copper losses [W]

Loses in a practical transformer comprises:

1. Copper loses (I^2R): the losses in the windings
2. Hysteresis and Eddy-current losses in the core
3. Stray losses due to currents induced in the oil tank and metallic supports by the leakage fluxes.

The losses appear in the form of heat resulting in an increase in temperature and reduction of efficiency. Unlike other electrical machines, transformers are designed to run at very high up to 99.50%.

3.2.4 Voltage regulation

Transformer voltage regulation is defined as the difference between no-load (NL) and full-load (FL) voltage expressed in percentage. Voltage regulation is defined by the equation below:

$$\text{Voltage regulation} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100 \qquad \text{Equation 3-13}$$

The voltages used in the equation above are the secondary voltage. The voltage regulation depends on the power factor of the load connected. For capacitive load, the full-load voltage may exceed the no-load voltage. In this case, the voltage regulation is negative (Wildi, 2006).

3.2.5 Transformer tapping

Under no-load conditions, the output voltage of the transformer is a function of input voltage and the turns ratio. When a load is connected to the transformer, the current flowing in the windings will create a voltage drop across the transformer. Thus, the output voltage will depend also on the current flowing in the windings. For this reason, transformer taps are introduced. The tapping will allow changing the turns ratio in doing so, the secondary voltage can be kept within predetermined boundaries.

Transformer taps are also used to keep the secondary voltage within predetermined boundaries while the primary voltage is changing. To explain how transformer tapping works, a transformer with 5 taps is assumed in Figure 3-11 below.

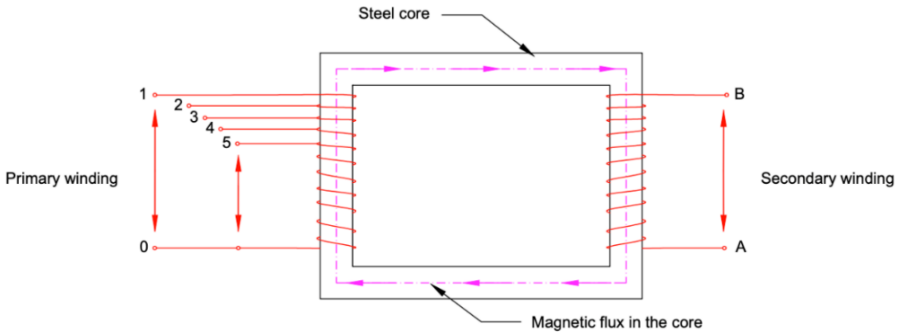


Figure 3-11: Transformer taps

Assuming the number of turns on the primary coil between point 0 and 1 to be 1000 turns (N_1) and on the secondary to be 50 turns (N_2). If 2400V (V_1) is the input voltage, at tap 1. The output voltage will be calculated as follows:

$$V_2 = \frac{V_1 \times N_2}{N_1} \rightarrow \frac{2400\text{V} \times 50}{1000} = 120\ \text{V} \qquad \text{Equation 3-14}$$

Should the primary voltage change for any reason let's assume 2300 V, the secondary will therefore drop to 115V. To keep the secondary voltage unchanged regardless of the change in the primary voltage, the turns ratio needs to change.

To keep the voltage on the secondary side to 120V with 2300 applied at the primary and the number of turns being 50 turns on the secondary, the primary winding must have approximately 958 turns.

If each tap o the transformer indicated in figure 3-11 above corresponds to 60 turns and the secondary side can variate between 125V and 115V, the table below shows various tap settings for the given voltage on the primary.

Table 3-1: Tap Setting and output/input voltage range

Tap	Input voltage range	Turns Ration	Output voltage range
1	2300V – 2500V	1000:50	115V – 125V
2	2185V – 2375V	950:50	115V – 125V
3	2070V – 2250V	900:50	115V – 125V
4	1955V – 2125V	850:50	115V – 125V
5	1840V – 2000V	800:50	115V – 125V

The tap settings can successfully be used to remedy voltage drop across the transformer due to the load current.

3.3 SPECIAL TRANSFORMERS

Transformers are generally designed to meet specified industrial applications. In this section, a list of the most popular special transformers is given.

- Dual-voltage distribution transformer
- Autotransformer
- Potential transformer
- Current Transformer
- High-impedance transformers
- Induction heating transformers
- High-frequency transformers

3.4 THREE PHASE TRANSFORMERS

Electrical power is generally generated using three-phase synchronous machines. It is then stepped up to a transmission level using three-phase transformers. At distribution substations, high voltage is stepped to medium and low voltage using three-phase transformers. In this section, we will discuss three-phase transformers, their construction, basic properties and connections.

3.4.1 Basic properties of 3-phase transformers

Three-phase transformers consist of three primary windings and three secondary windings. The windings can be connected in various scenarios, the primary may be connected in star/delta and the secondary in star/delta or vice versa. Various configurations will be discussed hereunder.

An important note about three-phase transformers, the output three-phase voltages is not only a function of turns ratio and input voltage but also the connection of windings. The three-phase connection can also create a phase shift between the input and out three-phase voltages. Figure 3-12 below illustrates 6 winding winded on a magnetic core.

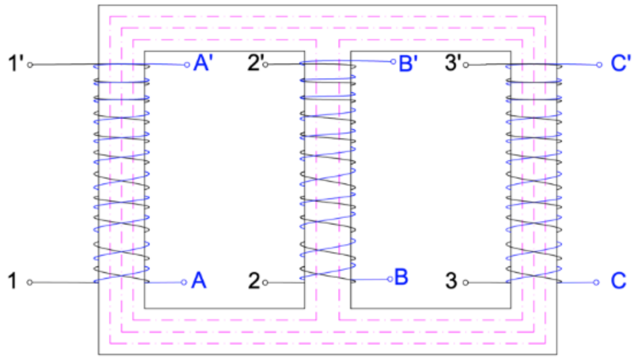


Figure 3-12: Three-phase transformer

Considering coils 1 – 1', 2 – 2' and 3 – 3' being the primary coil having an identical number of turns and coil A – A', B – B', C – C' being the secondary coil having an identical number of turns. Each coil represents a phase. The winding group can either be connected in star or delta resulting in a combination of 4 configurations. i.e.:

- Delta – Delta connection (∆/∆)
- Delta – star connection (∆/Y or ∆/Yn)
- Star – Delta (Y/∆)
- Star – Star (Y/Y, Y/Yn, Yn/Yn, Yn/Y)

Figure 3-13 below shows the typical winding connection of a delta–star transformer (∆/Yn)

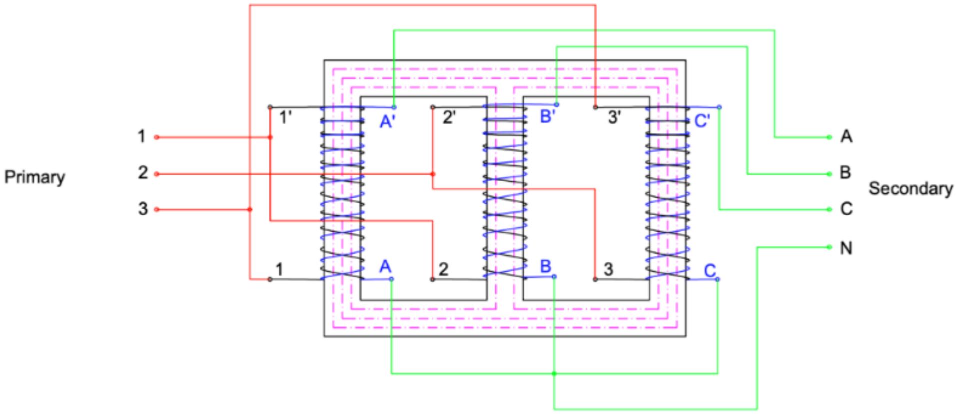


Figure 3-13:Three-phase transformer Delta - Star connection

Figure 3-14 below shows the phasor diagram of a Delta – star (Δ/Yn) connected transformer with a neutral connection on the star side.

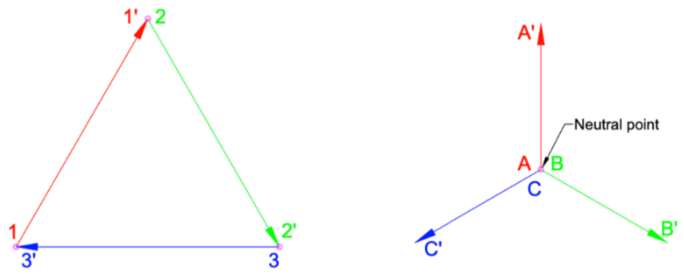


Figure 3-14: Delta and star connection phase diagram

Under normal/balanced conditions, the three primary voltages have equal magnitude and 120º phase shift from each other. The same applies to secondary voltages.

The volt voltage relationship between the primary and the secondary can be obtained for each of the 4 connection scenarios listed above as follows:

- Delta – Delta connection (Δ/Δ): For this connection, the voltage will depend on the turns ratio only.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = c$$ Equation 3-15

Where,

E_1 is the primary line voltage

E_2 is the secondary line voltage

N_1 is the number of turns of the primary coil

N_2 is the number of turns of the secondary coil

I_1 is the primary line current

I_2 is the secondary line current

C is a constant.

- Delta – star connection (Δ/Y or Δ/Yn): For this connection, a $\sqrt{3}$ factor will be introduced for the conversion of delta to star.

$$\frac{E_1}{E_2} = \frac{N_1\sqrt{3}}{N_2} = \frac{I_2}{I_1} = c \qquad \text{Equation 3-16}$$

- Star – Delta (Y/Δ): For this connection, a $\sqrt{3}$ factor will be introduced for the conversion of a star to the delta.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2\sqrt{3}} = \frac{I_2}{I_1} = c \qquad \text{Equation 3-17}$$

- Star – Star (Y/Y, Y/Yn, Yn/Yn, Yn/Y): For this connection, the voltage will depend on the turn's ratio only.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = c \qquad \text{Equation 3-18}$$

3.4.2 Phase shift in three-phase transformers

A three-phase system gives the ability to shift the output voltage and/or create a system of two-phase, six-phase, twelve-phase from an ordinary three-phase system. Phase shift in a three-phase transformer can be accomplished by using a rheostat or by arranging the windings in a certain configuration (Wildi, 2006). In the following texts, we will discuss the accomplishment of phase shift by arranging windings around the magnetic core.

3.5 TRANSFORMER TAP CHANGER

Transformer taps help to alter turns transformer turns ratio thus, changing the relation between the input and output voltage. The main application of taps in the power system is to control and adjust the voltage. The change in loading results in a change in the power system voltage. It is noted that taps can be used to accomplish phase shifts as well (Jawad and Siahkolah, 2011).

Transformer tap-changers can be classified into two main categories namely:

i. Off-load or no-load tap-changers.
ii. On-load or under-load tap-changer.

Tap-changer featuring the ability to change the taps while the transformer is connected to the power is called an on-load tap-changer. The off-load tap-changer allows the changing of tap only when it is not when disconnected from the power system. Taps are generally changed manually in off-load tap-changer utilizing a mechanism installed on the outside of the transformer and called a selector (Jawad and Siahkolah, 2011). The selector can be of circular or linear structure. The structure of a circular selector is shown in Figure 3-15 below.

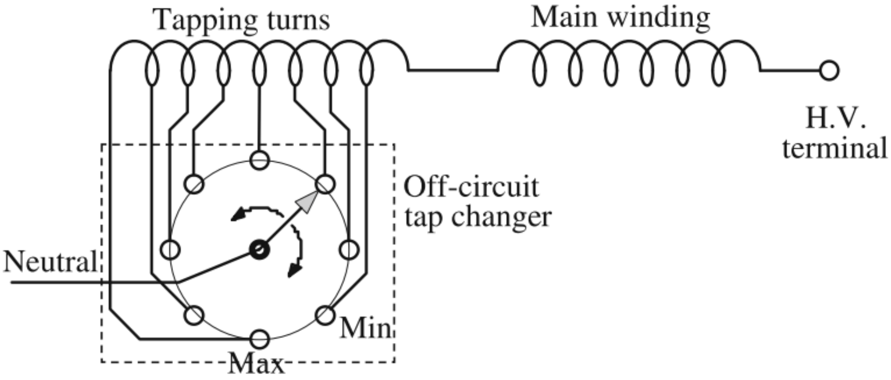


Figure 3-15: Stricture of a no-load tap-changer circular selector (Jawad and Siahkolah, 2011)

3.5.1 On-load tap changer

Before the age of large power networks, the primary technic used to adjust the voltage in miniature and isolated power networks was the varying generator excitation system. However, this technic can no longer be used in modern networks due to its nature. On-load tap-changers are useful tools used to accomplish voltage adjust in modern power systems. The stricture of an on-load tap-changer is complex compared to the one of a no-load tap-changer. The control is accomplished remotely or automatically dictated by pre-programmed logic statements. Note that during the tap changing stage, to maintain the supply to the load, the next tap will have to be engaged before the current tap is disconnected. In the following paragraphs, we will briefly discuss the types of on-load tap changers.

3.5.1.1 Reactor on-load tap-changer

The reactor on-load tap changer was invented in 1926 (Westinghouse, 1964). It comprises more than one circuit. The simplest form of reactor on-load tap-changer is illustrated in Figure 3-16 below.

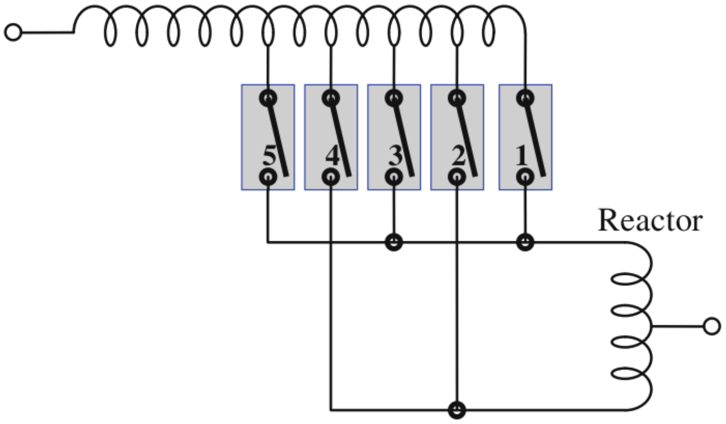


Figure 3-16: Reactor on-load tap-changer

The operation of the on-load tap-changer illustrated in Figure 3-20 above can be summarised in Table 3-2 below. It is important to note that two consecutive switches can be in position on at the same time outputting a mid-tap voltage. Thus, the combination of the 5 taps indicated in Figure 2-20 above produces 9 taps setting as summarized in Table 3-2 below.

Table 3-2 : Reactor on-load tap-changer

Switch no/tap setting	1	2	3	4	5	6	7	8	9
1	On	On							
2		On	On	On					
3				On	On	On			
4						On	On	On	
5								On	On

3.5.1.2 Resister on-load tap changer

Around 1998, on-load tap changers were almost completely replaced by fast resistor on-load tap changers (Serafini, 1998). They can generally be classified into two categories based on their circuit arrangements namely:

1. Type i: Are those that select taps and do load current deviation in one single contact
2. Type ii: Are those which have distinguishable diverter switches and tap selector switches.

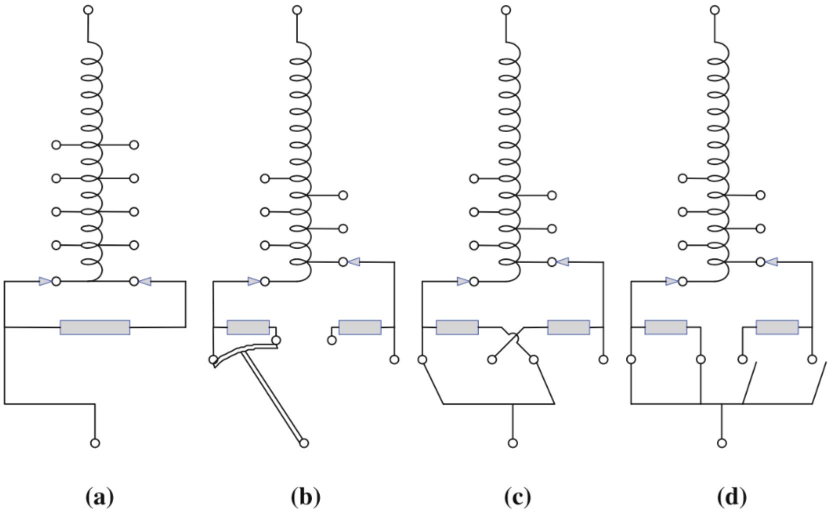


Figure 3-17: Switch arrangements in resistor on-load tap-changer (Jawad and Siahkolah, 2011)

Figure 3-17 above illustrates various switch circuit arrangements in resister on-load tap-changers. Figure 3-17(a) shows the type i arrangement. This arrangement is most of the time accomplished with the use of rotating switches and it is named pennant cycle (Jawad and Siahkolah, 2011). Figure 3-18 below illustrates the different steps of tap changing in type i arrangement. Figure 3-17(b), (c) and (d) illustrate the type ii arrangement. This arrangement is called the flag cycle (Jawad and Siahkolah, 2011). This arrangement is commonly used in large transformers. Tap changing stages of this type are illustrated in figure 3-19 further down in the text.

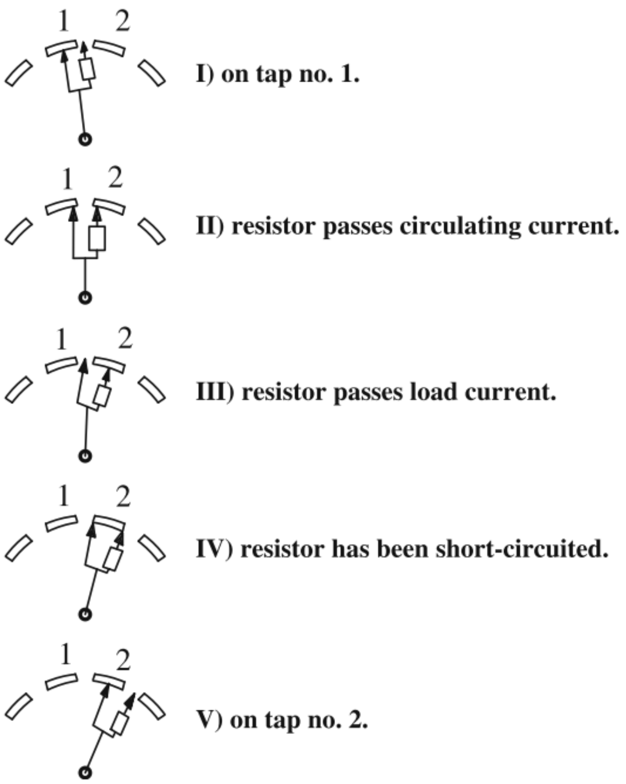


Figure 3-18: Tap transition from tap 1 to tap 2 of type i arrangement of a resistor on-load tap-changer (Jawad and Siahkolah, 2011)

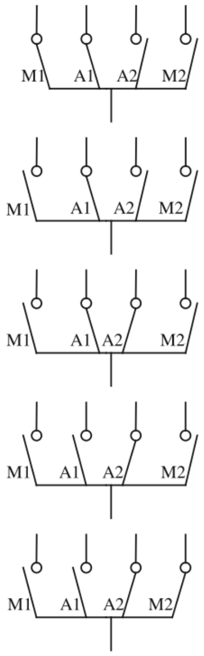


Figure 3-19: Tap changing stages of the structure illustrated in figure 3-21(d) *(Jawad and Siahkolah, 2011)*.

3.5.1.3 Laminations: Mechanical on-load tap-changers

Despite progression in the structure of mechanical under-load tap-changers, these tap-changers have a few disadvantages; for instance, the main consideration which makes harm to power transformers is their tap-changer failure. A few disadvantages of mechanical on-load tap-changers are as per the following (Jawad and Siahkolah, 2011) :

- High maintenance and costly service
- Formation of contact arc in diverter switches during tap-changing
- Slow tap-changing process
- Great power losses during tap-changing

To remedy the above advantages, two on-load tap changers are introduced. These are Hybrid on-load tap changers and solid-state on-load tap changers. The two tap changers are the most used in modern and smart power systems. They will be discussed in detail in the text hereunder.

3.5.1.4 Hybrid on-load tap-changer

Hybrid on-load tap changers also known as electronically assisted on-load tap changers were introduced to remedy the arcing issue with mechanical on-load tap changers. Electronic switches offer more controllability as opposed to mechanical switches. The first suggest circuit of the hybrid on-load tap-changer was very similar to the circuit of the resister on-load tap changer. In fact, (Jawad and Siahkolah, 2011) suggested that it was just an improvement of the resistor on-load tap changer. The suggested circuit is illustrated below.

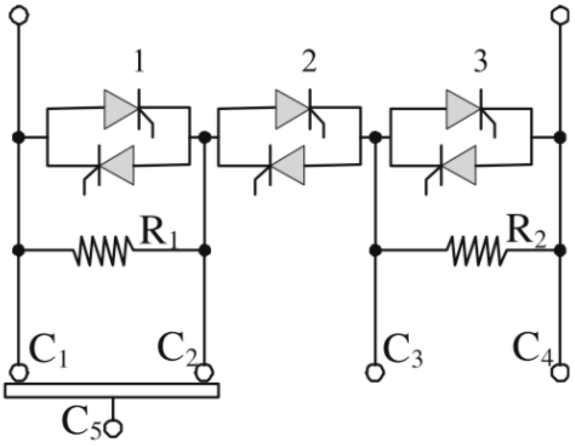


Figure 3-20: First suggested circuit of hybrid on-load tap changer

To transition from one tap setting to another, the moving contact indicates C_5 in Figure 2-20 above must slide from left to right or vice versa(mechanical). During the transition, the relevant transistors are switched on diverting the current previously responsible for arching in fully mechanical on-load tap changers. Thyristors indicated in Figure 3-20 above solve the issue with arcing on one hand on the other it reduces the reliability of the system with the possibility of burning. To remedy the problem, the circuit in Figure 3-21 is recommended.

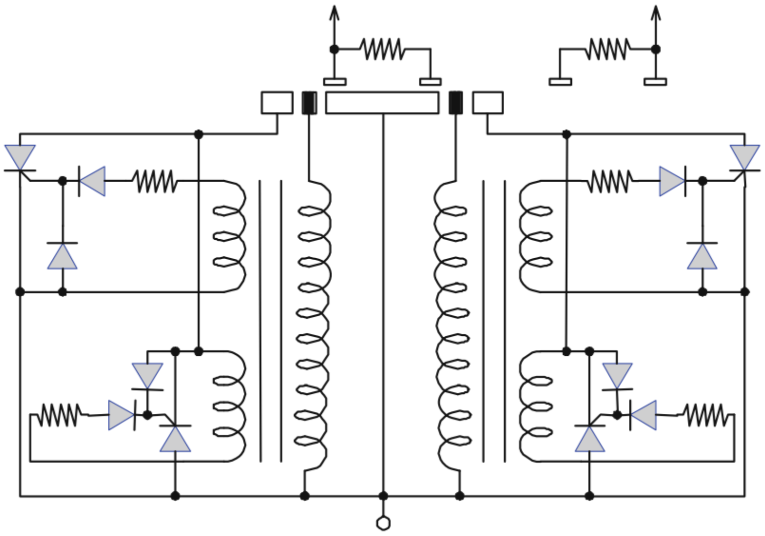


Figure 3-21: Hybrid on-load tap changer structure (Jawad and Siahkolah, 2011)

Thyristor pairs in the structure illustrated in figure 3-21 are connected to the circuit only during tap transition otherwise it is isolated from the main circuit. This increases the reliability of the system because should thyristor pairs fail, the on-load tap changer system will not still function. The operation of this proposed structure can be well explained by observing Figure 3-22 below. It describes the positions of contacts during the switch-on and switch-off period.

C_2, C_3 and C_4 in Figure 3-22 below are mobile contacts that move from left to right to connect the switch S as follows:

- C_4, the auxiliary contact moves to the left to connect to contact C_1. At this stage, the thyristors gates restrict the flow of current. Thus, there is no current flowing through the thyristors.

In addition to C_4, the sensing contact C_3 also connects to C_1 short-circuiting the primary side of the transformer Tr_1 indicated in Figure 3-22 below. Then the command is issued to the thyristors gates to allow the current to flow. The total load current is then transferred to terminal C_2. C_2 and C_3 are then discontented, the switch connecting process is completed.

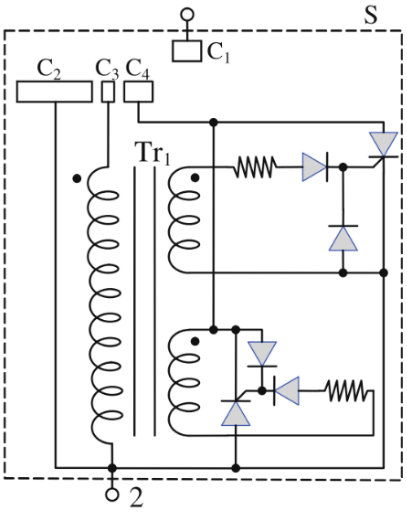


Figure 3-22: Contact position during switch on/off(Jawad and Siahkolah, 2011)

3.5.1.5 Solid-state on-load tap changer.

The concept of solid-state on-load tap changers was introduced in 1973. However, they were limited to uncommon applications. It is only in the 90's that the very first extensive academic investigation of solid-state on-load tap changers was conducted, at that point exploration proceeded (Jawad and Siahkolah, 2011).

The prime characteristic of a solid-state on-load tap changer is that there are no moving parts in the mechanism resulting in the inevitability of no formation of arc during tap transition. Below listed are some of the top advantages of a Solid-state on-load tap changer.

- Very low maintenance cost: Because there are no movable parts in the structure, no arc can be generated during tap transition. Thus, the maintenance is almost zero.
- High speed: solid-state on-load tap changers are known for very fast tap changing process. In half a cycle it can execute at least one ta change.
- Tap jumping: solid-state on-load tap changer ambles tap jumping since there is no circulating current between taps.
- Better performance: solid-state on-load tap changers are known for high-speed tap changing and its controllability of switches. This leads to an infinite number of possible configurations of the switches. In addition to this, there is a possibility of customisation of the tap changer and applying it in intelligent applications to tackle voltage slag issues.

- No limit to tap-changing time.

Some of the disadvantages of solid-state on-load tap changers are listed below (Jawad and Siahkolah, 2011).

- High cost: fully electronic on-load tap changers are expensive compared to mechanical ones.
- High losses: solid-state on-load tap changers present larger voltage drop across switches as opposed to mechanical switches.
- Solid-state on-load tap changers are required to withstand full fault current, and larger transient current caused by lightning.

The typical structure of a solid-state on-load tap changer is illustrated in Figure 3-23 below. On the left-hand side is the tap changer with a passing impedance, on the right is the one without a passing impedance. All switches in the structure are AC power electronic switches comprising thyristor pairs. In addition to thyristor pairs, a vacuum switch or high power rated thyristor is used to bypass fault conditions, transformer inrush and protect other thyristor switches(Jawad and Siahkolah, 2011).

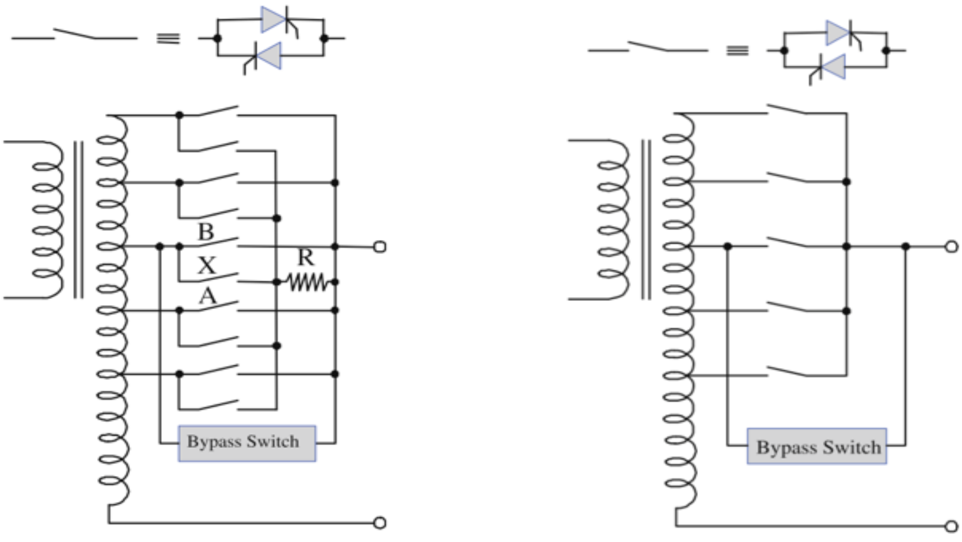


Figure 3-23: Typical structures of a solid-state (Jawad and Siahkolah, 2011)

Figure 3-24 below shows the circuit model of the secondary of transformer equipped with a tap changer.

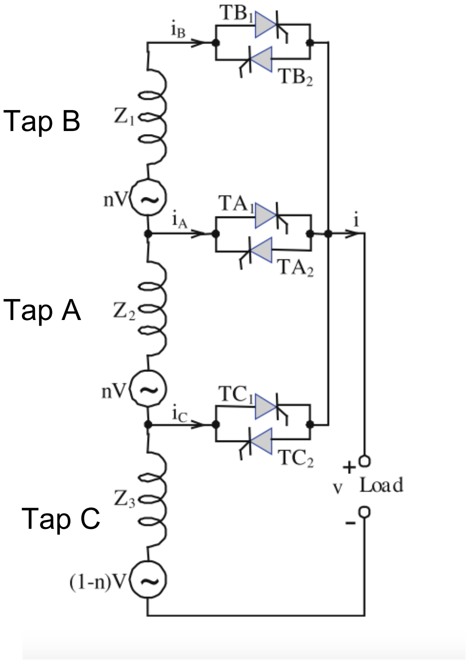


Figure 3-24: Circuit model of the secondary of a transformer equipped with solid-state on-load tap changer

To transit from tap A to tap B in the solid-state tap changer illustrated in Figure 3-24 above, the following stages are observed:

- At first, the gate signal of thyristor pair A is off meanwhile the one for pair X is on.
- In the following cycle, the gate signal of thyristor pair B and X are on both simultaneously.

It is noticed that signals issued at the gate of the thyristors are responsible for turning them on. However, it is not necessary to send signals that turn them off. Essentially the gate's off signal or inverse applied voltage causes the thyristor current to inexact to zero. Thus, when a gate signal of thyristor pair A is off and that thyristor pair X is held, thyristor pair X isn't really switched off while pair-thyristor B is on and prepared to allow the current to pass. Subsequently, there is most likely a circulating current between thyristor pair A and pair X. This current will be limited by the passing impedance R. once thyristor pair A is completely switched off, the next stage of tap transition continues (Jawad and Siahkolah, 2011).

The structure on the right-hand side in Figure 3-23 is a strategy of switch arrangement to reduce the number of switches and eliminate the circulating current.

It can be observed that the passing impedance has been removed. The same structure is illustrated in Figure 2-24. For simplicity reasons, only three taps are indicated. For the tap position to change from tap A to B or C, the signal off signal is sent to thyristor pair A, and the on signal to the proposed tap associated switch. Care must be taken while this operation is performing to avoid taps short-circuiting – typically of about one cycle. To prevent harm to the switches from short circuit current, the switching instance must be precisely controlled (Jawad and Siahkolah, 2011).

It is noted that switches in solid-state transformer tap-changer are high frequency. Thus, solid-state tap is referred to as high-frequency AC to AC converter. Insulated-gate bipolar transistors (IGBTs) are often used as solid-state switches. High-frequency switching in solid-state tap-changer leads to the enhancement of the capabilities of tap-changer (Jawad and Siahkolah, 2011). Some of the capabilities are improving the waveform and continuously output voltage control and regulation. On the other hand, some drawbacks are the complexity of the system, generation of high frequencies harmonics and high tap changer losses. These put limitations on its uses (Jawad and Siahkolah, 2011).

Solid-state on-load tap changers enable automatic tap communication as well as a remote control. Consequently, automatic voltage regulation. With proper interaction systems and remote supervision, smart devices such as smart transformers are created (De Oliveira Quevedo *et al.*, 2017).

3.6 ON-LOAD TAP-CHANGER CONTROL OF TRANSFORMERS

Traditional power systems are characterised by their simplicity. The system is often arranged in radial configuration and transformers operate in solo mode. The current electricity demand requirements inevitably resulted in complex power systems with spider connections. Thus, the control of transformers equipped with on-load tap changers is no longer just a simple response to a voltage deviation at the secondary terminal of the transformer. Modern on-load tap changer control technics involve the use of complex algorithms and intelligent electronic devices. They include tones of ancillary functions and use calculated parameters shared utilizing communications capabilities, i.e. IEC61850 standards.

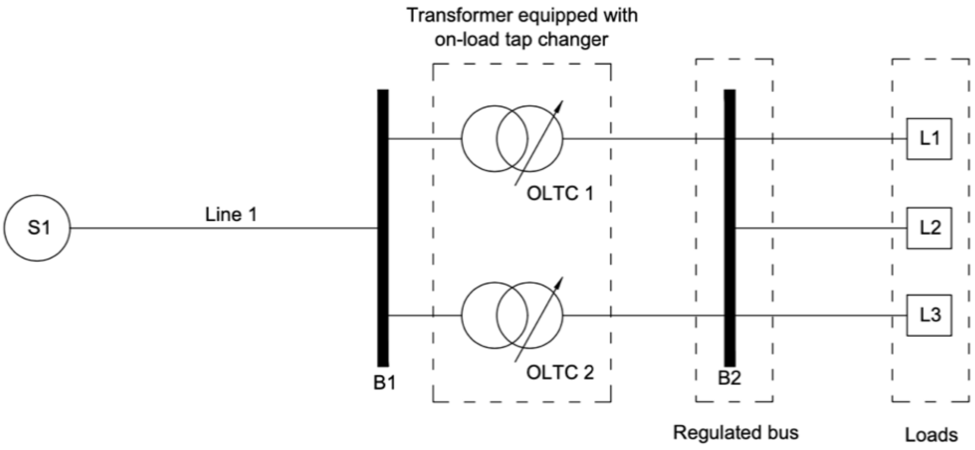


Figure 3-25: Voltage regulation by means transformer equipped with OLTC

In this section, parallel operation of transformer equipped with on-load tap changer will be discussed. Controlling methods and technics will be detailed in depth.

3.6.1 On Load Tap-Changer Control inputs

In many cases, transformers equipped with OLTC involve 33 voltage taps of 0.625% nominal voltage or 17 taps of 1.25% nominal voltage. In both cases, the voltage deviation from the rated ranges from -10% to 10% (Harlow, 2012). The control comprises a set of predefined algorithms, set points and logic. Inputs are analogue measured quantities converted to digital and calculated parameters.

3.6.2 On Load Tap-Changer Voltage input

The voltage is the primary input of the tap controlling system. For radial networks with no reverse power flow, the primary voltage of the transformer is of no use. However, in power networks where power can flow in the opposite direction the primary voltage is of huge importance.

The control system uses low voltage apparatus. Thus, potential transformers are required to step down the system voltage to a safe low voltage typically 120V.

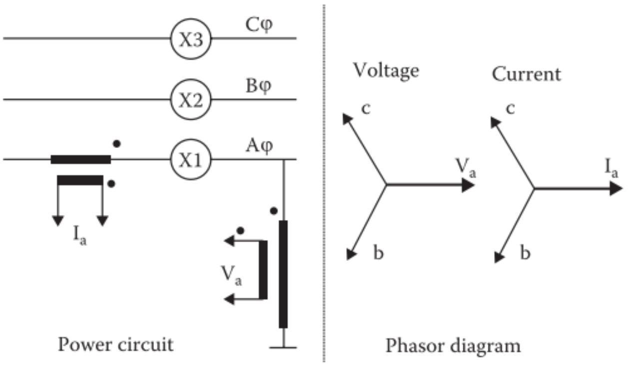
3.6.3 On Load Tap-Changer Current input

Current information is obtained with the help of current transformers. They are generally rated 1A and 5A secondary current. Most transformer manufacturers provide current transformers that supply current for the control circuit. This current usually range between 0.15A and 0.20A when the transformer is carrying the rated full load current (Harlow, 2012).

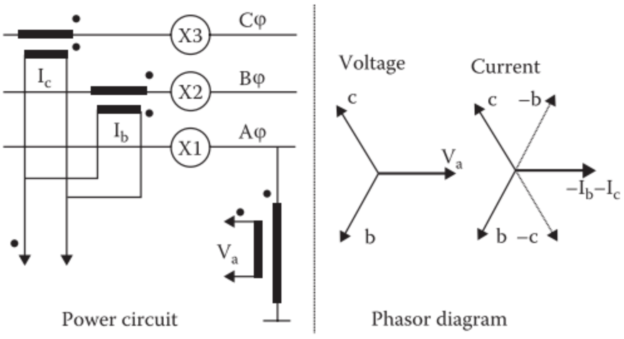
3.6.4 On Load Tap-Changer Phasing between voltage and current

Current and voltage input signals transferred to the control circuit are required to reflect the true phase shifting of the primary circuit. A set of CT's and VT's is used in a predefined configuration to extract the phasing between voltage and current. This information is crucial when performing power factor correction or using the circulating current method.

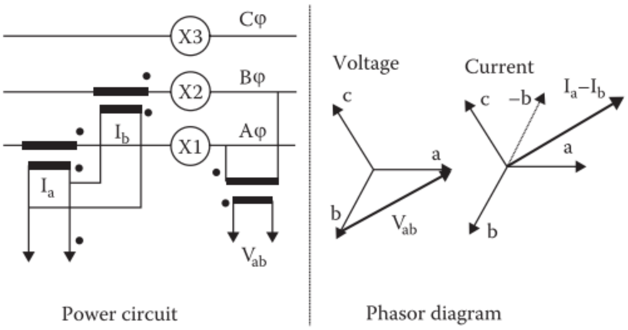
Figure 3-26 below illustrates the three possible CT and VT arrangements for three-phase systems. For each arrangement illustrated below, CT and VT can be constantly shifted to other phases with no effect on the objective (Harlow, 2004).



VT (L-G), 1 CT on same phase



VT (L-G), 2 CTs on other phase



VT (L-L), 2 CTs on same phases

Figure 3-26: Phasing of voltage and current(Harlow, 2004)

3.6.5 On Load Tap-Changer Voltage set point

In many cases if not all, the main objective of the on-load tap changer is to maintain the bus voltage within desired boundaries. Typically, in the control circuit, the setpoint is the nominal is 120V or 1pu. To compensate for the voltage drop in the line between the controlled bus and its load, the voltage setpoint will have to be greater than 120V or 1pu.

3.6.6 On Load Tap-Changer Voltage Bandwidth

Since it is still impossible these days to maintain the voltage constant at a controlled bus, the voltage setpoint is used in the control logic to determine the acceptable voltage range. The bandwidth is the voltage range in which there is no need to raise or lower the tap position. The bandwidth must always be greater than the maximum voltage per tap. For example, if the voltage per tap on the control circuit is 0.75V, the bandwidth will have to be greater than 0.75V.

3.6.7 On Load Tap-Changer Time delay

As for the protection schemes, On-load tap changer controls introduce a time delay between the time that the voltage is out of a predefined range and the time that the raise/lower command is executed. This is simply to discriminate between short voltage sags in the system and swells that may lead to unwanted or unnecessarily tap changing actions. In most cases, linear time-delay characteristics are used. In other cases, the time delay is inversely proportional to the voltage digression from the predefined value.

3.7 VOLTAGE DROP ACROSS THE LINES.

Although it was said above that the main objective of the on-load tap is to regulate the voltage at a controlled bus, the mission, in the long run, is actually to maintain the voltage at the end-user terminals within an acceptable safe range. For this reason, the voltage dropped across the lines will have to be taken into consideration when developing the control scheme. However, this might not be as simple as it sounds since the voltage at the load is not commonly measured and communicated to the control scheme. Therefore, the voltage at the end-user terminals will have to be calculated. The calculation involves measured current, the voltage at the substation bus and the line impedance($R+jX_L$) between the end-user terminals.

The principles of determining the voltage dropped across the lines is subjected to lots of debates because of the following reason:

- The ambiguity of deciding where the load centre is to be when it is distributed,
- Consequently, determining the line impedance will encounter inaccuracies.

The phasor representation of line drop compensation is illustrated in Figure 3-27 below.

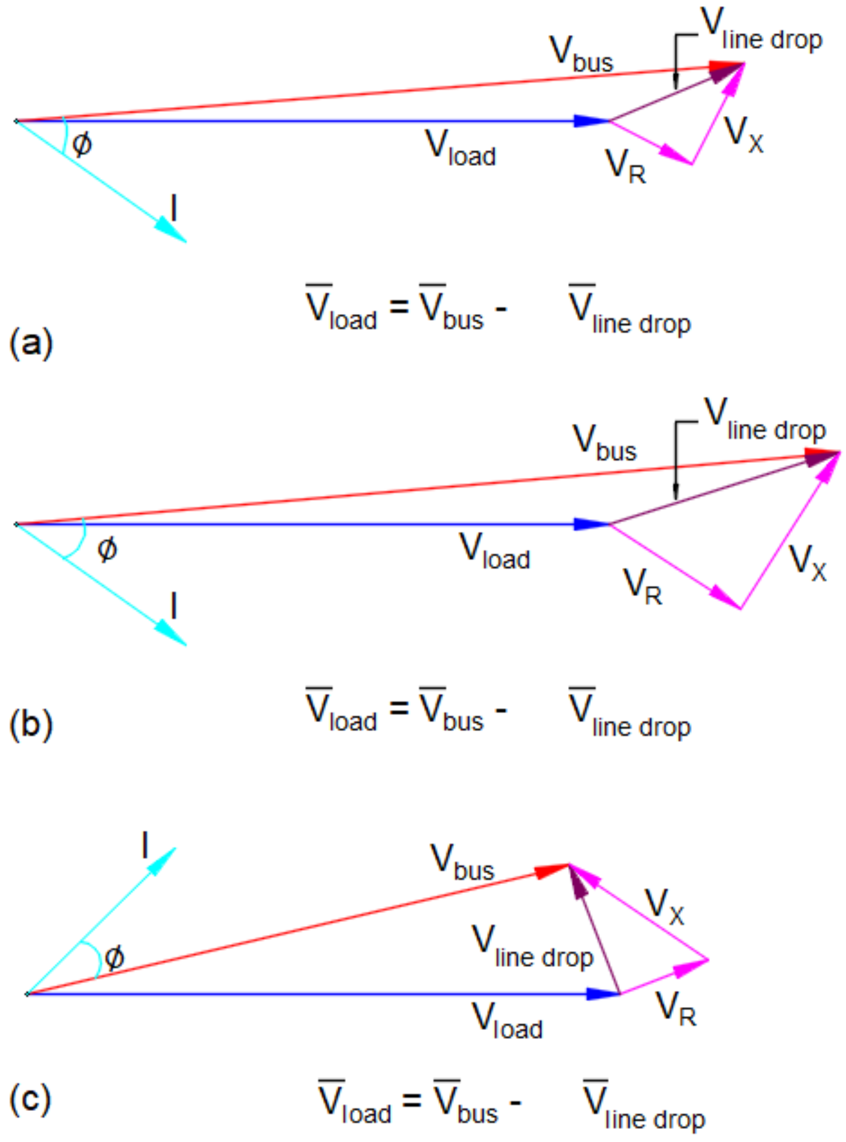


Figure 3-27: (a) Load phasor diagram -normal lagging loading, (b) Heavy lagging loading, (b) normal leading loading

For simplicity, Z-compensation – an alternative to line drop compensation – is used. The controllers are programmed to issue raise or lower tap commend as a linear function of the current drawn by the load. This method does not take into consideration the power factor of the load (Harlow, 2004).

3.8 CONTROL OF SINGLE THREE-PHASE TRANSFORMER

Figure 3-28 below illustrates inputs required to perform On-load Tap Changing on a three-phase transformer operating in solo mode. Control logics need to be created and implemented in an intelligent electronic device. Decisions are made based on the variation of current, voltage and the duration of such variations.

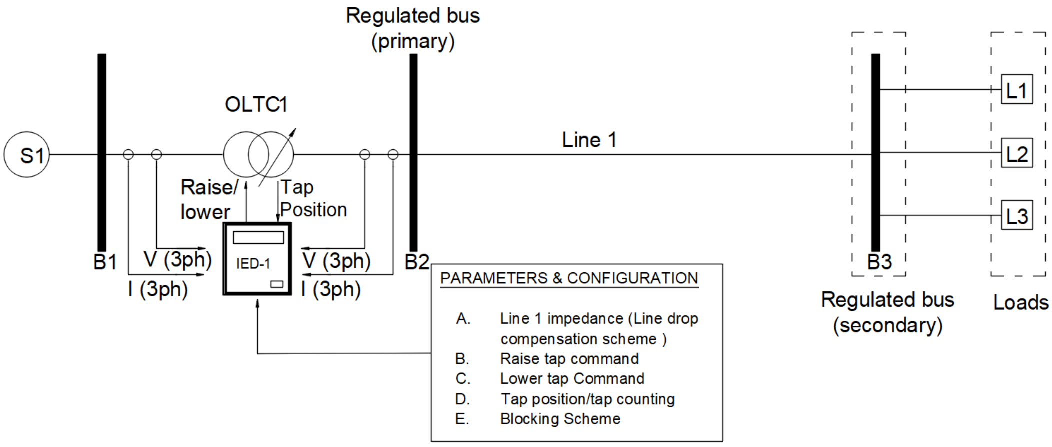


Figure 3-28: OLTC Control block diagram for a single three-phase transformer

Parameters and configurations are loaded only once until a change in the requirements occurs. Real-time current and voltage quantities are communicated to the IED to perform the necessary actions in due time.

3.8.1 Transformers in parallel

Harmony is required when controlling a group of two or more transformers in parallel. in addition to the input in close 4.3., transformers operating in parallel are required to maintain the same secondary voltage to avoid excessive circulating current which might lead to unwanted overloading and overheating. To illustrate what happens to transformers operating in parallel and presenting different voltages on their secondary side, four identical transformers are simulated in DigSilent with the taps on a different setting.

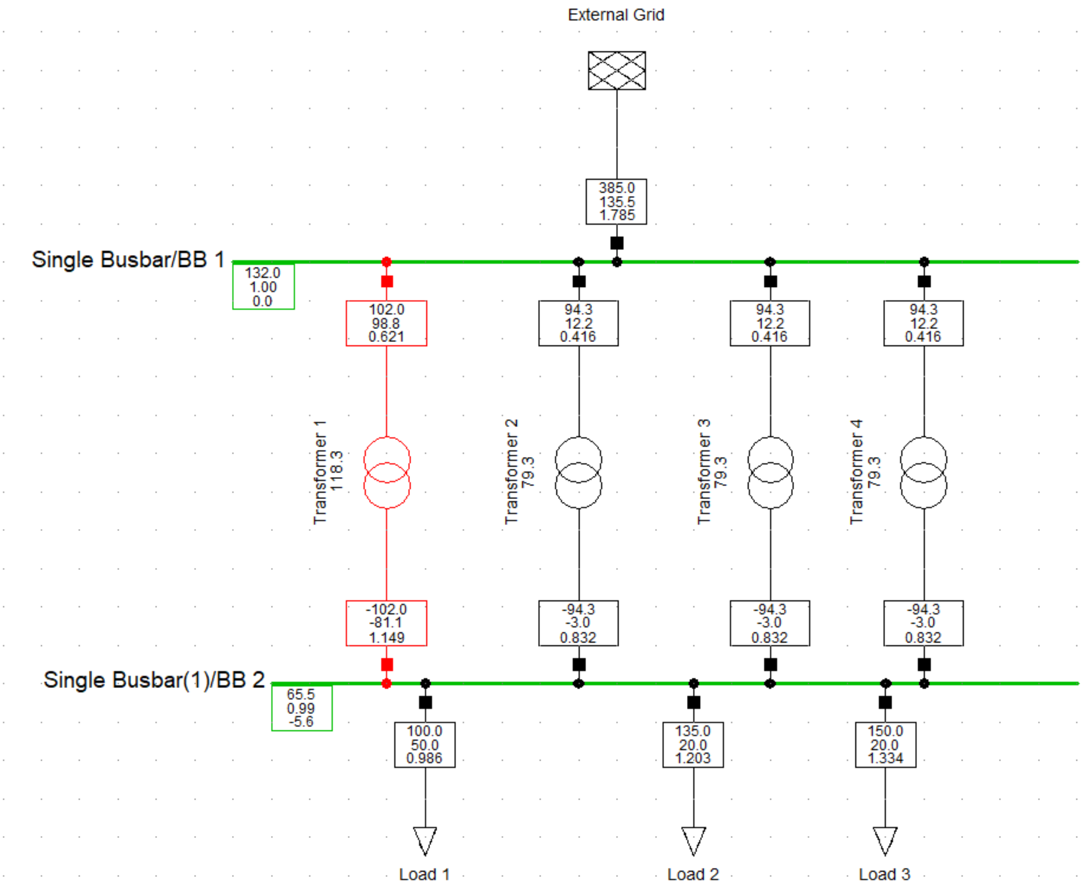


Figure 3-29: Transformer operating in Parallel

It can be seen from Figure 3-29 above that transformer 1 is overloaded while the rest are not. This is attributed to the fact that transformer 1 is on a different tap setting making the path through it the least resistant to the flow of current. The second fact is the presence of circulating current owing to the difference in no-load voltage of transformer 1 to one of the other transformers. To avoid a situation like this, the three most used methods of controlling transformer OLTC in parallel are listed below

- Master-slave method
- Circulating current method
- Negative feedback method.

The last two methods tolerate the difference in transformer property. The first method applies only to transformers with the same electrical properties.

3.8.1.1 Master-Slave method

This method is purely as the name indicates, one controller (IED) is designated as the master and the rest are followers. The idea is to bring all transformers in parallel to the same tap position as the master. This method is only effective for identical transformers (Harlow, 2012).

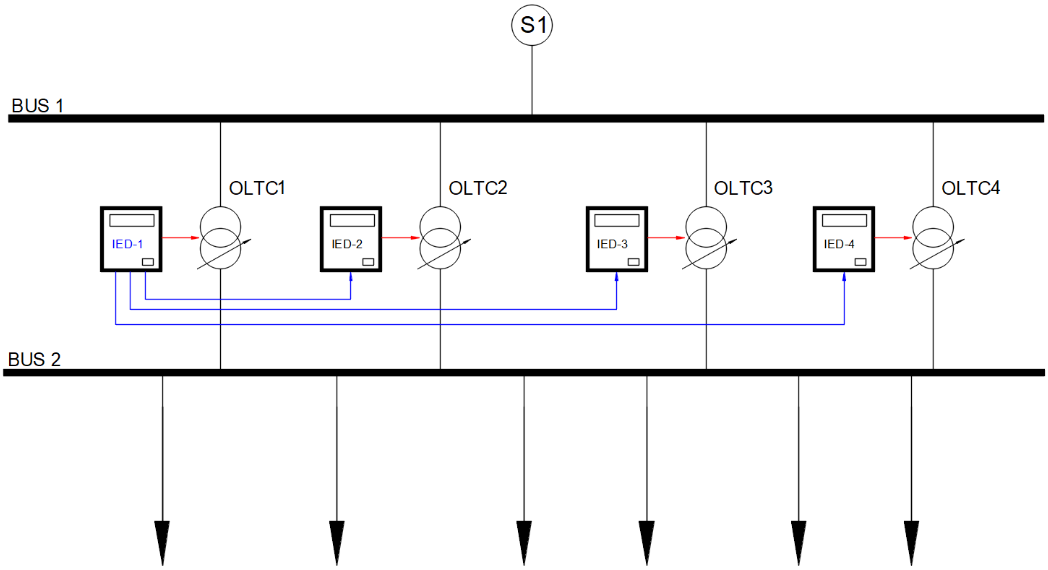


Figure 3-30: Master-slave method

Figure 3-30 above illustrates the master-slave method, where IED-1 is designated as the master.

3.8.1.2 Circulating current method

The circulating current method makes use of circulating current to make decisions to raise or lower the tap position. The circulating current is created when two or more transformers (voltage sources) are connected in parallel and present different voltage levels at their terminals. The principle aims to reduce the circulating current by equalling the voltage output of transformers in parallel. Consequently, the method can work under certain conditions with transformers of different electrical properties.

The great challenge with this method is the calculation of the circulating current between the transformers in parallel. As of today, the circulating current between transformers in parallel cannot be measured with currently available equipment. Thus, it is calculated.

To illustrate how the circulating current can be calculated, let us assume two transformers in parallel as indicated in Figure 3-31 below.

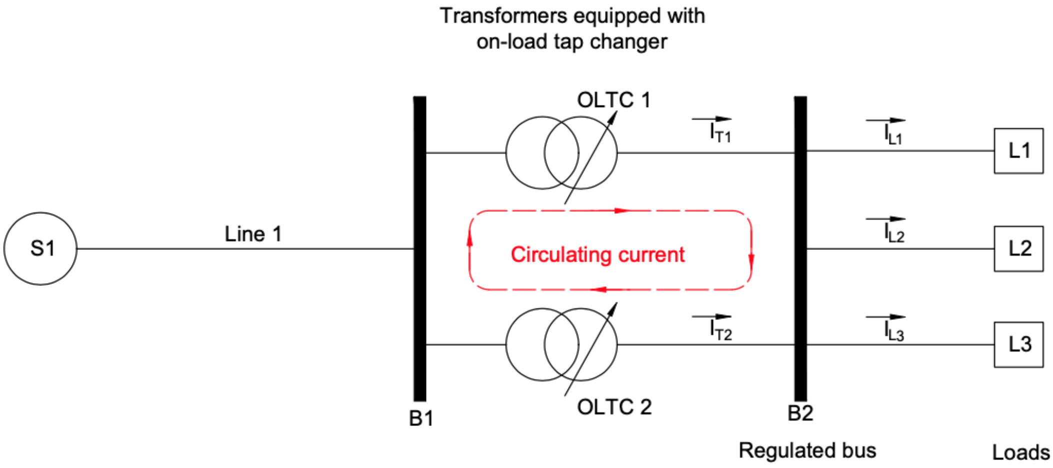


Figure 3-31: Circulating current between two transformers

The circulating current will flow in the system illustrated in Figure 3-35 above when the voltages of the secondary side of the transformers are unequal. The circulating current will be equal to the difference in voltages over the series impedance of the transformer. Since the impedance of the transformer is usually very inductive, the resistance will be ignored in the calculation. Thus, the circulating current between the two transformers will be given by:

$$|I_{circ}| = \frac{|E_1 - E_2|}{X_1 + X_2} \qquad \text{Equation 3-19}$$

Where:

I_{circ}: Is the circulating current between the two transformers

E_1: Is the secondary voltage of the transformer 1

E_2: Is the secondary voltage of the transformer 2

X_1: Is the reactance of the transformer 1

X_2: Is the reactance of the transformer 2

Practically E1 and E2 cannot be measured separately since they are connected in parallel. For this reason, other technics are used to calculate the circulating current. Figure 3- 36 below shows the vector representation of the currents in Figure 3-31 above.

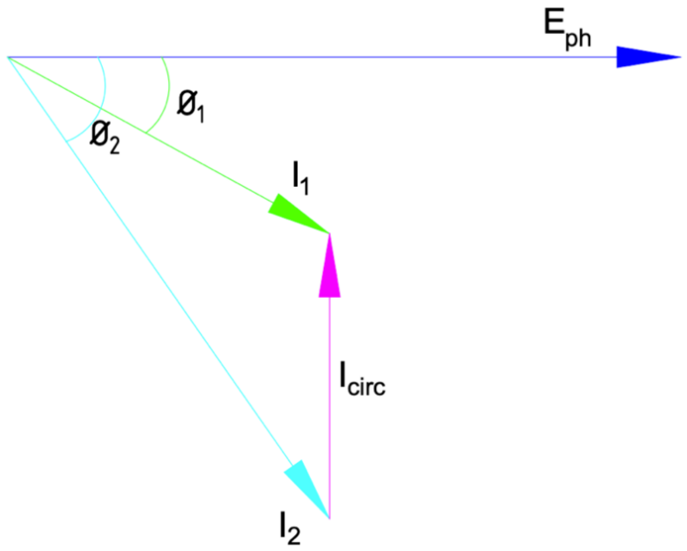


Figure 3-32: Phasor representation

From the phasor representation above, we can see that the circulating current can be determined by the following expression:

$$I_{circ} = I_1 \sin \varnothing_1 - I_2 \sin \varnothing_2 \qquad \text{Equation 3-20}$$

Note that when the system comprises only two transformers, the amount of the circulating current flowing in the transformers will be the same because it is flowing in a loop. For a system comprising more than 2 transformers, the circulating current flowing in the parallel-connected transformer will not be the same. A larger share of the circulating current will flow in the transformer presenting the lowest no-load voltage – this will be more likely the transformer with the lowest tap setting, consequently the lower impedance –. To illustrate how to calculate circulating current in more than two parallel operated transformers, let's consider the four transformers in Figure 3-33 below. The current in each transformer can be given as follows:

$$I_{Tn} = I_{LTn} + jI_{circTn} \qquad \text{Equation 3-21}$$

$$I_{Tn} = (I_{RLTn} + jI_{XLTn}) + (I_{RcircTn} + jI_{XcircTn}) \qquad \text{Equation 3-22}$$

Were:

I_{Tn} is the current flowing in the transformer.

I_{LTn} is the portion of the share of load current flowing in transformer n.

I_{circTn} is the circulating current flowing in transformer n.

I_{RLTn} & jI_{XLTn} are respectively the real and imaginary components of the load current in transformer n

$I_{RcircTn}$ & $jI_{XcircTn}$ are respectively the real and imaginary components of the circulating current in transformer n

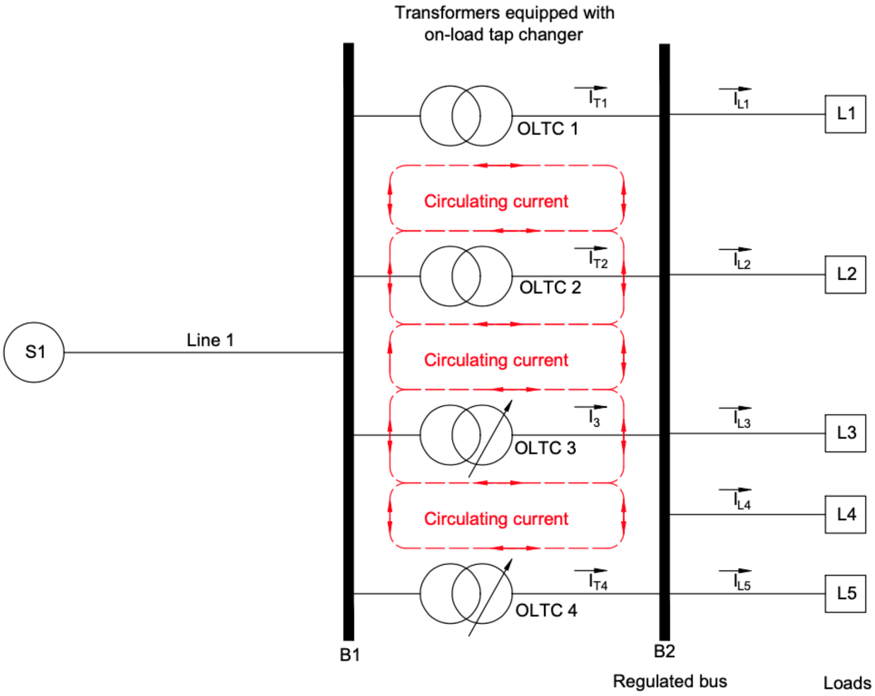


Figure 3-33: Circulating current in 4 transformers in parallel

Since circulating current is created from voltage difference and transformer impedance, - transformer impedance being over 10 times more inductive than resistive- the real part of the circulating can be ignored. Thus, the current in the parallel operated transformer can be expressed as follows:

$$\mathrm{I_{Tn} = I_{RLTn} + jI_{XLTn} + jI_{XcircTn}} \qquad \text{Equation 3-23}$$

Since circulating currents flow in closed loops, the algebraic sum of all circulating currents of a parallel group of transformers is equal to zero

$$\sum \mathrm{I_{circTn}} = 0 \qquad \text{Equation 3-24}$$

Therefore, the algebraic sum of current flowing in each transformer will be equal to the load current. From the load current, the phase angle can be determined.

$$\mathrm{I_L} = \mathrm{I_{T1}} + \mathrm{I_{T2}} + \mathrm{I_{T3}} + \cdots + \mathrm{I_{Tn}} = \sum \mathrm{I_T} \tag*{Equation 3-25}$$

$$\sum \mathrm{I_T} = \sum \mathrm{I_{RLT}} + \mathrm{j} \sum \mathrm{I_{XLT}} + \mathrm{j} \sum \mathrm{I_{XcircT}} \tag*{Equation 3-26}$$

$$\mathrm{I_L} = \sum \mathrm{I_{RLT}} + \mathrm{j} \sum \mathrm{I_{XLT}} \tag*{Equation 3-27}$$

$$\theta_\mathrm{L} = \tan^{-1} \frac{\sum \mathrm{I_{XLT}}}{\sum \mathrm{I_{RLT}}} \tag*{Equation 3-28}$$

Where:

θ_L is the load current phase angle. This angle is controlled directly by the nature of the load connect downstream of the transformer

I_L is the total load current

The load current angle obtained will then be used to extract the circulating current as follows:

$$\mathrm{I_{XcircTn}} = \mathrm{I_{Tn}} - \mathrm{I_{RLTn}} - \mathrm{I_{XLTn}} \tag*{Equation 3-29}$$

$$\mathrm{jI_{RLTn}} \sin \theta_\mathrm{L} \sin \theta_\mathrm{L}\, \mathrm{I_{XLTn}} = \mathrm{jI_{RLTn}} \sin \theta_\mathrm{L} \tag*{Equation 3-30}$$

$$\mathrm{I_{XcircTn}} = \mathrm{I_{Tn}} - \mathrm{I_{RLTn}}(1 + \mathrm{j} \sin \theta_\mathrm{L}) \tag*{Equation 3-31}$$

For example, the circulating current in transformer 4 of Figure 3-37 will be determined as follow:

$$\mathrm{I_{XcircT4}} = \mathrm{I_{T4}} - \mathrm{I_{RLT4}}(1 + \mathrm{j} \sin \theta_\mathrm{L}) \tag*{Equation 3-32}$$

$$\theta_\mathrm{L} = \tan^{-1} \frac{(\mathrm{I_{XT1}} + \mathrm{I_{XT2}} + \mathrm{I_{XT3}} + \mathrm{I_{XT4}})}{(\mathrm{I_{RT1}} + \mathrm{I_{XT2}} + \mathrm{I_{XT3}} + \mathrm{I_{XT4}})} \tag*{Equation 3-33}$$

Where:

I_{T4} is the measured current expressed in complex form. i.e.: $I_{XT4} + jI_{XT4}$

3.8.1.3 Negative reactance method

The negative reactance method is different from the two methods stated above. It uses the line drop compensation parameters. The inductive component of the line drop compensation (LDC) X is a negative value, hence the nomination. The resistive component of the LDC R is set to reduce the voltage error based on the load current nature for which settings are fixed (Harlow, 2012).

The negative reactance method appears to be the traditionally preferred method of implementation of the On-load tap changer for parallel transformers. The method does not require any sort of communication between IED's the parallel group(Harlow, 2012).

3.9 POWER SYSTEM STABILITY

Power system stability can be generally classified into two main categories, angle stability also referred to as rotor angle stability and voltage stability. The angle stability can be described as "the ability of interconnected synchronous machines of a power system to remain in synchronism." It involves the investigation of electromechanical oscillations in the power systems (Mondal, Chakrabarti and Sengupta, 2020). Figure 3-34 below shows the historical division of the power system into the mechanical and electrical subsystems.

Voltage stability can in general be described as the "ability of a system to maintain steady acceptable voltages at all buses following a system contingency or disturbance." A power system is said to be under a state of voltage instability when there is a developing uncontrollable voltage change following a disturbance or a change in the system conditions (Mondal, Chakrabarti and Sengupta, 2020).

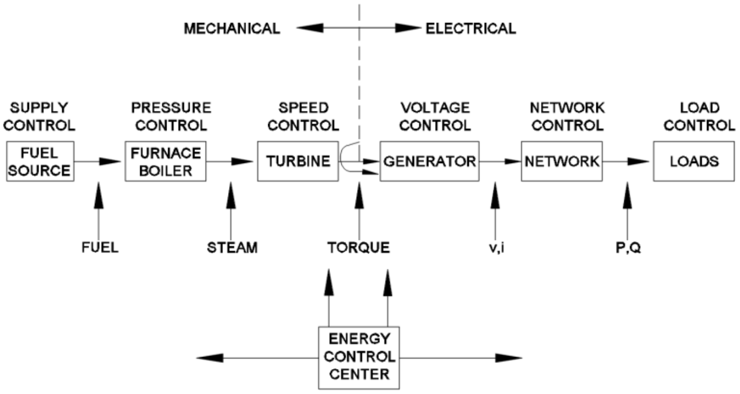


Figure 3-34:Power system dynamic structure (Sauer, Pai and Chow, 2017)

The literature of this section will mainly focus on voltage stability in general and particulate the mitigation of voltage instability using transformers equipped with on-load tap changers.

3.9.1 Angle stability

The angle stability can broadly be categorised into two types, steady-state/dynamic stability and transient stability. Dynamic instability occurs as a result of the incapability to maintain synchronism and/or diminish the system transients and oscillations resulting from changes in the system conditions. Transient instability is to maintain synchronism following a fault in the system or equipment failure.

Transient stability studies aim to analyse the ability of the machine in the power system to return to a steady synchronised state after a massive disturbance. The analysis involves solving the equation of motion of synchronous machines also known as the "swing equation" given by the expression below (Mondal, Chakrabarti and Sengupta, 2020).

$$\frac{2\mathrm{H}}{\omega_{\mathrm{syn}}}\omega_{\mathrm{syn}}(\mathrm{t})\frac{\mathrm{d}^2\delta(\mathrm{t})}{\mathrm{dt}^2} = \mathrm{P}_{\mathrm{mpu}}(\mathrm{t}) - \mathrm{P}_{\mathrm{epu}}(\mathrm{t}) = \mathrm{P}_{\mathrm{apu}}(\mathrm{t}) \qquad \text{Equation 3-34}$$

Where:

H	is the normalised inertia constant
ω_{syn}	is the synchronous electrical radian frequency (angular velocity)
$\delta(\mathrm{t})$	is the electrical power angle.
$P_{mpu}(t)$	is the mechanical power exerted by the prime mover excluding all mechanical losses total electrical torque including all electrical losses and expressed in per unit
$P_{epu}(t)$	is the electrical power output of the generator including all electrical losses and expressed in per unit.
$P_{apu}(t)$	is the accelerating power.

3.9.2 Voltage stability

Voltage insatiability is generally load driven; this is why it is referred to in some theories as load instability. However, the load is not the only player in the voltage instability but also the generation systems and the transmission systems. Generation and transmission systems are designed with a limit to the amounts of power they can generate and transfer. These limits make the inception of voltage instability (Van Cutsem and Vournas, 2008).

3.9.3 Effect of on-load top changer on voltage stability.

Transformer equipped with on-load tap changer is one of the key tools employed in load restoration to perform automatic voltage regulation. The transformer adjusts the voltage on the controlled bus by altering the turn ratio *r*. The transition from one turn ratio to another is a discontinued and slow process. The minimum typical time required for the OLTC to complete the transition from one tap to another is 5 seconds (Van Cutsem and Vournas, 2008).

Transformer equipped with OLTC indirectly performs load restoration. When it successfully restores the voltage on the distribution side, the load power is also restored. Note that the load power is dependent on the bus voltage. The load restoration by transformer equipped with OLTC is illustrated using the system in Figure 3-35 below.

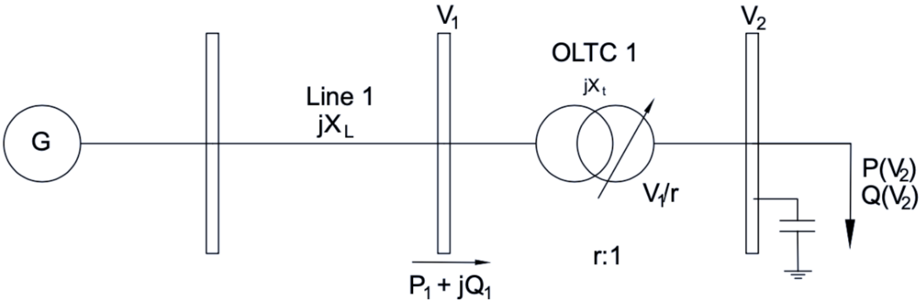


Figure 3-35: Generator line transformer (OLTC) system

For this analysis, the transformer illustrated in Figure 3-35 above is ideal. The copper losses are ignored. We then draw 2-off network characteristic curves (P_1 V_1), each for a given value of X_L.

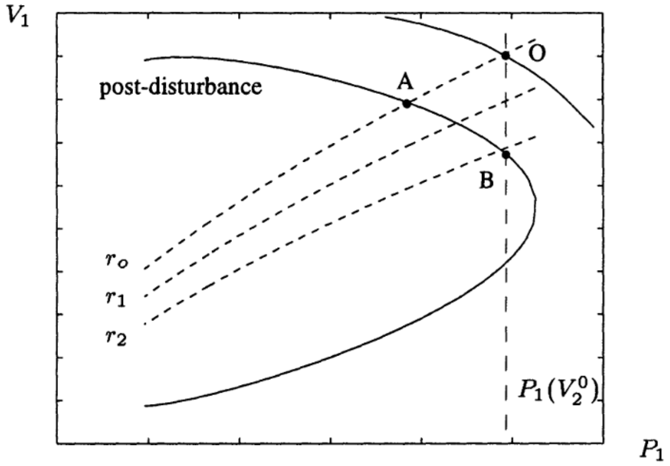


Figure 3-36: PV Curves of the system in figure 3-39 above

Now let us consider the PV characteristic as seen from the transformer's high voltage side. Assuming the power as a function of load voltage as follow:

$$P = P(V_2) \quad \text{Equation 3-35}$$

$$Q = Q(V_2) \quad \text{Equation 3-36}$$

The relation between the secondary and primary voltage of the transformer will be given by the following expression.

$$\left(\frac{V_1}{r}\right)^2 = \left[V_2 + \left(\frac{Q(V_2)}{V_2} - BV_2\right)X_t\right]^2 + \left[\frac{Q(V_2)}{V_2}\right]^2 \quad \text{Equation 3-37}$$

The power ($P_1 + jQ_1$) through the transformer is made up of the power drawn by the load and the power losses in the transformer due to its reactance omitted of the reactive power injected (BV^2).

$$P_1 = P(V_2) \quad \text{Equation 3-38}$$

$$Q_1 = Q(V_2) + \frac{P(V_2)^2 + Q(V_2)^2}{{V_2}^2}X_t - BV_2^2 \quad \text{Equation 3-39}$$

Using the expression of the relationship between the primary and the secondary voltage of the transformer, we can then write P_1 and Q_1 as a function of $\frac{V_1}{r}$:

$$P_1 = P\left(\frac{V_1}{r}\right) \quad \text{Equation 3-40}$$

$$Q_1 = Q\left(\frac{V_1}{r}\right) \quad \text{Equation 3-41}$$

This expression above gives the transient load characteristic from the transformer at a given tap setting(r). The three dotted lines in figure 3-36 illustrate the transient load characteristic at three different tap settings (Van Cutsem and Vournas, 2008).

3.10 CONCLUSION

In this chapter, the basic principles of transformers were discussed, and various special transformers were highlighted. For more flexibility, some transformers are equipped with a tap changer to allow manoeuvring the output voltage by varying the turns ratio while the transformer is carrying its load.

It was noted that the concept of an on-load tap changer was initially reserved for special applications up until the ’90s when the first comprehensive academic investigation was conducted. This investigation led to the invention of a mechanical on-load tap changer which was developed into a hybrid and finally into the current fully electronic on-load tap-changer.

This chapter also gave an overview of control methods for parallel-connected transformers equipped with on-load tap changers. Master-follower being the most used, it requires the transformers in the parallel group to be of some electrical properties. Circulating current is the second method, it works with transformers of different electrical properties. The negative reactance method is the least used. Unlike the two first methods, Negative reactance does not require any communications between various relays in the parallel group.

Furthermore, a comprehensive overview of power system stability was presented in this chapter. The effect of the on-load tap changer on power system stability was discussed. In the next chapter, the application of an on-load tap-changer for transformers operating in parallel will be discussed. The second part of the chapter will discuss the communication protocols between the transformers.

CHAPTER 4

SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

4.1 INTRODUCTION

Nowadays power systems are required to be environmentally friendly while remaining reliable and maintaining high efficiency in transmission and distribution. Traditional power systems can no longer cope with current power delivery requirements. Therefore, utilities all over the world are migrating to the next generation smart grid. The smart grid features an amalgamation of the latest technologies in signal processing, intelligent electric devices, advanced instrumentation, wide area protection, automation and sophisticated computer applications (Mini S. Thomas and Joh D. McDonald, 2015).

Communication plays a crucial role in smart grids as it enables data communication between various components of the power system. It also enables remote interactions between the operator and the substation in form of monitoring or control of the power system. Power systems are always meant to be controlled to take appropriate actions when required. To assist the human, automation is created to act or issue warning alarms when normal predefined conditions are bridged. As the need to assist humans evolved, “Supervisory Control and Data Acquisition” (SCADA) was developed. As the name indicates, SCADA implementation involves two major activities: Supervisory control (Control) and Data acquisition (Monitoring) leading to complete automation (Mini S. Thomas and Joh D. McDonald, 2015).

The monitoring activity involves the following steps:

- Assembling of data from the power system
- Converting of assembled data into a transmittable format
- Grouping of data into packets.
- Transmission of the packets of data over communication media
- Reception of the data at the control centre
- The decryption of the data
- Displaying of the data at the appropriate points on the screens of the operator.

The automation activities ensure that the command issued gets transmitted and translated into the appropriate action in the power system. It involves the following steps (Mini S. Thomas and Joh D. McDonald, 2015):

- Issue control command(s)
- Group control command(s) as data packet(s)
- Transmit the packet(s) over the communication media
- Power system device(s) receives and decrypt the command
- The control action is initiated using the appropriate device actuation.

4.2 COMPONENTS OF SCADA SYSTEM

Supervisory Control And Data Acquisition comprise the following four major components (Mini S. Thomas and Joh D. McDonald, 2015):

1. Remote terminal units (RTU): The main task of RTU is to acquire all power data from various power system devices. a great analogy will be to compare them to the eyes and ears of a human being. They monitor the surroundings, process data and transmit relevant data to where it is required. RTU's are used to execute commands just as human hands execute instructions from the brain. In current power stations, IED's are used as RTU.

2. Communication System: The communication system is the backbone of SCADA. It refers to the channels used to exchange data between field devices and the control centre computer in the centralised system. It also refers to the communications channels used between various RTUs in decentralised systems. The rate of data exchange is limited by the bandwidth of the channel employed.

3. Control centre/Master station: This is an assortment of Computers, peripherals, and proper input and output (I/O) frameworks that empower the administrators to screen the condition of the power system (or a procedure) and control it.

4. Human-Machine Interface (HMI): This allows the interface required for the cooperation between the control centre and the administrators or users of

the SCADA framework. It is the common language spoken by the operator and the machine.

4.3 COMMUNICATION SYSTEM

Modern power systems can be seen as a well-ahead version of traditional power systems with heightened communication capabilities. Under all operating conditions, dozens or hundreds of diverse data flow occurs. Each varies in payload size, payload type, desired reliability and security. For this reason, modern power systems are deemed to be very complex. Thus, communication technologies should be able to accommodate all demanding requirements.

The elementary requirements for a communication system for a power system are as follows (Kabalci and Kabalci, 2019):

1. Latency: The majority of SCADA applications are time critical. They require real-time data exchange with a time delay tolerance of about half a cycle (about 10ms). Nevertheless, some applications tolerate a delay of up to 15 minutes. This is the case with consumer automatic metering infrastructure (AMI). An ideal communication system ought to offer an optimized delay execution, considering the variety in latency limitations.
2. Reliability: Most SCADA applications are mission critical. Thus, the communication system is mandated to be of higher reliability. The communication system ought to prioritize data exchange and deliver a reliable performance based on the criticality of the application in question.
3. Data Rate: The communication system ought to be able to deliver the required bandwidth to avoid or reduce data losses during transmission.
4. Scalability: An infinite number of new smart devices are predicted to be connected to the power system. The communication system should be able to accommodate the inevitable growth.
5. Interoperability: Some applications might use devices from different vender with different technologies. Thus, interoperability between devices from different venders and different technologies is imperative.
6. Security: The information conveyed by the communication system may include data relating to consumer privacy or some network sensitive data. Accordingly, the underlying system must be unassailable and versatile to assaults.

4.3.1 Communication techniques

Mullions of information and commends are exchanged between smart devices in smart power systems. To avoid situations where contradictory commands are sent to the same device or collision of information, the following communication techniques are observed (Mini S. Thomas and Joh D. McDonald, 2015).

1. Master-Slave: In this communication mode, one device is designated as the master controlling the communication and timing. For the rest of the devices, slaves can communicate strictly under the master's initiation and authorisation. The master authorisation is required even for Inter-slave communication. This communication mode has the drawback of using the communication resources at minimal. This is because initiation and/or authorisation are required from the master every single time communication is required. This slows the communication speed.

2. Peer-to-peer: In this communication mode, all devices are authorised to initiate communication with any other when required. All devices are at the same time masters and slaves although in some instances a bus administrator is employed to regulate the traffic. The communication resources are optimally used in peer-to-peer communication mode. However, when the number of nodes increases, the performance is affected negatively.

3. Multi-peer: This communication mode permutes the communication from an active device to the rest of the devices or a targeted group of devices in the network. When the message is intended for all other devices in the network, the multi-peer mode is called broadcast. When the message is intended for a predefined group, it is called Multicast. In both cases, an acknowledgement of the message is not required.

4.3.2 Time Synchronization

In modern power systems, sequence-of-events (SOE) logging also known as time tagging of the event is of higher purposes. The subsystem responsible for timekeeping is incorporated into the remote terminal units (IED’s). It is important to note that most SCADA applications are time-critical and require information from more than one source (IED’s). For this reason, the time for all devices needs to be synchronised with at most 1ms accuracy (Mini S. Thomas and Joh D. McDonald, 2015).

IED's are built with the functionality to receive time from the external time source. The global position system(GPS) provides an accurate and reliable time that can be traced to the coordinated universal time (UTC) with acceptable accuracy (Mini S. Thomas and Joh D. McDonald, 2015).

4.4 IEC 61850 COMMUNICATION STANDARDS

IEC 61850 is an international standard for substation equipment communication. The abstract data and object models of the standard are directly mapped to well-known protocols and transmitted through local area networks (LAN's) to accomplish the required maximum response time. Some of the protocols used to directly map data in IEC 61850 are the following:

- Manufacturing Message Specific (MMS)
- Generic Object-Oriented Substation Event (GOOSE)
- Sampled Measured values (SMV)

4.4.1 IEC 61850 Substation Architecture

IEC 61850 substation architecture comprises three levels namely: substation level, bay level and process level. The station level is the human-machine interface for monitoring and control automation etc. The bay level comprises the protection and controls IED's. The last level consists of sensing devices such as CT's and VT's. IEC 61850 substation architecture is illustrated in Figure 4-1 below.

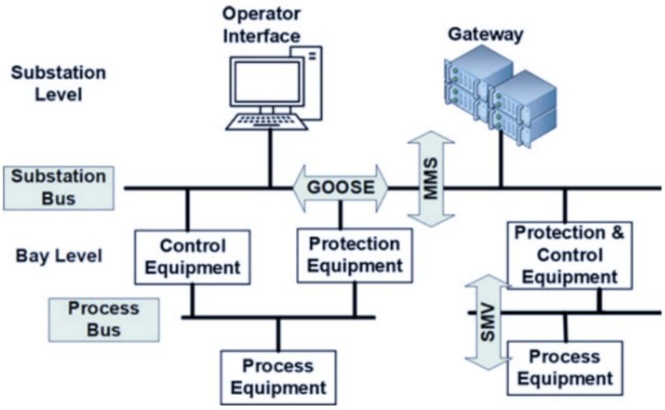


Figure 4-1: IEC 61850 Substation architecture (Kabalci and Kabalci, 2019)

The communication between process level equipment and bay level equipment is achieved through sampled measured values (SMV) messages via the process bus. Communication among bay level devices can be achieved using GOOSE messages. The communication between the substation level and the bay level is built upon MMS. The relationship between these two levels is the client-server relationship (Kabalci and Kabalci, 2019).

4.4.2 Object data model and mapping

IEC 61850 data models start with the identification of the physical device that is connected to the network which is identified using the network address. The device in turn consists of several logical devices (LD’s). Each logical device is composed of logical nodes (LN’s) having each a distinct name. At the far end, each logical node consists of several or a single data object (DO’s). For instance, a circuit breaker is identifiable by the logical node “XCBR”. This logical node may contain data objects such as “Loc”, “Pos” determining whether the operation is local or remote and the position respectively (Kabalci and Kabalci, 2019). IEC 61850 data model is illustrated in Figure 4-2 below.

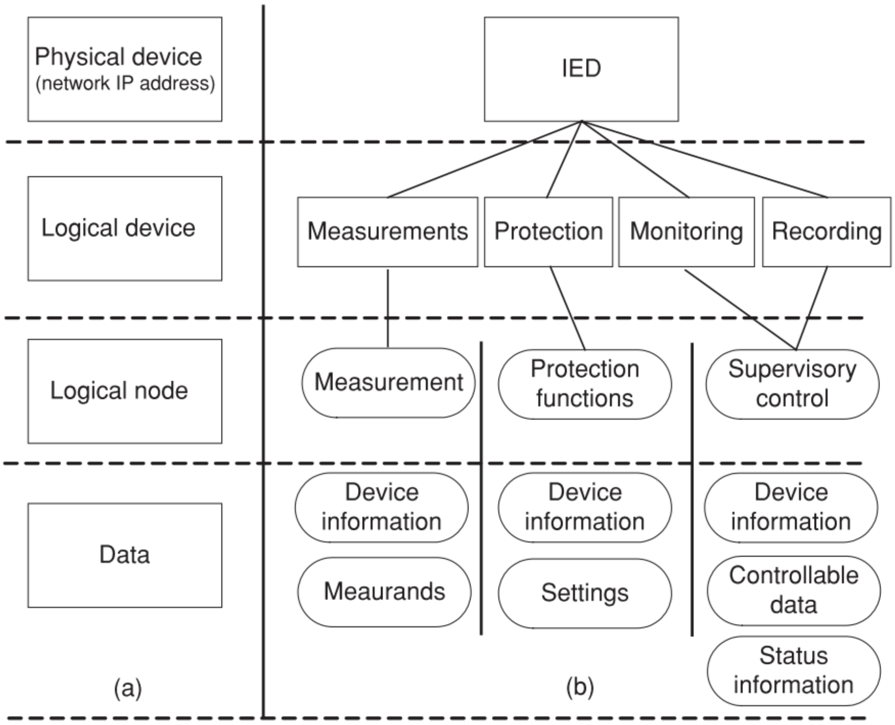


Figure 4-2: IEC 61850 data model (Ekanayake et al., 2012)

IEC 61850 abstract data and object models outline a standardised way to describe devices in power systems that make all intelligent electronic devices presenting data structurally identical and directly matching their functions in the power system. The Abstract Communication Service Interface (ACSI) models of IEC 61850 describe several services and their responses empowering all IED's to act in an indistinguishable way from the network point of view. Thus, achieving interoperability. Due to the capability of supporting complex named objects, MMS protocol is the perfect choice for IEC data objects mapping. Table 4-1 and 4-2 below show a summary of IEC61850 object and service mapping (Mackiewicz and Heights, 2006).

Table 4-1: IEC 61850 to MMS Object mapping *(Mackiewicz and Heights, 2006)*

IEC 61850 Objects	**MMS Object**
SERVER class	Virtual Manufacturing Device (VMD)
LOGICAL DEVICE class	Domain
LOGICAL NODE class	Named Variable
DATA class	Named Variable
DATA-SET class	Named Variable List
SETTING-GROUP-CONTROL- BLOCK class	Named Variable
REPORT-CONTROL-BLOCK class	Named Variable
LOG class	Journal
LOG-CONTROL-BLOCK class	Named Variable
GOOSE-CONTROL-BLOCK class	Named Variable
GSSE-CONTROL-BLOCK class	Named Variable
CONTROL class	Named Variable
Files	Files

Table 4-2: IEC 61850 to MMS service mapping *(Mackiewicz and Heights, 2006)*

IEC 61850 Services	**MMS Services**
LogicalDeviceDirectory	GetNameList
GetAllDataValues	Read
GetDataValues	Read
SetDataValues	Write
GetDataDirectory	GetNameList
GetDataDefinition	GetVariableAccessAttributes
GetDataSetValues	Read
SetDataSetValues	Write
CreateDataSet	CreateNamedVariableList
DeleteDataSet	DeleteNamedVariableList
GetDataSetDirectory	GetNameList
Report (Buffered and Unbuffered)	InformationReport
GetBRCBValues/GetURCBValues	Read
SetBRCBValues/SetURCBValues	Write
GetLCBValues	Read
SetLCBValues	Write
QueryLogByTime	ReadJournal
QueryLogAfter	ReadJournal
GetLogStatusValues	GetJournalStatus

Select	Read/Write
SelectWithValue	Read/Write
Cancel	Write
Operate	Write
Command-Termination	Write
TimeActivated-Operate	Write
GetFile	FileOpen/FileRead/FileClose
SetFile	ObtainFile
DeleteFile	FileDelete
GetFileAttributeValues	FileDirectory

Moreover, Figure 4-3 below shows other communication layers whose profiles are also described in part 8.1 of IEC 61850. We note GOOSE and SMV applications map directly into the Ethernet data frame eradicating the need for intermediate layers. Manufacturing Message Specific (MMS) Connection-Oriented layer can operate over Transmission Control Protocol (TCP) / Internet Protocol (IP) or Open Systems Interconnection (ISO). The Generic Substation Status Event (GSSE) is identically implemented as the GOOSE and operates over connectionless ISO services. All data maps onto an Ethernet data frame using either the “Ethertype” data type in the case of Sampled Values, GOOSE, TimeSync, and TCP/IP or “802.3” data type for the ISO and GSSE messages (Mackiewicz and Heights, 2006).

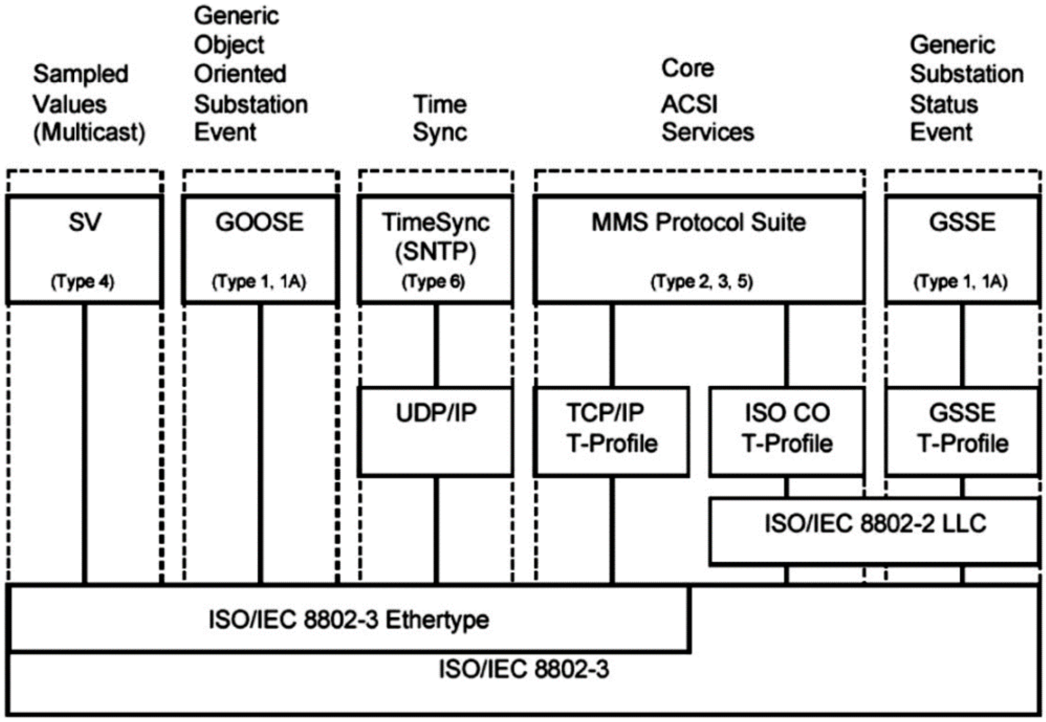


Figure 4-3: IEC 61850 Communication profiles

4.5 NETWORK TOPOLOGY

The substation communication system is of very high importance as the control automation, monitoring and protection systems rely on it. Hence, it is required to have high reliability. Depending on the budget available, some networks are designed in a manner that if one network link fails, the system still works on the backup link. The main two network topologies are Star topology and ring topology as indicated in the two figures below.

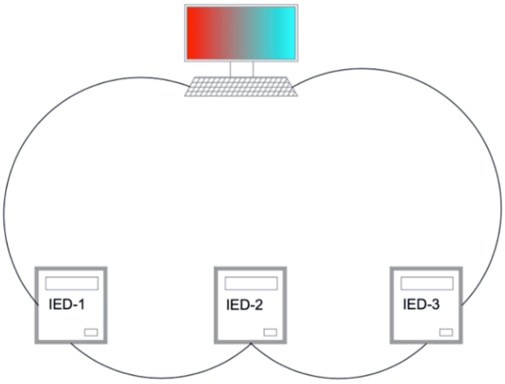


Figure 4-4: Ring network topology

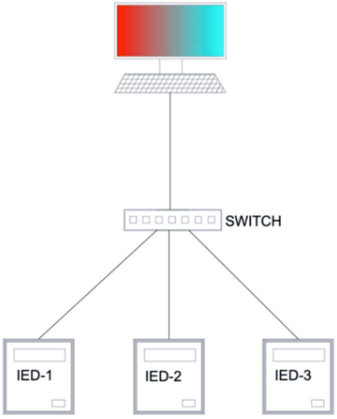


Figure 4-5: Star network topology

For more reliability, two network switches can be used in a double star arrangement. Two rings or a ring and a star can also be used to increase for this purpose. Such combinations are illustrated in Figure 4-6 and Figure 4-7 below. It is important to note that the use of combinations of star and ring configuration results in a complex design which is often not straightforward when it comes to troubleshooting.

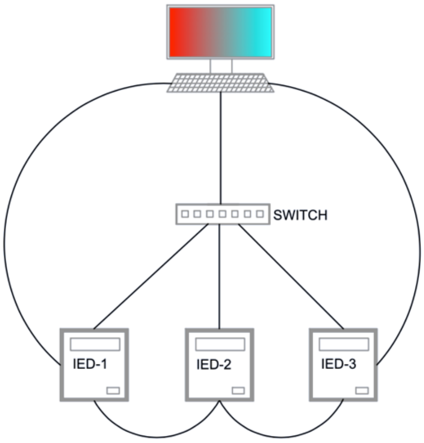


Figure 4-6: Star-ring network topology

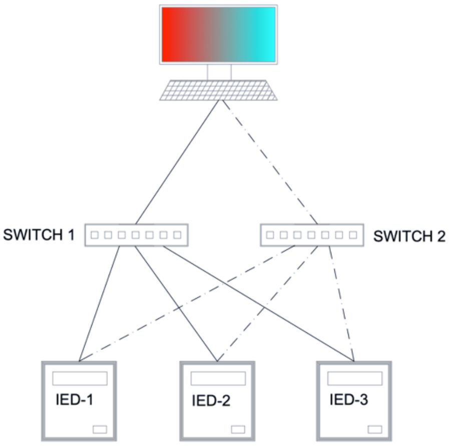


Figure 4-7: Double star network topology

4.6 CONCLUSION

This chapter described the architecture of a typical IEC 61850 substation. The chapter focuses on communication for control, monitoring and automation in the substation. The data model and the object mapping were explained. A brief description of the SCADA system is given. The four main components of the SCADA system – Remote Terminal Units, Communication system, Control centre and Human-Machine Interface – are described. The communication techniques are listed and explained in detail. The chapter also gives a brief explanation of the network topology.

The two main network topologies, star and ring, are explained and the advantages are listed. For redundancy, two topologies can be combined to increase reliability. This can be a Double star, double delta or a combination of a star and delta. This chapter also highlighted the importance of time synchronisation.

Chapter five below will focus on the modelling and simulation of the selected network for this project. Chapter six will make use of the content of this chapter to design communications between controllers under development.

CHAPTER 5

MODELLING AND SIMULATION

5.1 INTRODUCTION

It has been customary to make use of computer-aided tools to simulate, analyse and optimise power system performance during normal and abnormal conditions. This reduces the space and cost required to perform such tasks. Tools evolved from just a simple single command-line interface to sophisticated, integrated and interactive computer programs. The strategic power system's elements to the model include:

- Power flow study
- Fault analysis
- Power system protection and automation design and testing
- Transient/dynamic stability
- Power system quality analysis
- Power system optimal power flow analysis

There is an infinite number of power systems simulating software packages on the market. The price ranges from free/ non-commercial to several hundred thousand. For this thesis, Real-Time Digital Simulator (RTDS) was selected to model and perform hardware-in-the-loop simulation of automation and control developed.

Intelligent Electronic Devices (IED) configuration tools were used to implement developed control logic into various IED's. A control and monitoring system was built on the RSCAD Runtime aiming to visualize the performance of the developed system under various operating conditions. The results are presented and discussed in Chapters 6 and 7.

5.2 RSCAD

RSCAD is a customised software and hardware combination designed precisely to accomplish power system simulation in real-time. The package features hardware-in-the-loop testing of protection, control automation and power system equipment.

5.2.1 Modules and capabilities of RSCAD

Circuit Construction: Define single- or three-phase circuits. Choose from extensive component libraries. User-friendly parameter search and entry.

Operator's Module: Start, stop, and interact with the simulation in real-time. Apply faults, adjust parameters, and view simulation data. Conveniently annotate and save data.

Scripting and Test Automation: Conveniently automate many tests via C-type scripts. Eliminate user intervention in running tests, changing parameters, and saving data.

Transmission Line and Cable Parameters: Generate the characteristic impedance and other key data for travelling wave lines and cable models based on physical/geometrical data or sequence components.

Component Builder: Use C language and a drawing facility to create a user-defined power system or controls components that run in real-time alongside existing library components.

Manuals and Documentation: Comprehensive documentation for library components, software modules, sample cases, and tutorials.

5.2.2 Power system component

Modern power systems are extensively interconnected across regions for economic reasons and to improve power system reliability. For this reason, the mathematical models of these power systems are non-linear and high dimensional nature. It comprises a huge number of nonlinear equations each representing a particular power system component or a relation between two or more components. Thus, modelling or analysing of complex power system starts by decomposing the system into independent basic components, such as the ones below (Bambaravanage, Rodrigo and Kumarawadu, 2018)

- Synchronous generators,
- Transmission lines,
- Underground cables,
- Transformers,
- Capacitor banks,
- Loads,

- Governors,
- Prime Movers,
- Etc…

Although the RSCAD library includes all these components pre-modelled as blocks, a proficient understanding of the nature and mathematical models of the components is required to perform configurations. Mathematical models of these components are the building block for the mathematical model of the power system regardless of the size or nature (Bambaravanage, Rodrigo and Kumarawadu, 2018).

For better use of computing resources, some components have multiple models with different computing accuracy and speed. Some problem analysis would require low accuracy with high-speed computation for some components and the opposite for others. A mathematical component model of a qualitative analysis would be complex as opposed to the one for quantitative analysis. Since computing accuracy tends to always be indirectly proportional to the computing speed, it is important to be aware of the accuracy required for a component used for the cases under study (Wang, Song and Irving, 2010).

In the following paragraph, RTDS/RSCAD based mathematical models of components used in this research will be discussed.

5.2.3 Modelling of Generator

Electric generators are devices tasked with the conversion of mechanical energy(movement) into electric energy or viscera. The conversion is accomplished through electromagnetic induction. They are responsible for a great amount of electrical power generated all around the world. RSCAD library comprises a variety of generator models. For all these models, a switch is used to dictate whether the machine should operate in “Lock” or “Free” mode. also known as “speed” or “torque” mode, respectively. Lock mode operation suppresses mechanical equation, the speed is directly advised by a control input. In Free mode, the mechanical torque on the shaft is advised by a control signal and speed is the result of the swing equations (RTDS Technologies, 2018).

Figures 5-1 and 5-2 below show connections between RTDS machine model, exciter, and governor. Each of the three components is a pre modelled block.

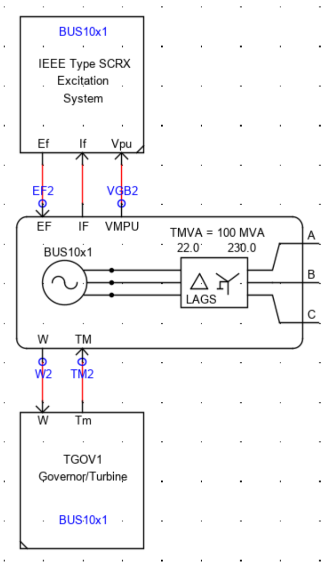
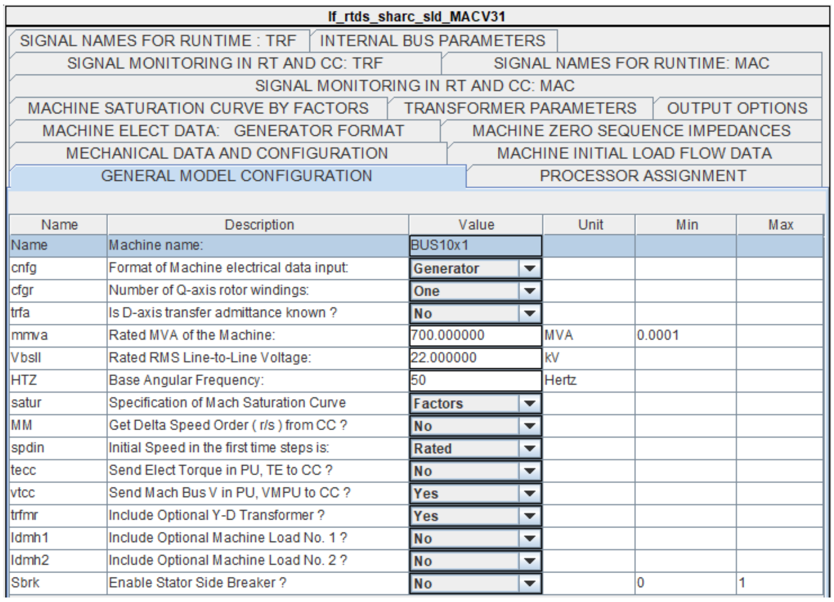


Figure 5-1: RSCAD Generator model



lf_rtds_sharc_sld_MACV31

SIGNAL NAMES FOR RUNTIME : TRF | INTERNAL BUS PARAMETERS
SIGNAL MONITORING IN RT AND CC: TRF | SIGNAL NAMES FOR RUNTIME: MAC
SIGNAL MONITORING IN RT AND CC: MAC
MACHINE SATURATION CURVE BY FACTORS | TRANSFORMER PARAMETERS | OUTPUT OPTIONS
MACHINE ELECT DATA: GENERATOR FORMAT | MACHINE ZERO SEQUENCE IMPEDANCES
MECHANICAL DATA AND CONFIGURATION | MACHINE INITIAL LOAD FLOW DATA
GENERAL MODEL CONFIGURATION | PROCESSOR ASSIGNMENT

Name	Description	Value	Unit	Min	Max
Name	Machine name:	BUS10x1			
cnfg	Format of Machine electrical data input:	Generator			
cfgr	Number of Q-axis rotor windings:	One			
trfa	Is D-axis transfer admittance known ?	No			
mmva	Rated MVA of the Machine:	700.000000	MVA	0.0001	
Vbsll	Rated RMS Line-to-Line Voltage:	22.000000	kV		
HTZ	Base Angular Frequency:	50	Hertz		
satur	Specification of Mach Saturation Curve	Factors			
MM	Get Delta Speed Order (r/s) from CC ?	No			
spdin	Initial Speed in the first time steps is:	Rated			
tecc	Send Elect Torque in PU, TE to CC ?	No			
vtcc	Send Mach Bus V in PU, VMPU to CC ?	Yes			
trfmr	Include Optional Y-D Transformer ?	Yes			
ldmh1	Include Optional Machine Load No. 1 ?	No			
ldmh2	Include Optional Machine Load No. 2 ?	No			
Sbrk	Enable Stator Side Breaker ?	No		0	1

Figure 5-2: RSCAD Generator Parameters

Where:

EF	is the Field Voltage (norm)
IF	is the Field Current (norm)
VMPU	is the Machine Voltage (p.u.)
W	is Machine Speed (Rad/sec.)
TM	is Mechanical Torque(pu)

A/B/C is Bus Connection Terminals

Note that the model includes an optional transformer and an internal bus. The transformer can be configured separately.

5.2.4 Modelling of Transformers

Transformers are electrical devices commonly used in the power system to convert voltage from one level to another. RSCAD library contains various transformer models pre-modelled as a block. Some power system components contain embedded transformers in their models. This is the case with the generating unit as stated in the previous section.

While selecting a type of transformer for a particular case study, it is important to consider the following parameters:

- Transformer ratings (e.g. voltage & power)
- Number of coupled windings
- Winding configuration (star, delta, auto−transformer)
- Number of limbs on the core (core or shell type)
- Leakage impedances
- Magnetizing currents
- Losses (eddy current, magnetizing, winding)
- Saturation and hysteresis
- Tap changers.

Three-phase transformers can be modelled as linear or ideal transformers. The linear model includes leakage and magnetizing parameters. The ideal type transformer does not include the magnetizing parameters. Thus, no magnetizing current (RTDS Technologies, 2018).

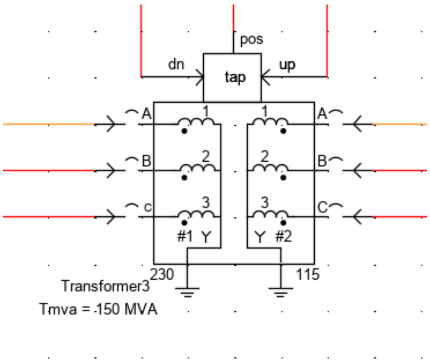
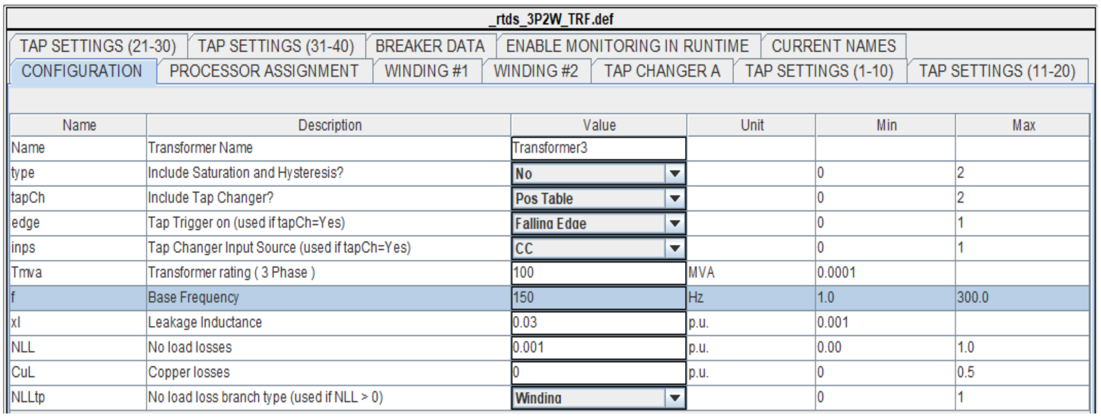


Figure 5-3: RSCAD three phase transformer model



Name	Description	Value	Unit	Min	Max
Name	Transformer Name	Transformer3			
type	Include Saturation and Hysteresis?	No		0	2
tapCh	Include Tap Changer?	Pos Table		0	2
edge	Tap Trigger on (used if tapCh=Yes)	Falling Edge		0	1
inps	Tap Changer Input Source (used if tapCh=Yes)	CC		0	1
Tmva	Transformer rating (3 Phase)	100	MVA	0.0001	
f	Base Frequency	150	Hz	1.0	300.0
xl	Leakage Inductance	0.03	p.u.	0.001	
NLL	No load losses	0.001	p.u.	0.00	1.0
CuL	Copper losses	0	p.u.	0	0.5
NLLtp	No load loss branch type (used if NLL > 0)	Winding		0	1

Figure 5-4:RSCAD three phase transformer model parameters

The parameters are captured in per unit based on the transformer MVA rating and voltage rating on the primary side. The tap changer can either be a table of positions associated with voltage in pu or a step/ Limit. The step/limit option gives the ability to capture the upper and lower, and step in pu of nominal voltage.

5.2.5 Modelling of Transmission lines

Transmission lines play a key role in power systems, they are the highways for electricity linking generation centres to consumption centres. Thus, it is crucial to ensure that transmission lines are modelled correctly. RSCAD library comprises two transmission lines models: “Travelling-wave models” and “PI section models”.

Travelling-wave models take into consideration the distributed nature of line parameters and include the speed of electrical signals over longer distances. For this reason, they are the preferred models. Moreover, the delays included in these models serve to divide the simulated network into separate small independent and concurrent problems. The PI section representation does not take into consideration the travelling time of the electrical signal. Thus, these models are suitable for case studies of short lines (RTDS Technologies, 2018).

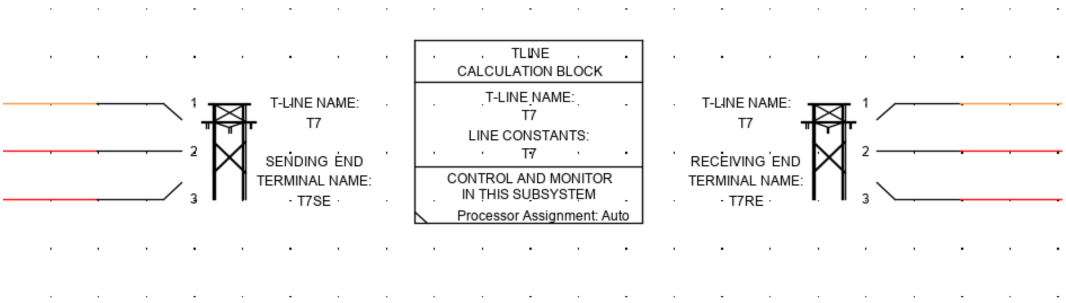
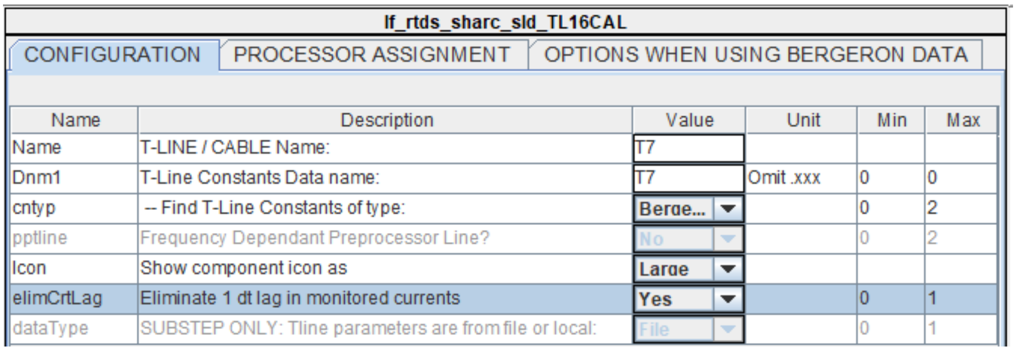


Figure 5-5: RSCAD Transmission model

The travelling-wave transmission line model can be modelled as the Bergeron model or Frequency-dependent phase model. Bergeron model is a simplified model of a real transmission line. It is modelled as a lossless line with resistances lumped at both ends of the line and the centre. The Frequency-dependent model is much more accurate. Thus, requiring more computation resources (RTDS Technologies, 2018).

Figure 5-5 above shows the transmission lines model (unified T-line). Note that the model comprises three blocks: Sending end, receiving end and calculation Block. The three blocks altogether enable the modelling of the transmission as Bergeron, Frequency-Dependent Phase and PI Section. This can be adjusted in the configuration tab of the calculation block as illustrated in Figure 5-6 below.



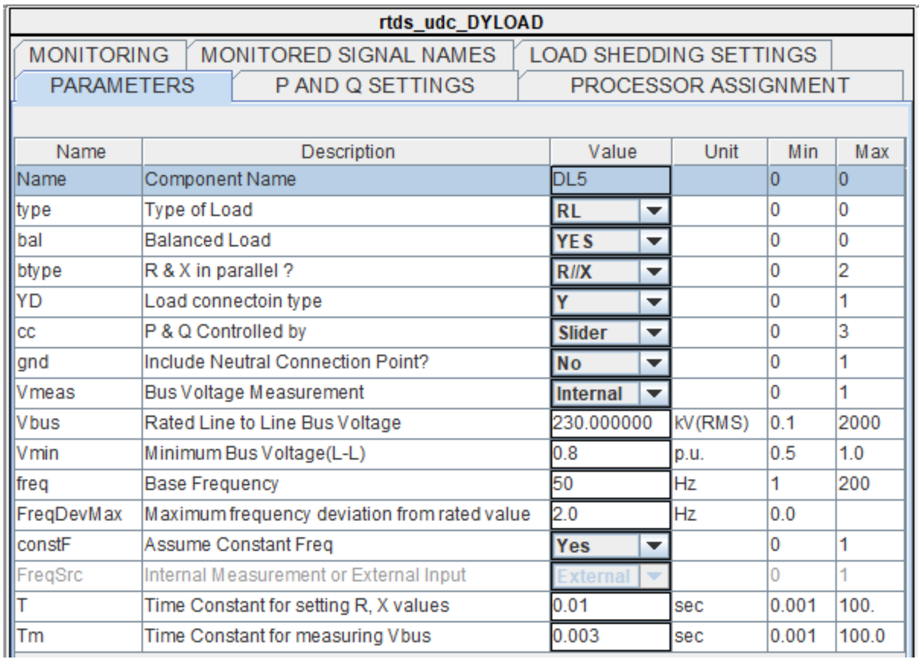
Name	Description	Value	Unit	Min	Max
Name	T-LINE / CABLE Name:	T7			
Dnm1	T-Line Constants Data name:	T7	Omit .xxx	0	0
cntyp	-- Find T-Line Constants of type:	Berge...		0	2
pptline	Frequency Dependant Preprocessor Line?	No		0	2
Icon	Show component icon as	Large			
elimCrtLag	Eliminate 1 dt lag in monitored currents	Yes		0	1
dataType	SUBSTEP ONLY: Tline parameters are from file or local:	File		0	1

Figure 5-6: RSCAD Parameter for unified transmission line

RSCAD also library includes models for cables. However, they are not going to be discussed in the sections.

5.2.6 Modelling of Dynamic Loads

RSCAD library includes a variety of dynamic loads. The load type can be modelled as a combination of a resistive and an inductive or capacitive component or the three (RL, RC, RX). For each combination, the connection can be set to parallel or series. The typical parameters menu of a dynamic load is indicated in Figure 5-7 below.



Name	Description	Value	Unit	Min	Max
Name	Component Name	DL5		0	0
type	Type of Load	RL		0	0
bal	Balanced Load	YES		0	0
btype	R & X in parallel ?	R//X		0	2
YD	Load connectoin type	Y		0	1
cc	P & Q Controlled by	Slider		0	3
gnd	Include Neutral Connection Point?	No		0	1
Vmeas	Bus Voltage Measurement	Internal		0	1
Vbus	Rated Line to Line Bus Voltage	230.000000	kV(RMS)	0.1	2000
Vmin	Minimum Bus Voltage(L-L)	0.8	p.u.	0.5	1.0
freq	Base Frequency	50	Hz	1	200
FreqDevMax	Maximum frequency deviation from rated value	2.0	Hz	0.0	
constF	Assume Constant Freq	Yes		0	1
FreqSrc	Internal Measurement or External Input	External		0	1
T	Time Constant for setting R, X values	0.01	sec	0.001	100.
Tm	Time Constant for measuring Vbus	0.003	sec	0.001	100.0

Figure 5-7: RSCAD Parameters menu for dynamic load

Real and reactive power can be controlled via the following:

- RSCAD/Runtime sliders, the initials values and limits are set on the draft.
- Control Component (CC)
- ConstZ, the load is no longer treated as dynamic
- ZIP, a parameter table is provided.

Figure 5-8 show dynamic load models each with a different setting selected.

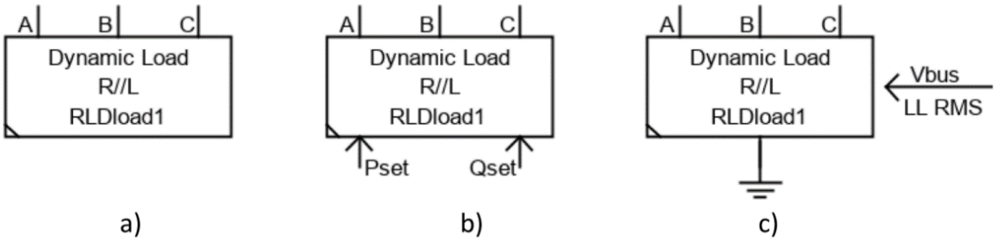


Figure 5-8: RSCAD Load model

Dynamic load models offer a feature enabling load shedding. Real and reactive power setpoints are changed by a factor. This is very useful in the case of a system having multiple loads needing to be adjusted.

5.3 POWER FLOW METHODS FOR SIMULATIONS

Power systems are limited in the amount of power they can produce, transmit and consume. Power flow analysis is conducted to make sure that the system is designed to operate within these limitations. The calculations involved are intense, thus the use of appropriated simulation computer-aided tools. Iterative load flow uses static load flow equations based on voltage and angles at a bus. A bus is selected as a reference and is called a swing bus, slack bus or just a reference bus. This bus is usually assigned a fixed voltage and angle. The voltages at other buses are computed utilizing numerical iterative equations due to the non-linear nature of the resulting equations. Modular load flow uses explicit expression to compute load flows, losses and voltages at buses (Hariharan, Varwandkar and Gupta, 2016).

The expression linking current and voltage in load flow calculation is given as follows:

$$\bar{I} = \overline{Y}\overline{V} \qquad \text{Equation 5-1}$$

The expression for power flow can be given as follows (Das, 2017):

$$S_s = P_s + jQ_s = V_s I_s^* \qquad s = 1, 2, \dots, n \qquad \text{Equation 5-2}$$

Where s is the number of buses.

Substituting the current with its expression in the power equations, we have the following:

$$S_s = P_s + jQ_s = V_s\left(\sum_{r=1}^{n} Y_{sr} V_r\right)^* \qquad r, s = 1, 2, \dots, n \quad \text{Equation 5-3}$$

In power systems, buses are divided into three categories based on known and unknown parameters. The three categories are tabulated in Table 5-1 below:

Table 5-1: Bus type **(Das, 2017)**

Bus Type	Known Variables	Unknown Variables
PV	Active Power & Voltage (P, V)	Current & Reactive Power (I, Q)
PQ	Active & Reactive Power (P, Q)	Current & Voltage (I, V)
Slack	Voltage (V)	Current, Active & Reactive Power (I, P & Q)

There are many power flow methods used in power systems. They all have one thing in common, iterations. Initial values are assigned, then multiple iterative calculations are performed until the desired accuracy is reached. In the following paragraphs, an overview of the most common power methods will be given.

5.3.1 Jacobi Method

This method is known to be the simplest of iterative load flow methods. It consists of assigning initials voltages values set for the first iterations. The successive iteration thereafter uses values resulting from the preceding iteration. The voltage V at bus k for the ith iteration is given by the expression below:

$$V_k^{(i+1)} = \frac{1}{Y_{kk}}\left(\frac{S_k^*}{V_k^{*(i)}} - \sum_{k=1, j\neq k}^{n} Y_{kj} V_J^{(i)}\right); k = 2,3,4, \ldots, n \quad \text{Equation 5-4}$$

The method follows the steps below (Lynn Powell, 2005):

1. Calculate current I_k at all buses using the equation using the expression:

$$I_k = \frac{S_k^*}{V_k^*} \quad \text{Equation 5-5}$$

2. Calculate at all buses:

$$\sum_{k=1, j\neq k}^{n} Y_{kj} V_{kj} \quad \text{Equation 5-6}$$

3. Solve equation 4 above
4. Compare obtained voltage values to corresponding predecessors if they agreed within the predefined tolerance. Should they not agree, return to step 1.

5.3.2 Gauss-Seidel Method

This method is known for its simplicity in programming computer solutions. It offers an improved convergence performance compared to Jacobi Method. This method uses the values of voltages immediately after they are calculated. The voltage V at bus k for the (i+1)th iteration is given by the expression below(Lynn Powell, 2005):

$$V_k^{(i+1)} = \frac{1}{Y_{kk}}\left(\frac{S_k^*}{V_k^{*(i)}} - \sum_{j=1}^{k-1} Y_{kj} V_J^{(i+1)} - \sum_{j=k+1}^{n} Y_{kj} V_j^{(i)}\right) \quad \text{Equation 5-7}$$

The steps involved in this method are as follows:

1. Calculate current I_h at bus h using the equation using the expression

$$I_h = \frac{S_h^*}{V_h^*} \quad \text{Equation 5-8}$$

2. Calculate:

$$\sum_{j=1,j\neq h}^{n} Y_{hj}V_j \qquad \text{Equation 5-9}$$

3. Subtract the current obtain in step 2 from the current in step 1 then divide by Y_{hh} to obtain a new value of V_h
4. For bus h+1, calculate:

$$I_{h+1} = \frac{S_{h+1}^*}{V_{h+1}^*} \qquad \text{Equation 5-10}$$

5. Using voltage V_h obtained from step 3 above, calculate:

$$\sum_{j=1,j\neq h+1}^{n} Y_{(h+1)j}V_j \qquad \text{Equation 5-11}$$

6. Subtract the solution obtained in from the one from 4 and divide by the corresponding admittance $Y_{(h+1)(h+1)}$ to obtain a new value of V_{h+1}
7. Repeat the process using the most recent calculated value of the voltage for all buses.
8. Compare obtained voltage values to corresponding predecessors if they agreed within the predefined tolerance. Should they not agree, return to step 1.

5.3.3 Z-Matrix Method

One of the most common problems with the two methods portrayed in the sections above is poor convergence and or divergence. To remedy this, this method makes use of Z-matrix. The voltage V at bus k is given by the expression below(Lynn Powell, 2005):

$$V_k = \sum_{j=2}^{n} Z_{kj}I_j - \sum_{j=2}^{n} Z_{kj}Y_{j1}V_1 \qquad \text{Equation 5-12}$$

The steps involved in this method are as follows:

1. Calculate C_k using the expression below:

$$C_k = \sum_{j=2}^{n} Z_{kj}Y_{j1}V_1 \qquad \text{Equation 5-13}$$

2. Find all injected current using the expression below:

$$I_i = \frac{S_i^*}{V_i^*} \quad \text{Equation 5-14}$$

3. Calculate voltages at all buses using equation 12 above.
4. Compare obtained voltage values to corresponding predecessors if they agreed within the predefined tolerance. Should they not agree, return to step 1.

5.3.4 Newton-Raphson Methods

This method is known for its rapid convergence characteristics. It however requires heavy computation and large storage space. Compared to other methods, its convergence requires a small number of iterations. This number does not increase even for larger systems provided that the initial values are not far off the final results(Brown, 2002).

The expression of the voltage at bus k for the (i+1)th iteration is given as follows (Lynn Powell, 2005):

$$V_k^{i+1} = V_k^i + J_1^{-1}\left[s - f(V_{1)}\right] \quad \text{Equation 5-15}$$

The steps involved in this method can be resumed as follows:

1. Formation of the admittance matrix
2. All PQ buses are assigned an initial voltage (magnitude and angle); PV buses get assigned phase angles and the magnitude equal to the slack bus'. Generally, both voltage and magnitudes are set equal to the one of the slack bus.
3. P and Q are calculated for all PQ buses
4. ∆P and ∆Q are therefore calculated based on given power at buses.
5. For all PV buses, only the limits of reactive power are known. Should the calculated value of reactive power be within the limitations, only ∆P is calculated. Else an appropriated value is imposed and ∆Q is calculated as the difference between the calculated value of Q and the known maximum.
6. Components of the Jacobian matrix are now calculated. This reveals the value of ∆θ and $\Delta|V|$.

7. Use the values of $\Delta\theta$ and $\Delta|V|$ to calculate new voltages (phase angle and magnitude)
8. Compare obtained voltage values to corresponding predecessors if they agreed within the predefined tolerance. Should they not agree, return to step 1.

5.3.5 Fast Decoupled Method

This method is a simplified version of Newton Raphson. The simplification is based on the fact that a change in voltage phase angle results in a negligible impact on reactive power flow. A change in voltage magnitude has little impact on active power flow.

ΔP and ΔQ can be given as follows(Lynn Powell, 2005):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ (\Delta|V|)/|V| \end{bmatrix} \quad \text{Equation 5-16}$$

Applying the independence between active power/voltage magnitude and reactive power voltage angle, the above equation becomes:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ (\Delta|V|)/|V| \end{bmatrix} \quad \text{Equation 5-17}$$

The simplifications above led to very fast power flow calculation methods.

5.4 POWER SYSTEM DATA

To accomplish the aim and objectives of this project, the 12 Bus IEEE test system is modified into a configuration accommodating parallel transformers equipped with a tap changer. Originally the system comprised 1 grid, 3 generators, 12 bus, 7 transmission lines, 6 transformers, 5 dynamic loads and 3 reactive compensators. The system is best suited for analyses of the following (Jiang, Annakkage and Gole, 2005):

- FACTS devices applications for congestion relief,
- Voltage support,
- Transient stability,
- Integration of wind generation.

The modifications of the original 12 bus IEEE test system consist of the following:

- Three transformers are added to the network in parallel at Bus 6 stepping down 230KV to 115KV.
- The dynamic load 6 is then modelled to be fed from the lower side of the transformers at a new bus 13.
- A backup generation plant is added at Bus 13.

5.4.1 Single line diagram

The single line diagram represented hereunder in Figure 5-9 is a snapshot of the modified 12 BUS IEEE network modelled in RTDS.

5.4.2 Transformer data

Table 5-2: Transformers data

	From Bus	To Bus	Rating (MVA)	No. of taps	Volt/tap (pu)	Impedance	
						R (pu)	**X (pu)**
Transformer 1	6	13	150	33	0.00625	0.0	0.02
Transformer 2	6	13	150	33	0.00625	0.0	0.02
Transformer 3	6	13	150	33	0.00625	0.0	0.02
Transformer 4	1	9	100	-	-	0.00	0.0075
Transformer 5	1	7	100	-	-	0.0	0.0075
Transformer 6	8	3	100	-	-	0.0	0.0075

5.4.3 Load data

Table 5-3: Load data

	Bus	Nominal Power Rating		Maximum Power Rating		Type
Dynamic Load 2	2	280MW	200MVar	560MW	400MVar	Dynamic Load
Dynamic Load 3	3	320MW	240MVar	640MW	480MVar	Dynamic Load
Dynamic Load 4	4	320MW	240MVar	640MW	480MVar	Dynamic Load
Dynamic Load 5	5	100MW	60MVar	200MW	120MVar	Dynamic Load
Dynamic Load 13	13	440MW	300MVar	880MW	600MVar	Dynamic Load

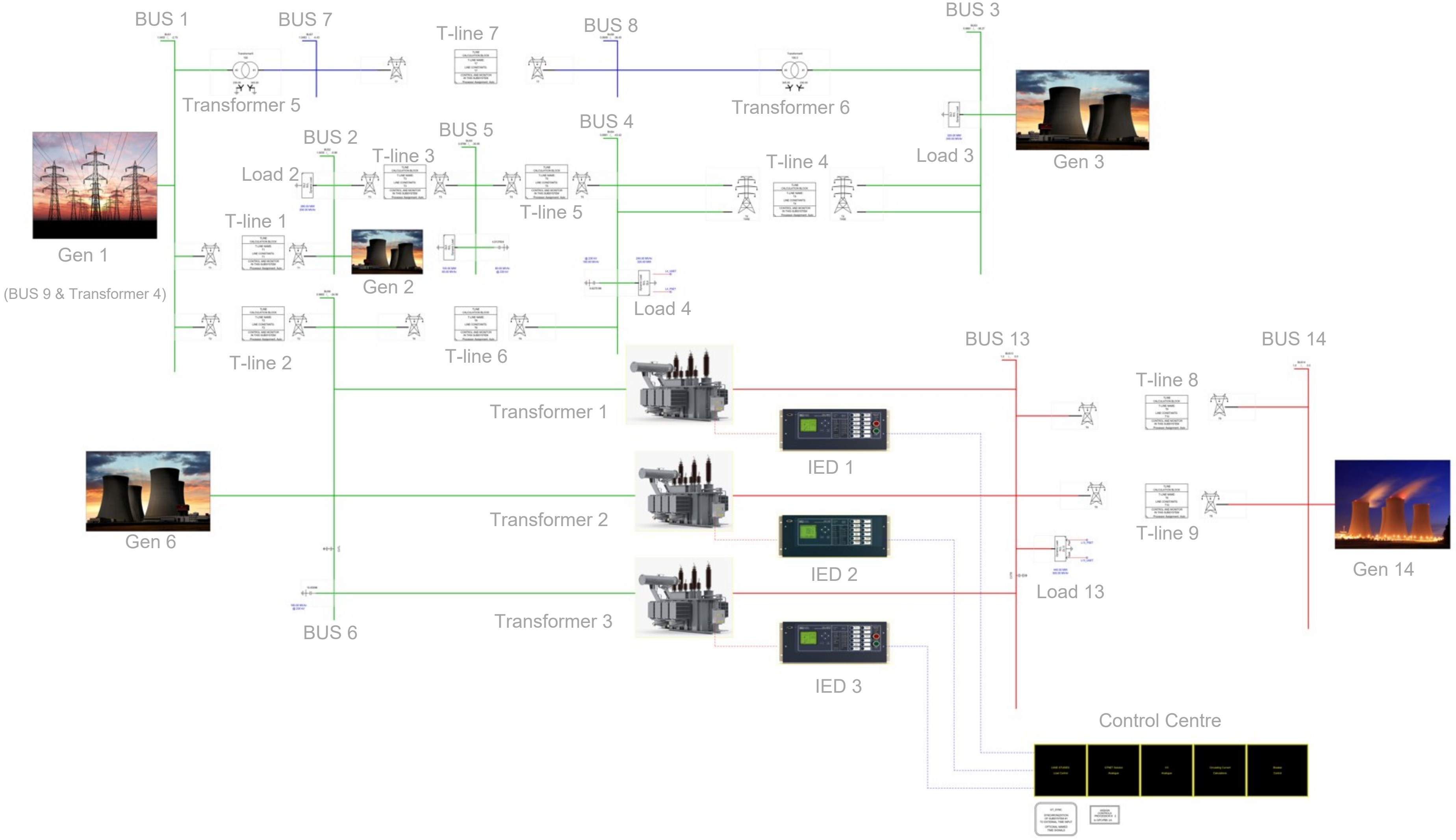


Figure 5-9: Modified IEEE 13 bus test system

5.4.4 Lines data

Table 5-4: Line Data

	Voltage Rating	Zone	impedance (pu on 100MVA base)		
			R	X	B
Line 1	230KV	Bus 1– Bus 2	0,01144	0,09111	0,18261
Line 2	230KV	Bus 1– Bus 6	0,03356	0,26656	0,55477
Line 3	230KV	Bus 2– Bus 5	0,03356	0,26656	0,55477
Line 4	230KV	Bus 3– Bus 4	0,01144	0,09111	0,18261
Line 5	230KV	Bus 4– Bus 5	0,03356	0,26656	0,55477
Line 6	230KV	Bus 4– Bus 6	0,03356	0,26656	0,55477
Line 7	315KV	Bus 7– Bus 8	0,01595	0,17214	3,28530
Line 8	115KV	Bus 13– Bus 14	0,00079	0,00867	0,16426
Line 9	115KV	Bus 13– Bus 14	0,00079	0,00867	0,16426

5.4.5 Shunt Capacitors data

Table 5-5: Shunt Capacitor data

	Power Rating	Nominal voltage	Location
Shunt Capacitor 4	160 MVar	230KV	Bus 4
Shunt Capacitor 5	80 MVar	230KV	Bus 5
Shunt Capacitor 6	180 MVar	230KV	Bus 6

5.4.6 Initial load flow result

Table 5-6 below shows load results for the modified network under initial conditions. During initial conditions, the generating unit at bus 14 is not operational. The results are obtained after 6 iterations.

Table 5-6: Initial load flow results

Bus identifier	Nominal Voltage	Load Flow V (pu)	Load Flow (deg)	Real power (MW)	Imaginary Power (Mvar)	Type
Bus 1	230KV	1,03866	-2,72313	-	-	PQ
Bus 2	230KV	1,00412	-1,2022	-	-	PQ
Bus 3	230KV	0,9852	-33,2485	-	-	PQ
Bus 4	230KV	0,9519	-37,4243	-	-	PQ
Bus 5	230KV	0,9715	-26,5770	-	-	PQ
Bus 6	230KV	0,9849	-29,6597	-	-	PQ
Bus 7	345KV	1,0448	-4,4560	-	-	PQ
Bus 8	345KV	0,9905	-31,4311	-	-	PQ
Bus 9	22KV	1,0400	0,0000	513,25	26,13	SLACK
Bus 10	22KV	1,0200	-28,4040	500,000	174,17	PV
Bus 11	22KV	1,0100	-62,0968	200,000	252,36	PV
Bus 12	22KV	1,0200	-56,2356	300,000	188.02	PV
Bus 13	115KV	0,96386	-31,43124	-	-	PQ
Bus 14	115KV	1,0200	-56,2356	-	-	PQ
Bus 15	22KV	-	-	-	-	PV

5.5 SCHEDULE OF CASE STUDIES

To achieve the various objectives of the project, the following case studies listed in the paragraphs below will be undertaken. Each of them with a specific aim. The following assumptions have been made concerning the case studies:

- Under-voltage and over-voltage have been taken care of by respective protection schemes. Thus, voltage fluctuation will go over the allowed limits during the simulation.
- Loading will be taken to the extreme to create sufficient voltage drop across the buses. The loading will have to be increased ignoring the network limitations.

5.5.1 Case Study 1: Forward operation

This case study aims to investigate the forward operation of developed controllers in chapter 6 below. This will be achieved by performing the following:

- Gradual increase of dynamic load at bus 12.
- Disconnection of one of the transformers in parallel.

Figure 5-10 below illustrates the voltage profiles at Bus 13 & B14 as a result of the Load Increase at Bus 13. The load is gradually increased in steps of 15 percentile varying from 50% to 200% of the nominal load at bus 13.

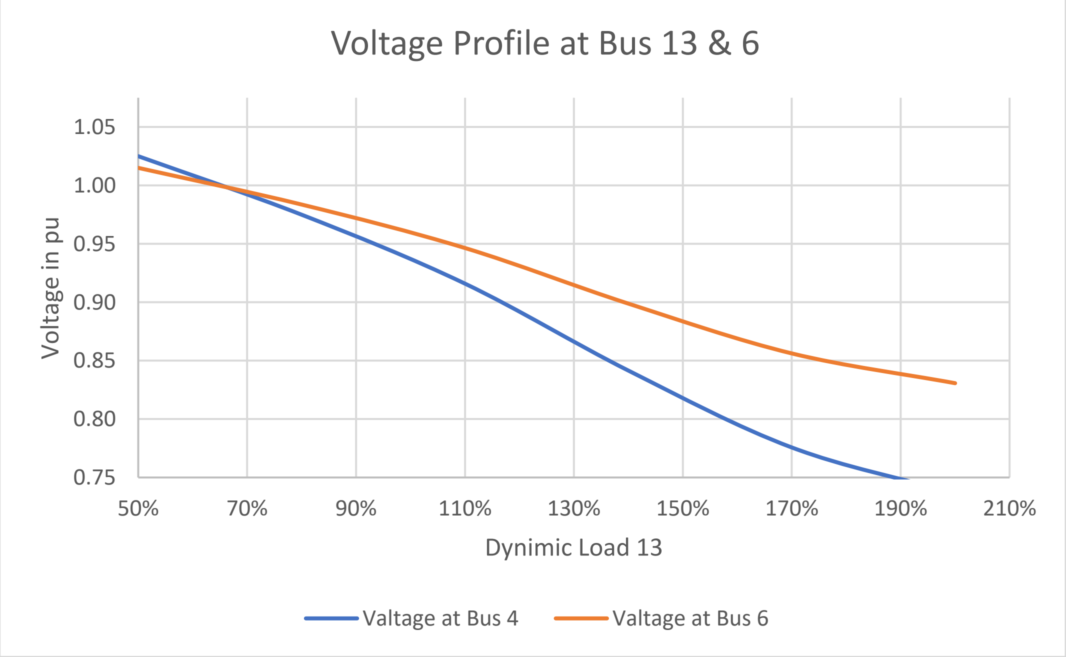


Figure 5-10:C/S 1: Voltage profile at Bus 13 & 6 vs Loading DL13

5.5.2 Case study 2: Reverse operation

This case study aims to investigate the reverse operation of developed controllers by performing the following tasks:

- Turn off the generating plant at bus 6 while transformers are on their lowest tap setting
- Disconnection of one of the transformers in parallel.

This case study involves bringing online the backup generation unit at Bus 15 to run power in the opposite direction. Since the load at Bus 13 has none to little effect on the current flowing in the parallel set transformer, Load 4 will then be used to drive more current in the transformers.

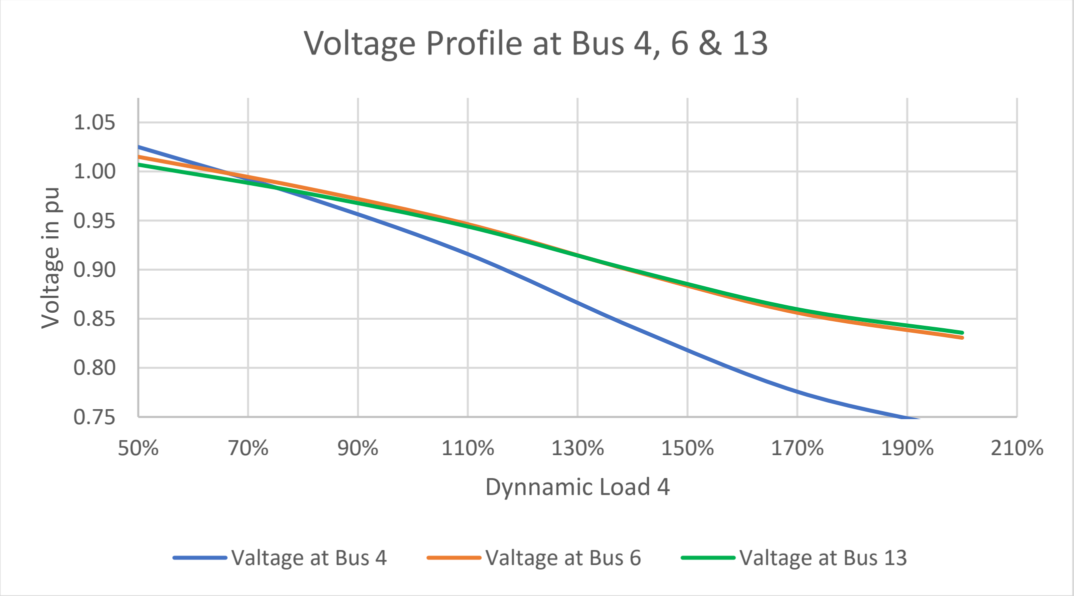


Figure 5-11: Voltage profile at Bus 4, 13 & 6 vs Loading DL4

5.5.3 Case study 3: Fault conditions

This case study aims to investigate the operation of the controllers under fault conditions. Various fault conditions will be simulated, and operations recorded and analysed.

Under fault conditions, the tap changer should not be the cause of aggravating the system already under stress. The results of this case study are given in chapter 7.

5.5.4 Case study 4: Different transformers performance

Under certain circumstances, the power system might be subjected to operate in parallel with unidentical transformers that achieve the minimum requirements. Developed controllers are designed to operate even for transformers that do not have the same electrical properties. This case study aims to investigate the performance of the controllers for unequal transformers. The circulating current between transformers will be monitored to ensure that it is below the maximum allowed level.

5.6 CONCLUSION

Computer-aided simulation software plays an important role in modern power systems. It allows the designing testing of protection and automation schemes among many other advantages. This chapter gave an overview of RTDS/ RSCAD; Various modules of the software were briefly discussed, and the modelling of key power system components was explained. To optimise the use of computation resources, it is important to identify various components' accuracy for the case study being investigated. The chapter gave a brief overview of various numerical methods for load flow calculation.

Furthermore, the test network to be used including data and initial load flow are given. Lastly, the schedule of case studies necessary to achieve the objectives of the projects are given. The following chapter will detail the development of the controller algorithm as well as the implementation.

CHAPTER 6

DESIGN OF ON-LOAD TAP CHANGER CONTROLLER FOR PARALLEL TRANSFORMERS

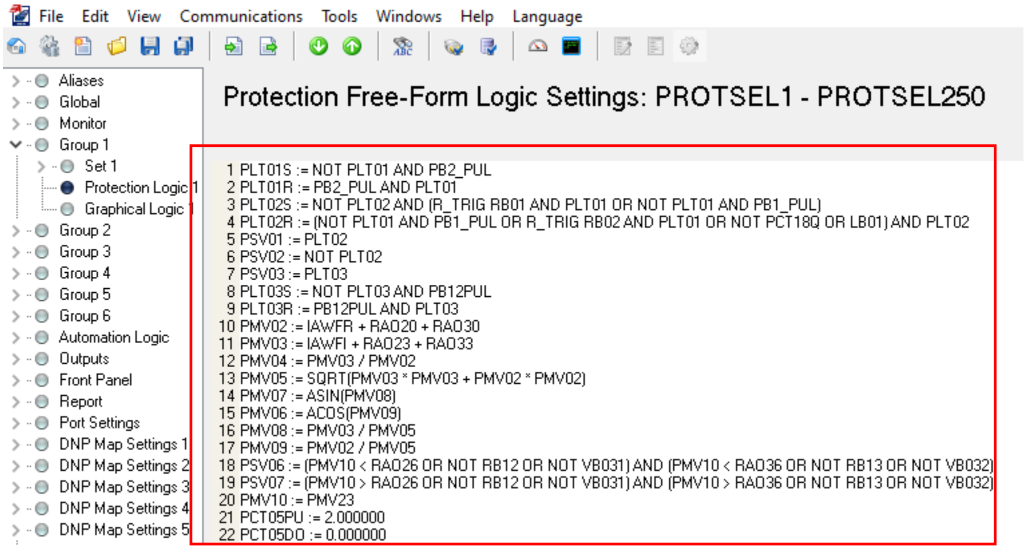
6.1 INTRODUCTION

On-load tap changer for application in current power system is more involved than just a simple response to a voltage change. The control gets more complex when a set of transformers are to be connected in parallel. Traditionally, the control of such arrangement was achieved utilizing a designated device, a parallel balancer. The control is achieved nowadays with the use of programmable logic controllers and intelligent electronic devices. They offer the possibility to develop custom logic satisfying the need of the user.

This chapter reveals the various steps involved in the design of the tap changer controller for the parallel operation of transformers. Logic diagrams are developed using the logic editor feature embedded in SEL devices. This is developed based on the circulating current principle. The logic is set to work in forward and reverse mode. For both modes, the voltage at the control bus is assessed against the predefined acceptable boundary. A raise or lower command is therefore issued accordingly with a predefined time delay. All devices/transformer operates independently. Should one of the devices or transformers fail, the rest carry on as if the faulty device never existed. The communication between devices involved is accomplished utilizing IEC 61850 Standards.

6.2 HARDWARE AND SOFTWARE

The control algorithm is developed using SEL IED’s. Thus, the SEL IED’s configuration software SEL-5030 acSELarator QuickSet and SEL-5032 acSELarator Architect are used for designing logic and configuring communications. The logic is created by entering lines of codes or by using the Graphical Logic Editor (GLE) – this is a feature that offers a computer-aided drawing interface. The use of this feature reduces typos as elements are dragged and dropped as indicated in Figure 6-2 below.



```
PLT01S := NOT PLT01 AND PB2_PUL
PLT01R := PB2_PUL AND PLT01
PLT02S := NOT PLT02 AND (R_TRIG RB01 AND PLT01 OR NOT PLT01 AND PB1_PUL)
PLT02R := (NOT PLT01 AND PB1_PUL OR R_TRIG RB02 AND PLT01 OR NOT PCT18Q OR LB01) AND PLT02
PSV01 := PLT02
PSV02 := NOT PLT02
PSV03 := PLT03
PLT03S := NOT PLT03 AND PB12PUL
PLT03R := PB12PUL AND PLT03
PMV02 := IAWFR + RA020 + RA030
PMV03 := IAWFI + RA023 + RA033
PMV04 := PMV03 / PMV02
PMV05 := SQRT(PMV03 * PMV03 + PMV02 * PMV02)
PMV07 := ASIN(PMV08)
PMV06 := ACOS(PMV09)
PMV08 := PMV03 / PMV05
PMV09 := PMV02 / PMV05
PSV06 := (PMV10 < RA026 OR NOT RB12 OR NOT VB031) AND (PMV10 < RA036 OR NOT RB13 OR NOT VB032)
PSV07 := (PMV10 > RA026 OR NOT RB12 OR NOT VB031) AND (PMV10 > RA036 OR NOT RB13 OR NOT VB032)
PMV10 := PMV23
PCT05PU := 2.000000
PCT05DO := 0.000000
```

Figure 6-1:Logic Editor - Code

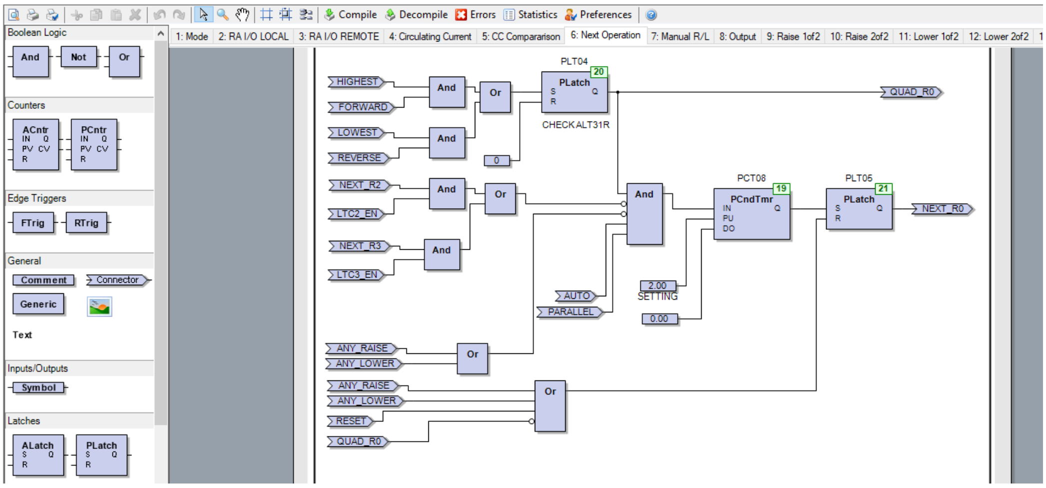


Figure 6-2: Graphical Logic Editor

The IED’s used are Protection Automation Control as detailed in table 6-1 below.

Table 6-1: IED's Details

Manufacturer	IED	Description
SEL	SEL-487V	Protection Automation Control
SEL	SEL-487V	Protection Automation Control
SEL	SEL-421	Protection Automation Control

6.3 ALGORITHM DEVELOPMENT

The development of the algorithm is based on the circulating current method. Thus, it is crucial to understand how the circulating current is computed. The computation of circulating current is explained in chapter 3.

The algorithm is subdivided into interdependent small logics. This is simply for ease of troubleshooting. The developed algorithm will be sub dived into automatic and manual mode controlled locally or remotely.

6.3.1 Manual operation

In manual operation, the control is initiated by push buttons (Local Raise and Local Lower) provided that the local mode is active. In remote mode, the control is initiated by remote bits (Remote Raise ad Remote Lower). Figure 6-3 below.

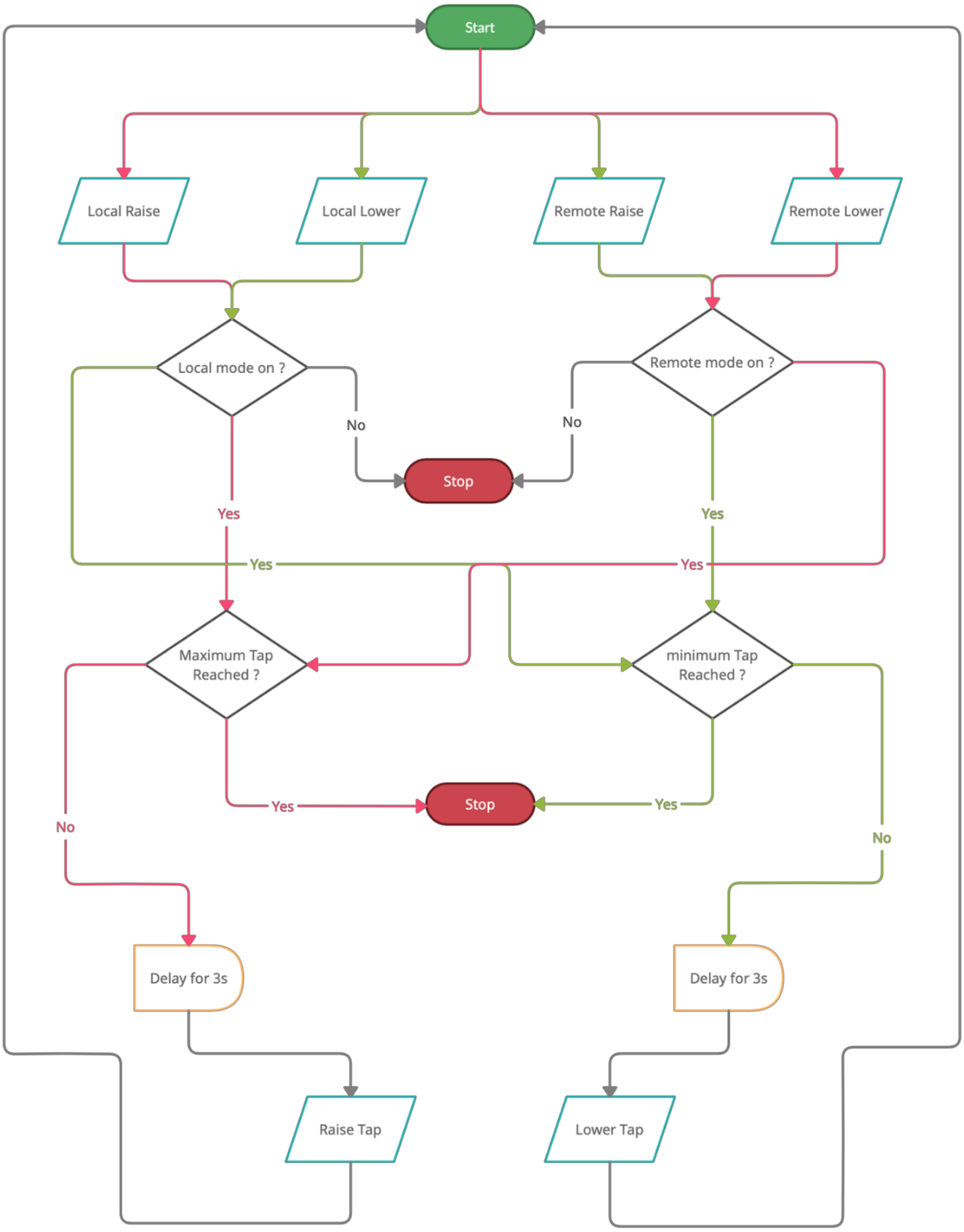


Figure 6-3: Manual Mode Algorithm

6.3.2 Automatic Mode

The automatic mode is much more involved than just voltage assessment. The algorithm has two parts: The first part is dedicated to transformers operating alone, and the second is for transformers in parallel.

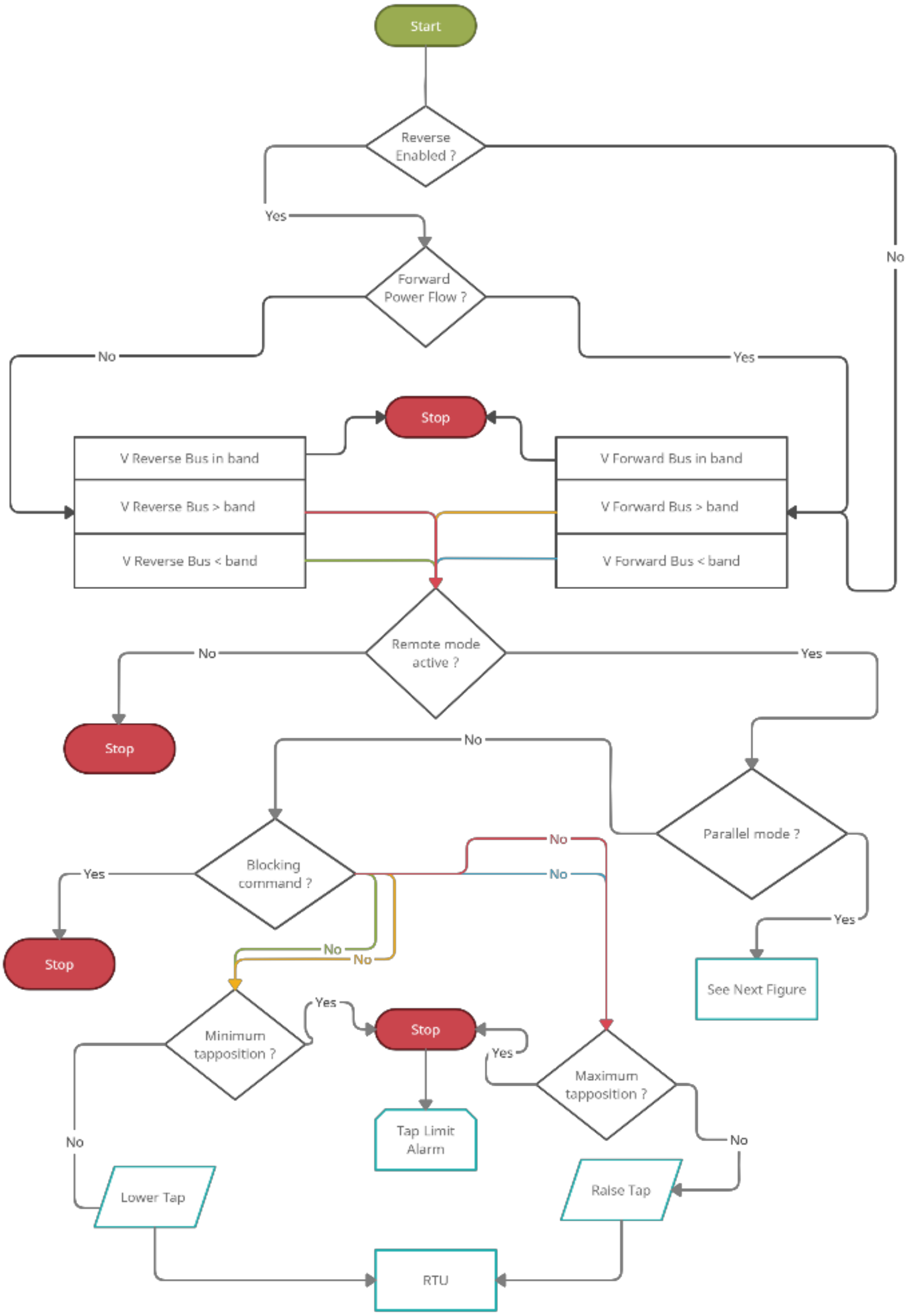


Figure 6-4: Automatic mode part 1

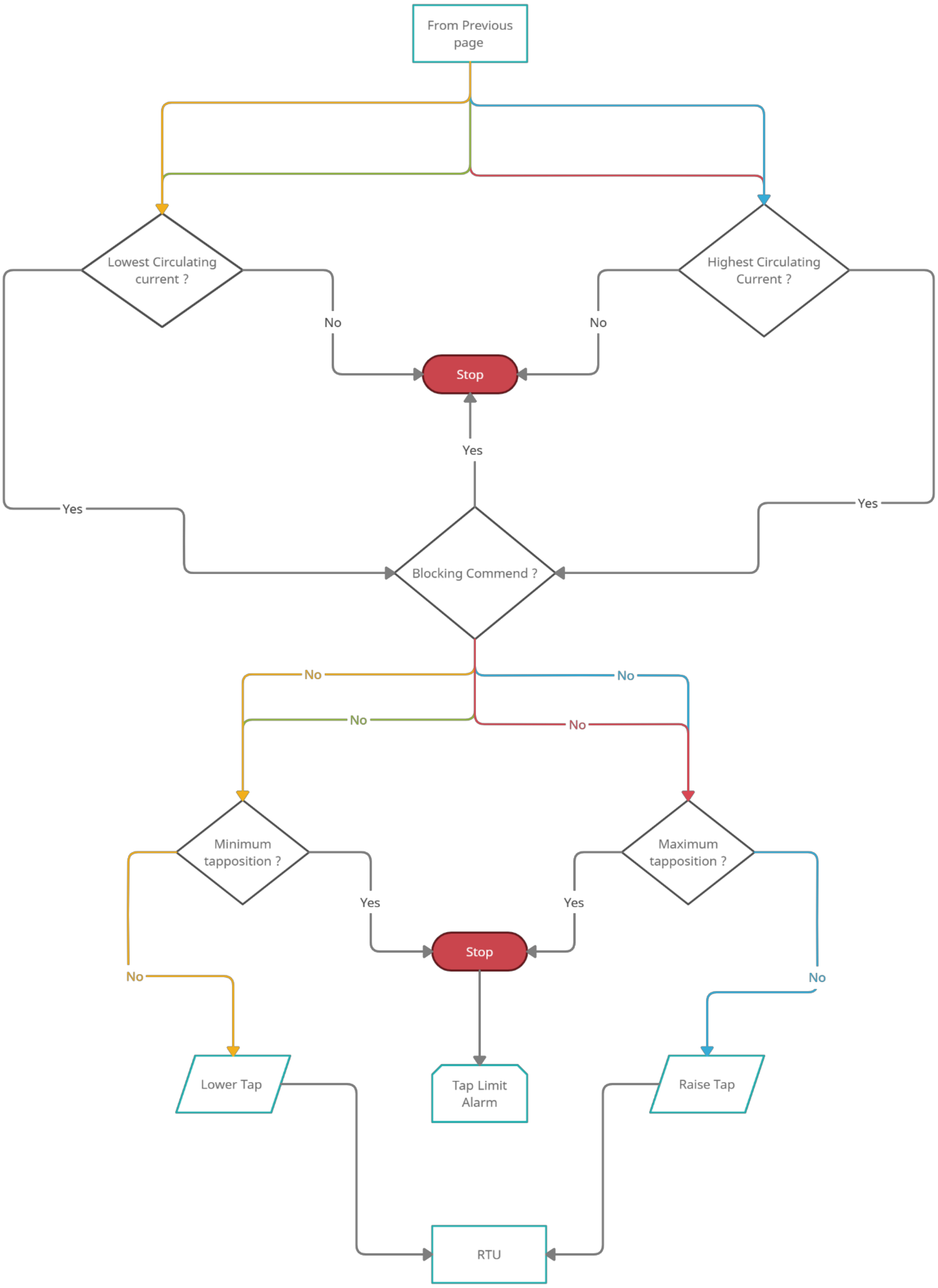


Figure 6-5: Automatic mode part 2

6.3.3 Communication

Harmony needs to be observed when controlling transformers running in parallel to avoid unwanted or uncoordinated tap operations. IEC 61850 standard is used to publish and subscribe to analogue and binary signals inputs and outputs to the developed algorithm. Each relay publishes a set of binary & analogue signals and subscribes to broadcasted signals published by other relays in the group. Figure 6-6 below illustrates the subscription, publication, and mapping of analogue and binary signals.

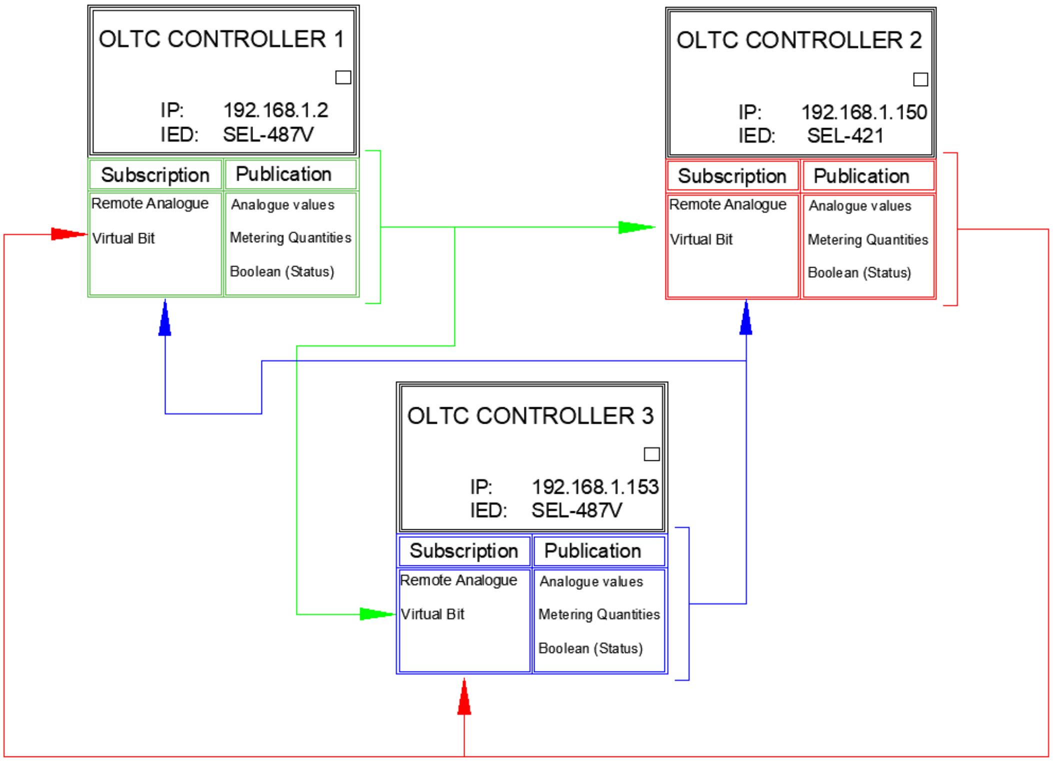


Figure 6-6: IEC61850 Mapping & Subscription

Although figure 69 only communication between IED's, it is important to note the communication between IED – RTU and IED – SCADA is also achieved using Goose messages. Analogue quantities are mapped to remote analogues and binaries are mapped to virtual bits. These are then used for comparison, calculation or as inputs to various logics.

6.4 LOGIC PROGRAMMING USING SEL GRAPHICAL LOGIC EDITOR

6.4.1 Operation mode

The operation mode controls the selection between the remote/local operation, Automatic or Manual and Enabling of Reverse mode. The switching between local and remote (PLT01) will be activated using a push button (PB02_PUL). In local mode, the push button (PB01_PUL) will toggle between manual and automatic mode (PLT02). When the remote mode is activated, Virtual bit VB01 and VB02 are used respectively to change to Auto and remote mode. Figure 6.7 below is the graphical representation of the operation mode selection.

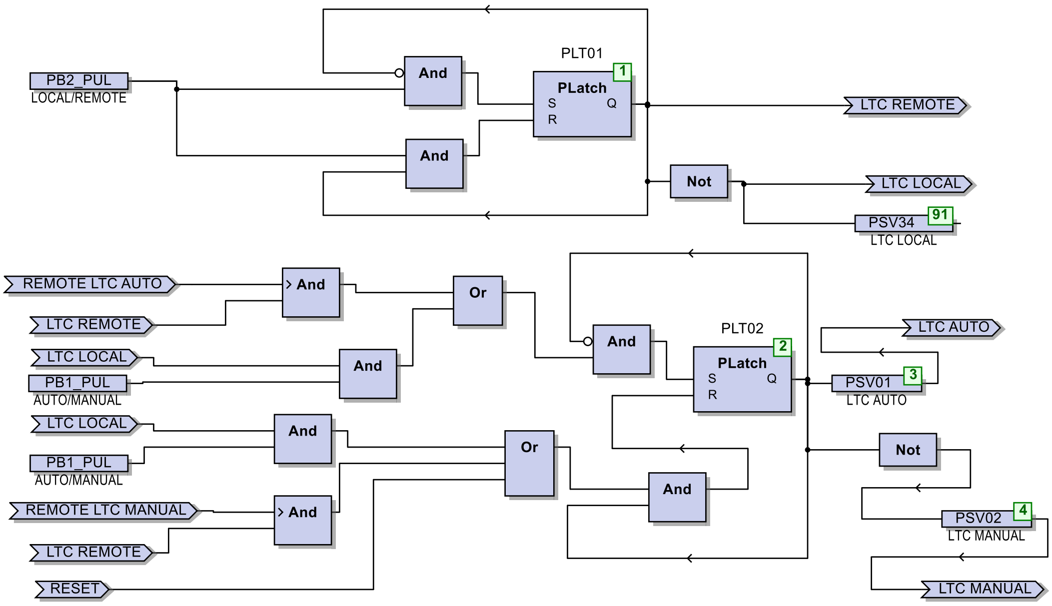


Figure 6-7: Local/Remote, Auto/Manual modes & Enable Reverse logics

Not shown in Figure 6-7 above is the enabling/disabling of reverse mode. This is achieved using Pushbutton (PB12_PUL), logic gates and latches. Enabling the reverse mode of one transformer enables the reverse mode for all in the parallel group. In Remote mode, this is achieved via SCADA using virtual bits to all transformers.

6.4.2 Manual Operation

In local mode, the manual operation is achieved using pushbuttons PB3 and PB9 to raise and lower, respectively. In remote, virtual bits VB003 and VB004 are used to raise and lower, respectively. As can be seen from Figure 6-8 below, the VB005 and VB006 are also used to raise and lower the tap, respectively. However, these signals are used when it is necessary to raise the tap of all transformers at once via SCADA control.

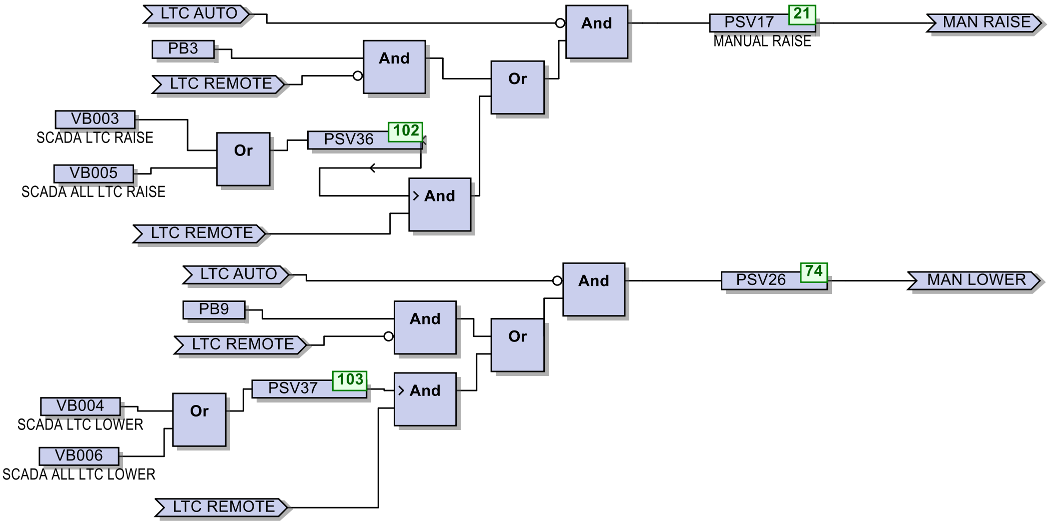


Figure 6-8: Manual Operation

The following section will describe logic playing a crucial role in the automatic tap changing.

6.4.3 Design consideration and Requirements

Automatic mode logics are designed based on parameters in Table 6-2 below. The denotation (L) stands for line or phase to phase quantities and (P) for Phase to neutral quantities. The ratio of primary VT and CT are chosen in such a way that the primary and secondary quantities of the transformer as seen by IED's are of the same range.

Table 6-2: Network parameter and requirements

	Forward			Reverse		
	Per unit (pu)	Actual (KV)	VT (V)	Per unit (pu)	Actual (KV)	VT (V)
Voltage set point	1	115	120	1	230	120
Voltage set point	1	66.395	69.282	1	132.791	69.282
Voltage per tap (L)	0.00625	0.71875	0.75	0.00625	1.4375	0.75
Voltage per tap (P)	0.00625	0.4150	0.433	0.00625	0.8299	0.433
Voltage	0.009375	1.078125	1.125	0.009375	2.15625	1.125
Voltage	0.009375	0.622456	0.6495	0.009375	1.2449	0.6495
Number of taps	33	33	33	33	33	33
Initial taps position	17	17	17	17	17	17

6.4.4 Voltage Setpoint

The voltage setpoint is controlled by the logic in Figure 6-9 below. The values used in this logic are obtained from Table 6-2 in the previous section.

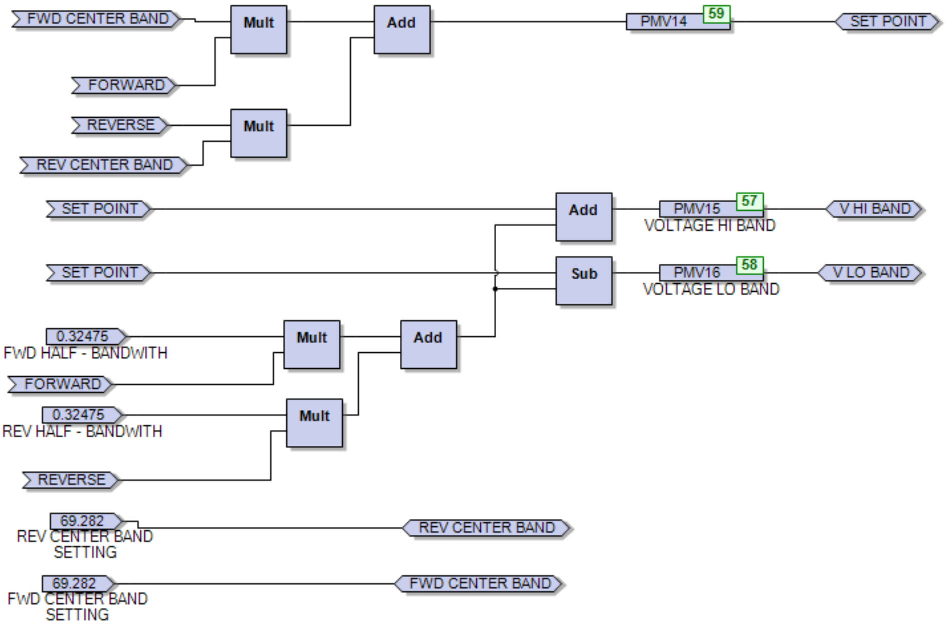


Figure 6-9: Voltage Setpoint logic

6.4.5 Circulating current calculation

This sub-logic calculates the circulating contribution of each transformer then compares the values to identify which transformer has a high or lower circulating current contribution. This is possible by continuously sharing load current as well computed circulating current of participating transformer via IEC 61850 protocols.

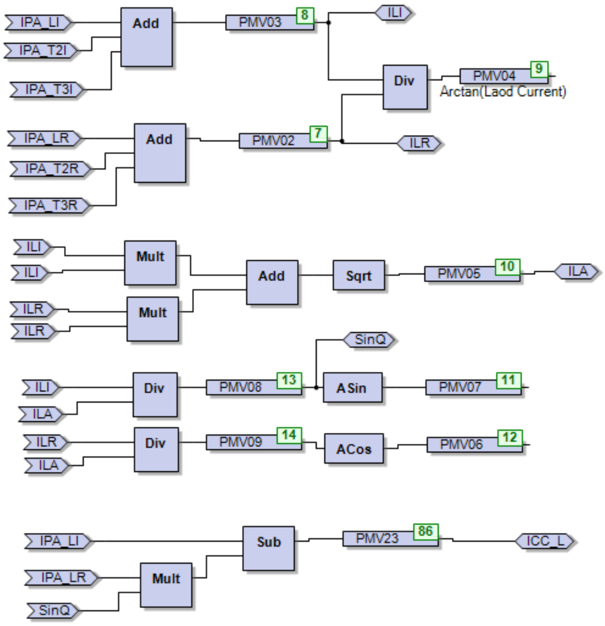


Figure 6-10: Circulating Current computation logic

From Figure 6-10 above,

- IPA_LI, IPA_T2I and IPA_T3I are the imaginary part of phase A current flowing in Local transformer(T1), Transformer 2(T2) and Transformer 3(T3) respectively. The sum of these quantities results in the imaginary part of phase A load current ILI stored under PMV03.
- IPA_LR, IPA_T2R and IPA_T3R are the real part of phase A current flowing in Local transformer(T1), Transformer 2(T2) and Transformer 3(T3) respectively. The sum of these quantities results in the real part of phase A load current ILR stored under PMV02.
- ILI and ILR are used to compute the load sine and cosine of load angle Q stored under PMV07 and PMV06, respectively. The sine Q computed is then used to calculate the circulating current ICC_L contribution of the local transformer(T1).

An auxiliary logic shown in Figure 6-11 below is used to identify the transformer in the parallel group with a higher/lower circulating current contribution.

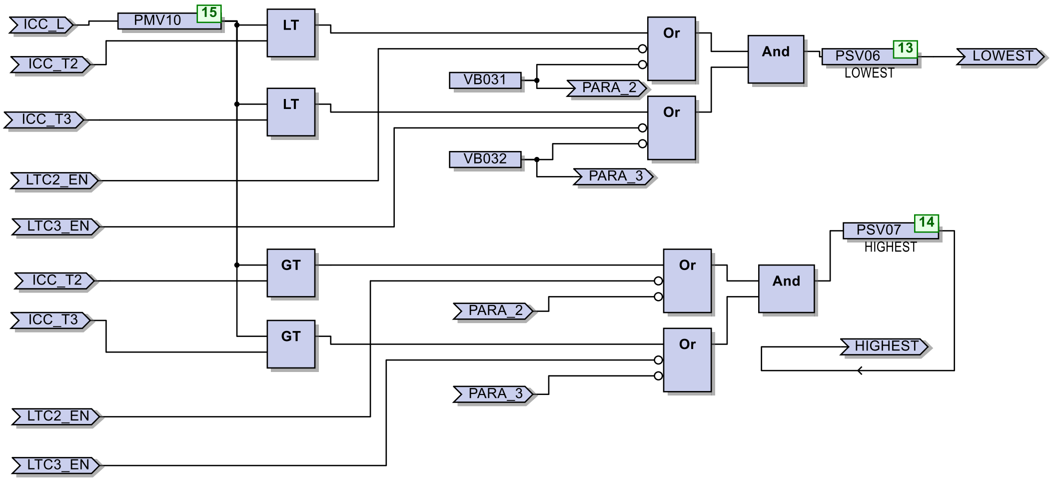


Figure 6-11: Circulating Current Comparison

6.4.6 Next operation

At all times, each IED assess whether its associated transformer is the next to operate. The assessment simply aims to reduce the circulation current contribution. This can be resumed in the truth table 6-3 below.

Table 6-3: Next operation

Circulating Current	Power flow	Next to Raise	Next to Lower
Highest	Forward	Y	N
Lowest	Forward	N	Y
Not Lowest nor Highest	Forward	N	N
Highest	Forward	N	Y
Lowest	Forward	Y	N
Not Lowest nor Highest	Forward	N	N

The graphical logic for this task is shown in Figure 6-12 below. It is important to note that some safety features are included to avoid inaccurate assessment. This is the case if multiple transformers claim to have the highest or lower circulating current at the same time.

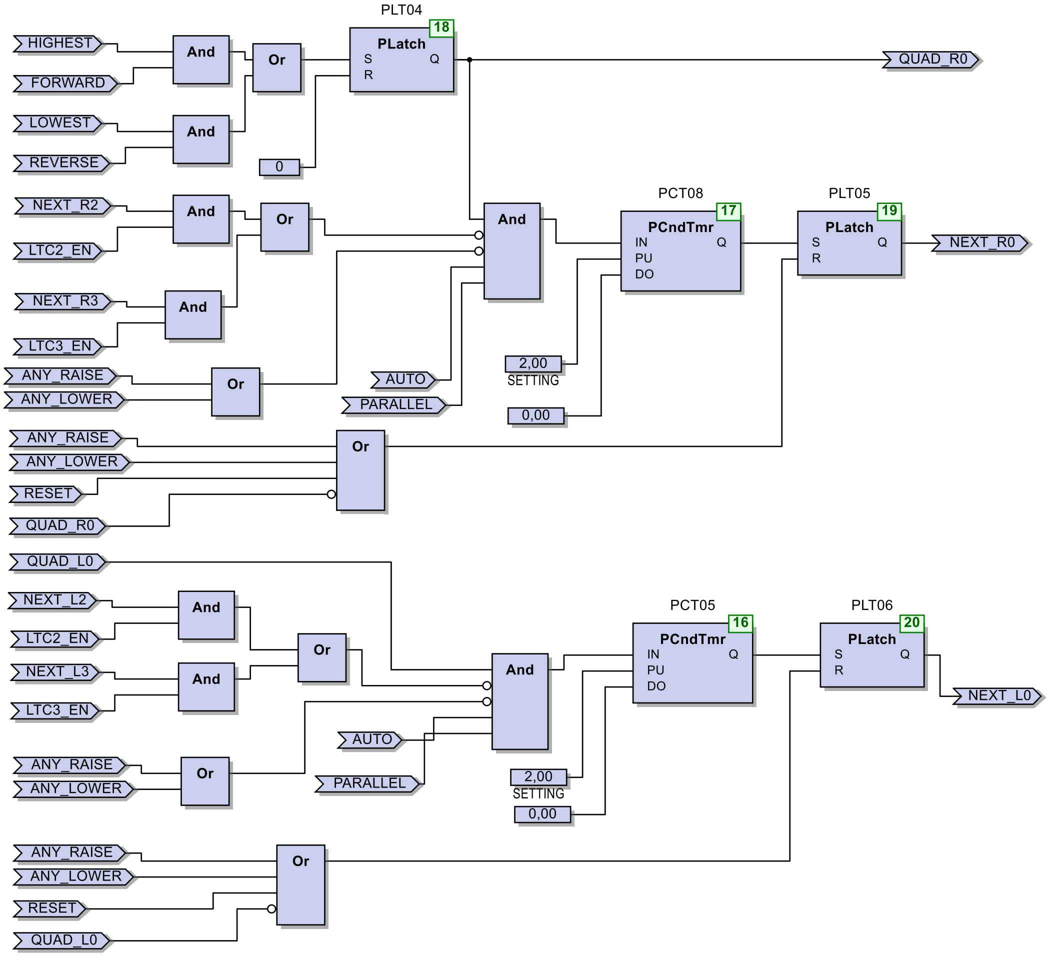


Figure 6-12: Next operation logic

6.4.7 Automatic raise

The automatic raise logic assesses the voltage magnitude against the defined set point to issue a raise commend. However, a small number of conditions must be met before the command is issued as can be seen in Figure 6-13 below.

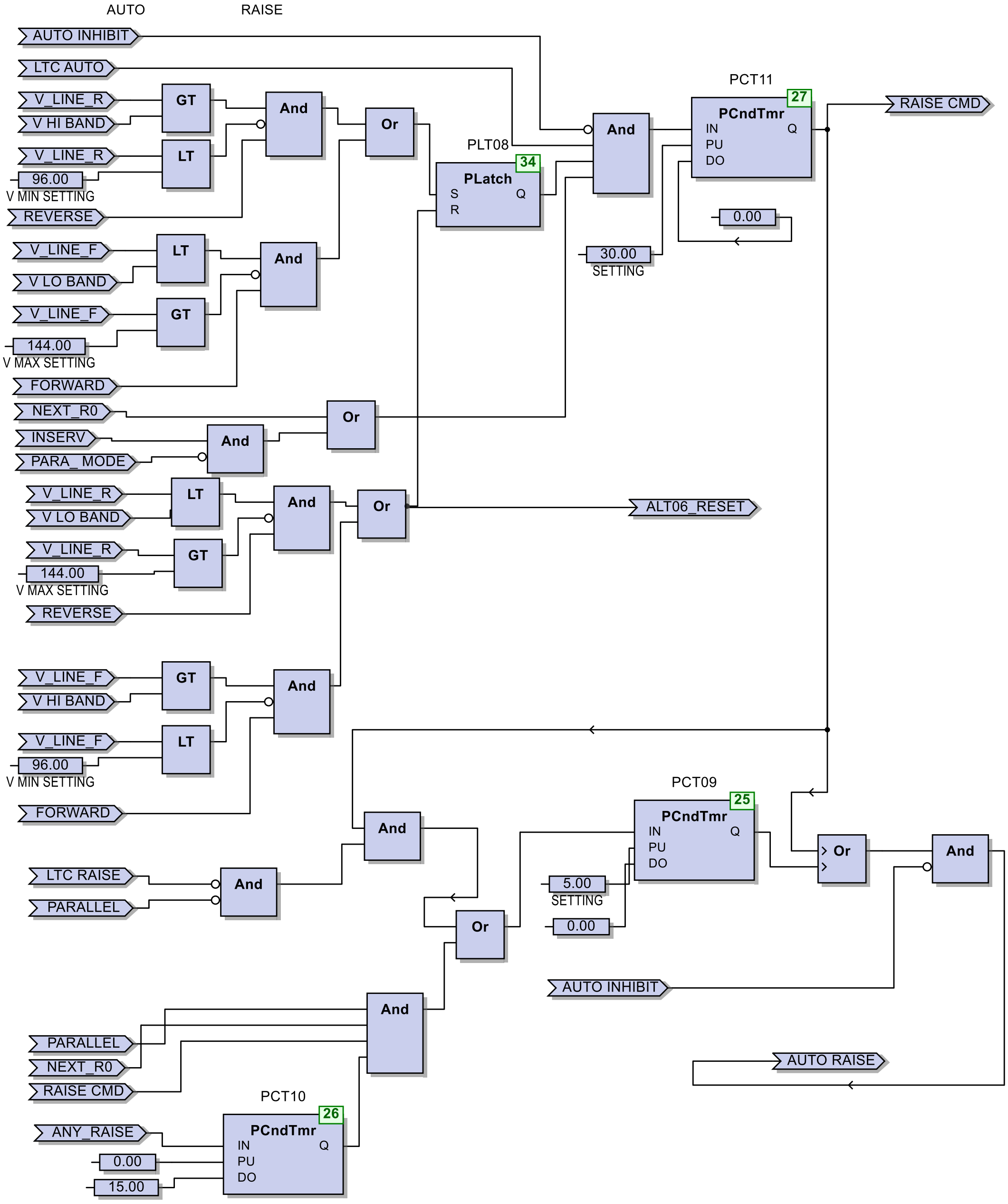


Figure 6-13: Automatic tap changer logic

6.4.8 Automatic lower

The automatic lower logic is shown in Figures 6-14 below. The logic works as the raise logic.

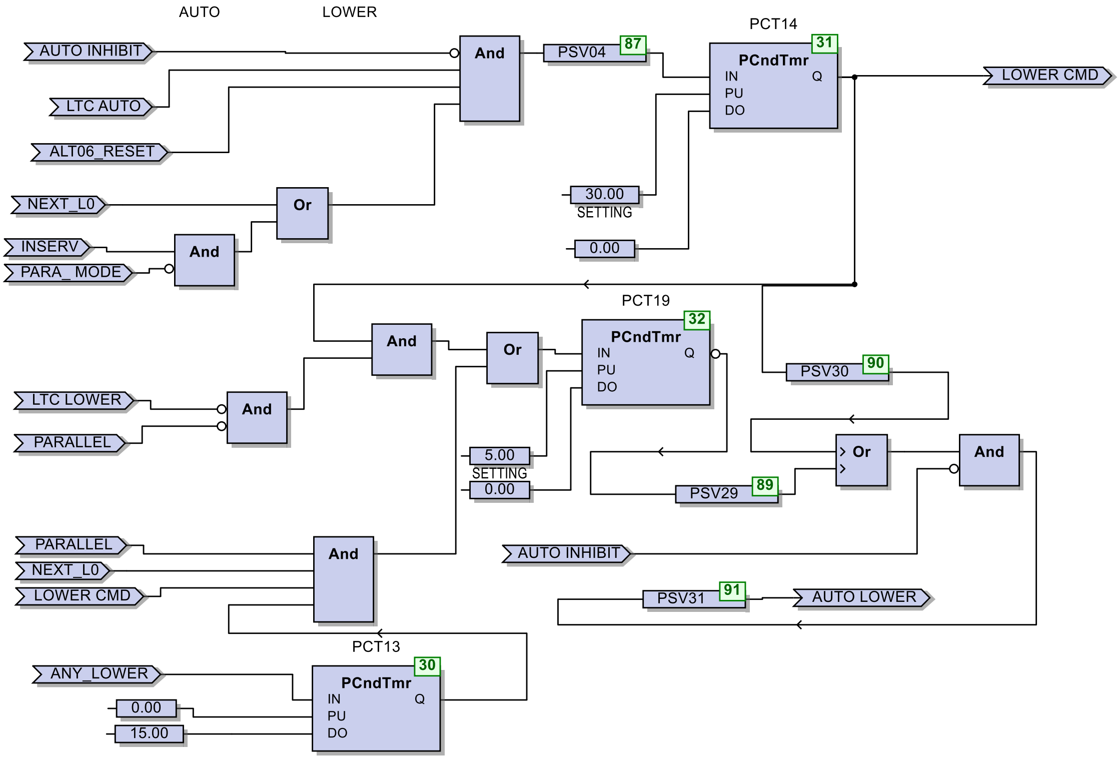


Figure 6-14: Automatic Lower Logic

6.4.9 Auxiliary logics

There are more logic involved in the automatic tap changer controller for parallel transformers applications. The logic discussed above are the main logic. The rest of the logic will be mentioned hereunder, and their function stated.

1) Synchronised reverse mode: Logic comprises lathes and logic gates used to synchronise the activation of reverse mode for all participating transformers.
2) Paralleling: This logic activates parallel mode and collects paralleling status from other transformers.
3) LED: assign various LEDs as indicators for predefined status.
4) Tap counter: The tap position relies on feedback from the RTU. No tap counting logic is designed. The logic also identifies the tap limits and issues a warning.
5) Power flow: The logic determines the direction of power flow to toggle between forward and reverse mode. This is useful only when the reverse mode is enabled.

6) Blocking: blocks the automatic operation in the event where the excessive current flow or the voltage drops/rises dramatically behind reasonable boundaries.

7) Alarm: manages all warnings and issues Alarms.

6.4.10 Outputs

The controllers have three output signals: Raise tap, Lower Tap and Alarm. They are controlled by the logic below.

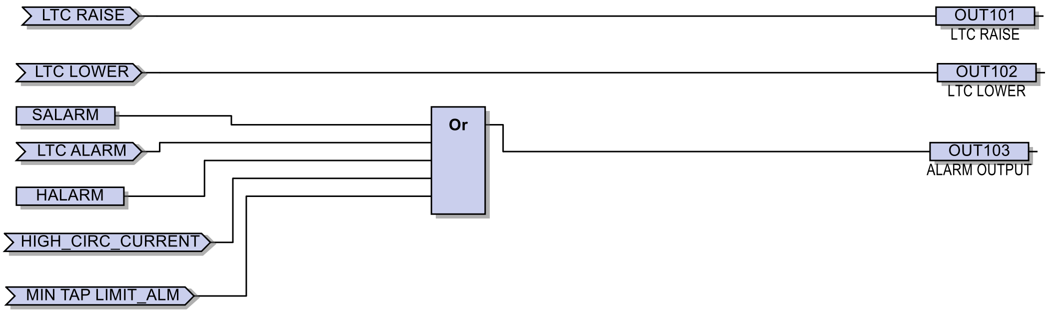
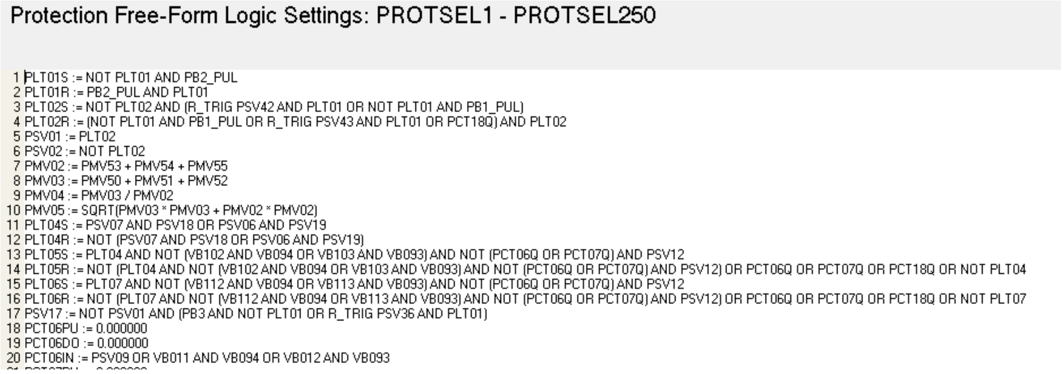


Figure 6-15: Outputs

6.5 CONTROL LOGIC AS LINES OF CODES

The GLE is used for visualizing the settings and ease of troubleshooting. All graphical logic is converted into lines of code then send to the IED. Figure 6-16 below shows the typical logic converted into lines of codes. The prefix P in the lines code stands for Protection, A for Automation. The IED allows to development of logic for protection and automation separately.



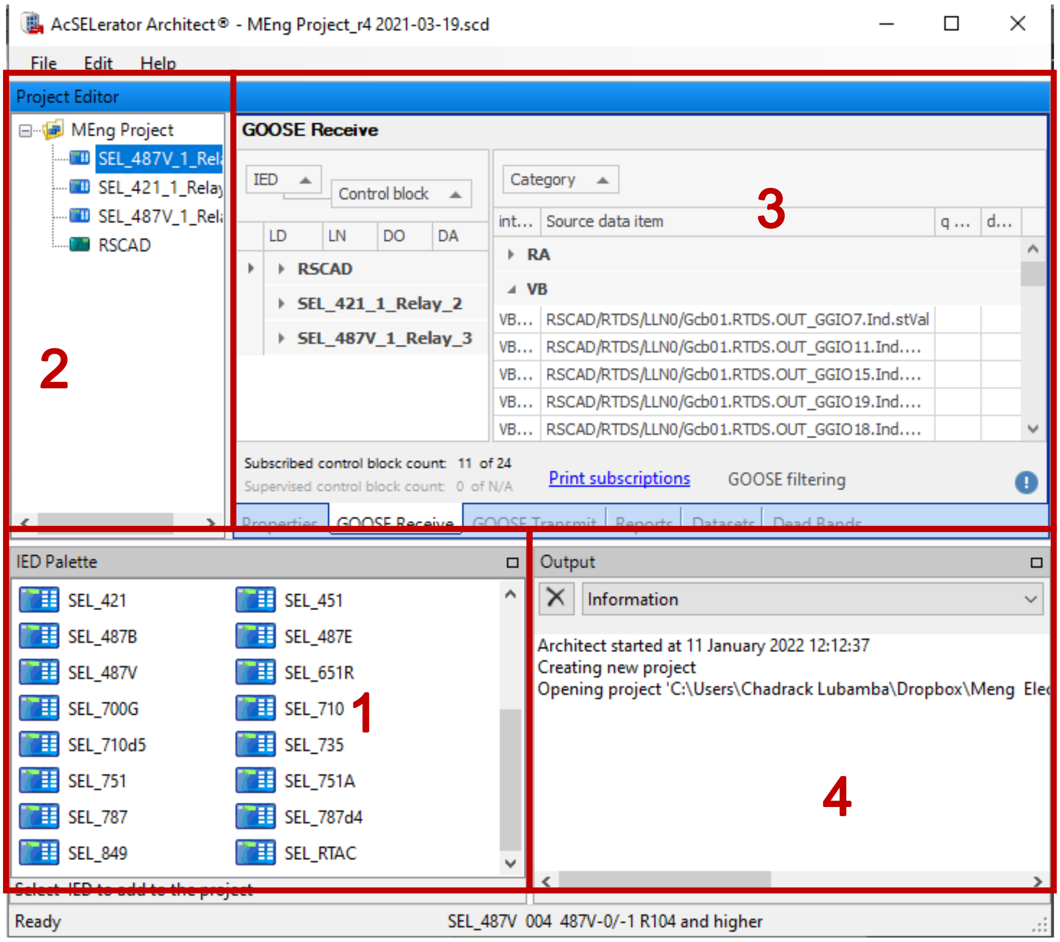
Protection Free-Form Logic Settings: PROTSEL1 - PROTSEL250

```
PLT01S := NOT PLT01 AND PB2_PUL
PLT01R := PB2_PUL AND PLT01
PLT02S := NOT PLT02 AND (R_TRIG PSV42 AND PLT01 OR NOT PLT01 AND PB1_PUL)
PLT02R := (NOT PLT01 AND PB1_PUL OR R_TRIG PSV43 AND PLT01 OR PCT18Q) AND PLT02
PSV01 := PLT02
PSV02 := NOT PLT02
PMV02 := PMV53 + PMV54 + PMV55
PMV03 := PMV50 + PMV51 + PMV52
PMV04 := PMV03 / PMV02
PMV05 := SQRT(PMV03 * PMV03 + PMV02 * PMV02)
PLT04S := PSV07 AND PSV18 OR PSV06 AND PSV19
PLT04R := NOT (PSV07 AND PSV18 OR PSV06 AND PSV19)
PLT05S := PLT04 AND NOT (VB102 AND VB094 OR VB103 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12
PLT05R := NOT (PLT04 AND NOT (VB102 AND VB094 OR VB103 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12) OR PCT06Q OR PCT07Q OR PCT18Q OR NOT PLT04
PLT06S := PLT07 AND NOT (VB112 AND VB094 OR VB113 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12
PLT06R := NOT (PLT07 AND NOT (VB112 AND VB094 OR VB113 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12) OR PCT06Q OR PCT07Q OR PCT18Q OR NOT PLT07
PSV17 := NOT PSV01 AND (PB3 AND NOT PLT01 OR R_TRIG PSV36 AND PLT01)
PCT06PU := 0.000000
PCT06DO := 0.000000
PCT06IN := PSV09 OR VB011 AND VB094 OR VB012 AND VB093
```

Figure 6-16: Extract lines of code

6.6 IEC 61850 DATA MAPPING

Mapping of data is achieved through the use of SEL AcSELerator Architect for SEL IED's and SCD Editor for RTDS/RSCAD. Figure 6-17 below shows the mapping steps in SEL AcSELerator Architect.



```
Architect started at 11 January 2022 12:12:37
Creating new project
Opening project 'C:\Users\Chadrack Lubamba\Dropbox\Meng Ele
```

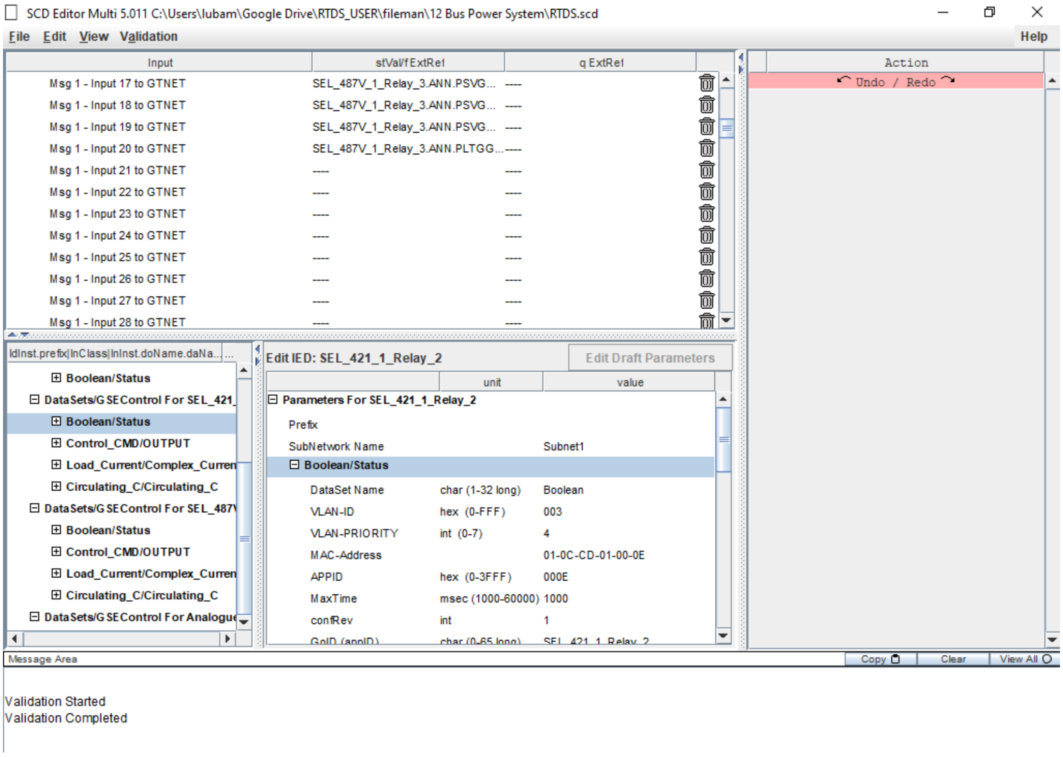
Figure 6-17: SEL-421 Protection Automation Control

Once the software is started, the user interface is similar to or equal to the one indicated in Figure 6-17 above. IED palette denoted with 1 must be used to IED for the particular project. The IED's are dragged and dropped in the palette denoted with 2. Note that by default, the software will only have SEL IED's loaded. IED's from other vendors will have to be imported to the software. Once all IED's are Loaded, the next steps will be as follows:

- Entering IED's Properties (IP Address, subnet mask, gateway …)
- Create Data sets, Goose transmit and Reports
- Proceed with mapping

- Save file and load to respective IED’s.

The process is similar in RTDS/RSCAD. The SCD Editor is accessed via GTNET-GSE component of RTDS/RSCAD. The interface is shown in Figure 6-18 below. The software allows only the subscription of data from external IED’s to RTDS/RSCAD GTNET-GSE.



SCD Editor Multi 5.011 C:\Users\lubam\Google Drive\RTDS_USER\fileman\12 Bus Power System\RTDS.scd

Input	stVal/f ExtRef	q ExtRef
Msg 1 - Input 17 to GTNET	SEL_487V_1_Relay_3.ANN.PSVG...	----
Msg 1 - Input 18 to GTNET	SEL_487V_1_Relay_3.ANN.PSVG...	----
Msg 1 - Input 19 to GTNET	SEL_487V_1_Relay_3.ANN.PSVG...	----
Msg 1 - Input 20 to GTNET	SEL_487V_1_Relay_3.ANN.PLTGG...	----
Msg 1 - Input 21 to GTNET	----	----
Msg 1 - Input 22 to GTNET	----	----
Msg 1 - Input 23 to GTNET	----	----
Msg 1 - Input 24 to GTNET	----	----
Msg 1 - Input 25 to GTNET	----	----
Msg 1 - Input 26 to GTNET	----	----
Msg 1 - Input 27 to GTNET	----	----
Msg 1 - Input 28 to GTNET	----	----

ldInst.prefix|lnClass|lnInst.doName.daNa... ...

- ⊞ Boolean/Status
- ⊟ DataSets/GSEControl For SEL_421_
  - ⊞ Boolean/Status
  - ⊞ Control_CMD/OUTPUT
  - ⊞ Load_Current/Complex_Curren
  - ⊞ Circulating_C/Circulating_C
- ⊟ DataSets/GSEControl For SEL_487V
  - ⊞ Boolean/Status
  - ⊞ Control_CMD/OUTPUT
  - ⊞ Load_Current/Complex_Curren
  - ⊞ Circulating_C/Circulating_C
- ⊟ DataSets/GSEControl For Analogue

Edit IED: SEL_421_1_Relay_2

	unit	value
⊟ Parameters For SEL_421_1_Relay_2		
Prefix		
SubNetwork Name		Subnet1
⊟ Boolean/Status		
DataSet Name	char (1-32 long)	Boolean
VLAN-ID	hex (0-FFF)	003
VLAN-PRIORITY	int (0-7)	4
MAC-Address		01-0C-CD-01-00-0E
APPID	hex (0-3FFF)	000E
MaxTime	msec (1000-60000)	1000
confRev	int	1
GoID (appID)	char (0-65 long)	SEL_421_1_Relay_2

Validation Started
Validation Completed

Figure 6-18: RSCAD/RTDS - SCD Editor

6.7 CONCLUSION

This chapter gave a comprehensive description of the steps involved in the development of the controllers. The chapter started by introducing the hardware and software necessary for the development of the controllers. SEL Protection Automation Controllers (SEL-487V, SEL-487V & SEL-421) are used for the development of the controllers. Thus, the SEL IED’s configuration software SEL-5030 acSELarator QuickSet and SEL-5032 acSELarator Architect are used for designing logic and configuring communications.

The algorithm illustrating various hierarchical decisions and inputs/ outputs involved in the controllers are given. The graphical representation of major logic are discussed. Furthermore, lines of code representing all developed logic are given in detail.

Chapter 7 will discuss the hardware in the loop simulation of the developed controllers. The results from the simulations will be presented and discussed in detail in Chapter 8 and a conclusion will be drawn.

CHAPTER 7

HARDWARE IN THE LOOP SIMULATION

7.1 INTRODUCTION

Traditionally, testing a protection scheme, automation controls or power system parameter/component controllers would require a separate test system. This often leads to exorbitant costs and space required. The era has come to the past with the invention of digital simulations. Depending on the size of the power system to be simulated, dedicated computers can be configured in parallel to achieve the computation power required to simulate any power system in real-time. To test the developed controllers, the IEEE 12 bus test power system is modified and used. The network is modelled over multiple racks to accommodate all power and control components required.

The performance of the controllers is tested in real-time in hardware-in-the-loop simulation. The test is sub-devised into 4 case studies, each with specific aims and objectives. The laboratory setup is revealed and results for each case study are discussed.

7.2 SCALING

After considerable consultation of the literature, norms and standards; no clear indication of the time interval between two consecutive tap operations was recorded. For this reason, the time delays for the controller are designed to be a user-configurable setting. For the case studies in this chapter, an initial time delay of 50 seconds is observed from the time of voltage definition to the first tap change commend. A minimum of 3 to a maximum of 10 seconds is observed thereafter between consecutive tap actions.

7.3 LABORATORY SETUP

The lab setup consists of a few components, each dedicated to a specific task. The lines below will list and describe the use of each piece of equipment.

7.3.1 RTDS Racks

The racks are the heart of the setup. They are supercomputers coupled together to produce incredible computation power. 3-off racks are needed to simulate the modified network and test the developed controllers.

The rack simulates the entire power system including load, instrument transformers, communication systems and many more. The simulator can input digital and/or analogue signals. Analogue signals are sent via hard wiring. Digital signals can be transmitted via hard wires or through a variety of communication protocols available.

The outputs of the simulator are amplified then nominal secondary protective signals are obtained from the amplifier’s outlets.

7.3.2 Setting up Workstation for development and testing

The computers are used for the design, modelling, configuration and monitoring of the system and devices. The setup comprises the following equipment:

- One desktop
- One laptop
- 34” Ultra-large screen
- 24” HD monitor
- 3 - off SEL 487V IED’s
- SEL Ethernet switch
- 3-off RTDS Racks
- Cables and sundries

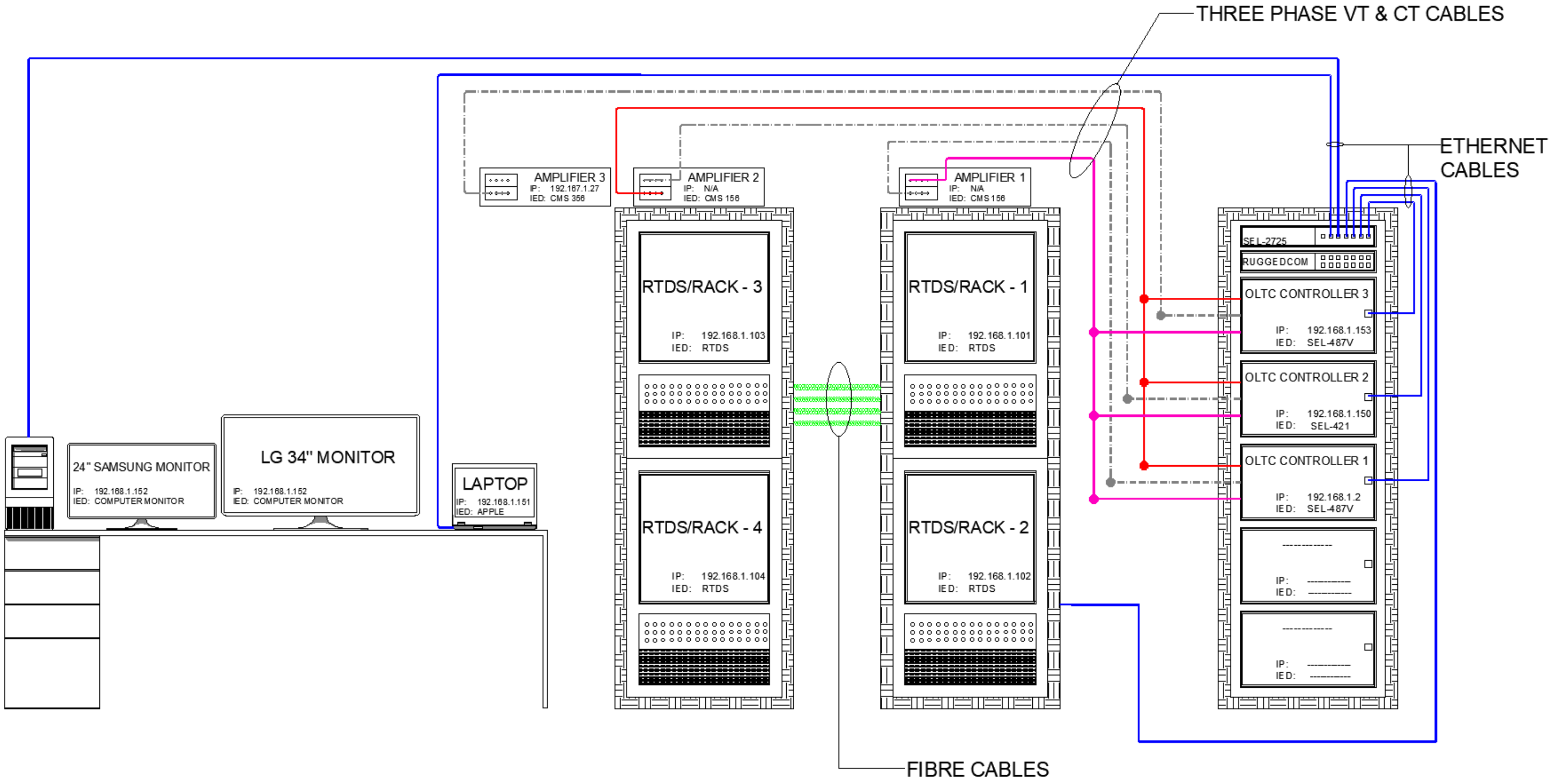


Figure 7-1: Test bench architecture

7.4 CASE STUDIES

To validate the developed controllers, a schedule of case studies is to be conducted to assess the performance of the controllers. Each case study will have objectives as well as expected results. These are discussed in the following sections.

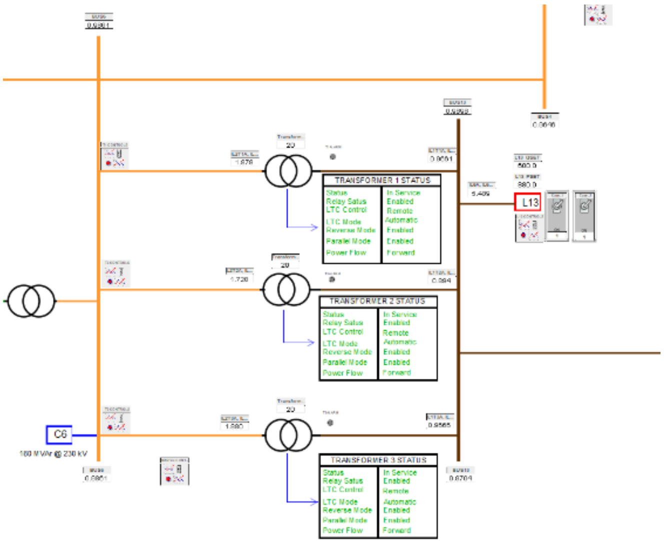
7.5 CASE STUDY NO 1: FORWARD POWER FLOW OPERATION

This case study aims to investigate and validate the forward operation of developed controllers by achieving the following objectives:

i. Detect the direction of power flow in each controlled transformer.
ii. Maintaining the voltage at bus 13 between 0.95pu and 1.05pu.
iii. Optimizing the operation of the tap changer by allowing a larger for the initial tap command then reduces the tap delay between taps operation for a fast voltage recovery.
iv. Optimized tap operation by restoring over-voltage and under-voltage to a recovery point of approximately 1.025pu and 0.975pu respectively.

7.5.1 Simulation Setup

The three transformers are all connected in parallel. The controller for each transformer is set to automatic mode with parallel and enables reverse power flow settings on. The status of each transformer is monitored remotely via runtime as illustrated in Figure 7-2 below and locally via the LCD and target LED’s on the controllers.



TRANSFORMER 1 STATUS	
Status	In Service
Relay Satus	Enabled
LTC Control	Remote
LTC Mode	Automatic
Reverse Mode	Enabled
Parallel Mode	Enabled
Power Flow	Forward

TRANSFORMER 2 STATUS	
Status	In Service
Relay Satus	Enabled
LTC Control	Remote
LTC Mode	Automatic
Reverse Mode	Enabled
Parallel Mode	Enabled
Power Flow	Forward

TRANSFORMER 3 STATUS	
Status	In Service
Relay Satus	Enabled
LTC Control	Remote
LTC Mode	Automatic
Reverse Mode	Enabled
Parallel Mode	Enabled
Power Flow	Forward

Figure 7-2: RSCAD runtime

7.5.2 Load Profile used for testing the Forward Mode

Utilities use load forecasting methods based on historical data available at their disposal to predict the load demand and schedule appropriate controls to ensure continuous and quality electricity is available at the consumer's terminals. Ideally, to validate the operation of the developed controllers, the load profile used should be a typical utility load profile. The only drawback with using this profile is that controllers will not be subjected to adverse loading conditions. Thus, a more unstable loading profile will be modelled and simulated to test the controllers. The loading is illustrated in Figure 7-3 below.

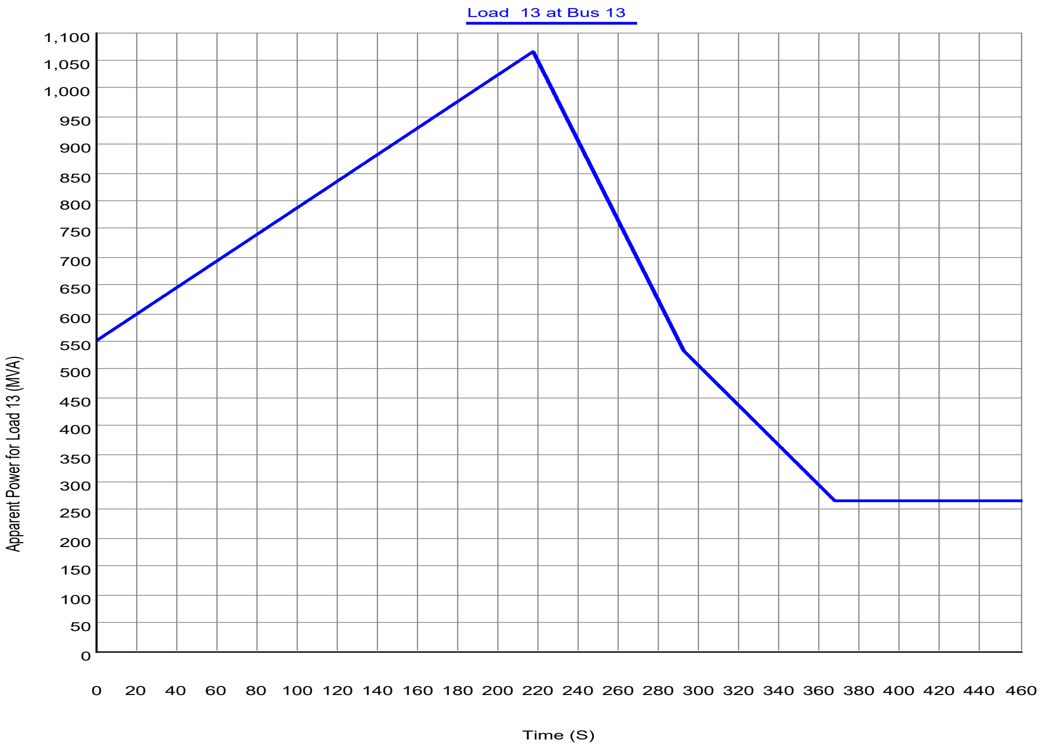


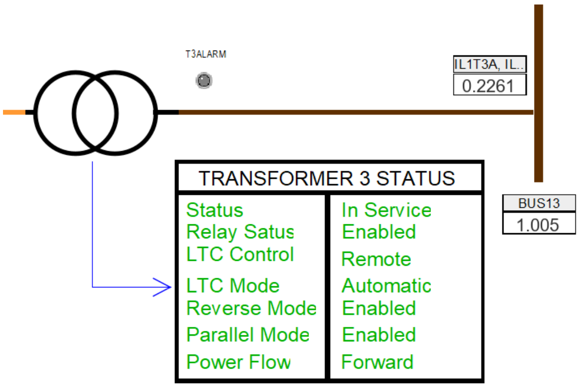
Figure 7-3: Case study 1 - load profile

Bus 13 is initially loaded with (440+300j) MVA, its nominal loading. The load is then gradually increased to 200% then decrease to 50%. This variation is sufficient to create a considerable voltage drop across the transformer thus creating the need to restore the voltage within the acceptable ranges.

7.5.3 Forward Power Flow Tap-Changer Control Results.

The controllers are designed to control the voltage on the secondary side of the transformers during the forward power flow. The primary side is controlled during reverse power flow. The direction is indicated locally via a target LED on the IED and remotely can be read from the status display via the RSCAD Runtime screen as illustrated in Figures 7-4 and 7-5 respectively below.

Figure 7-4: Case study 1 - IED's Status via target LED's



TRANSFORMER 3 STATUS	
Status	In Service
Relay Satus	Enabled
LTC Control	Remote
LTC Mode	Automatic
Reverse Mode	Enabled
Parallel Mode	Enabled
Power Flow	Forward

Figure 7-5: Case Study 1 - Case study 1 - IED's Status via Runtime

The direction for this case is the forward direction. Thus, Bus 13 is the controlled bus. The voltage and tap position will be monitored and recorded as the load increases.

7.5.4 Voltage profile for forward power flow

The graph in Figure 7-6 below shows the RMS voltage at bus 6 and bus 13 in red and blue respectively. The gradual increase in load at bus 13 results in a degradation of voltage at both buses 6 and 13. The secondary voltage drops below the acceptable range at t = 51,72 seconds of the simulation. The voltage keeps dropping for 50 more seconds to a minimum of 0.935pu. At this point, the voltage starts increasing regardless of the continuous decrease of the primary voltage.

The increase in voltage at bus 13 due to tap action can be identified by looking at the ripple. The increase stops at t = 218.25s the secondary voltage is 0.975pu.

At t= 2018.25s, the primary voltage starts increasing resulting in the secondary voltage increasing as well until the upper limit of 1.05pu is exceeded. 50 seconds after the limit is exceeded, the secondary voltage is then brought back to under 1.025pu

It can be noticed that at each point in the voltage on the secondary side of the transformer is being forced to remain between 0.95 pu and 1.05 pu regardless of the voltage on the primary side.

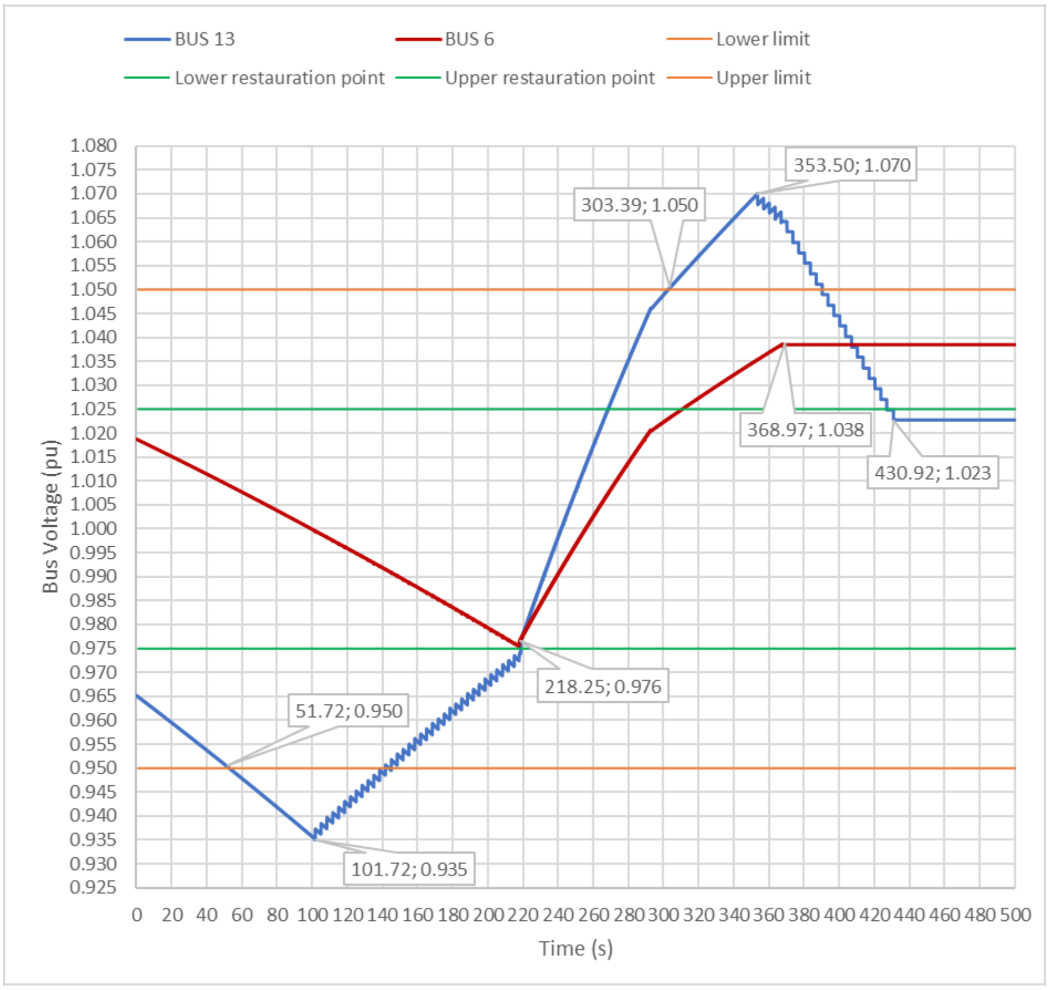


Figure 7-6:Case study 1 - Voltage Profile

7.5.5 Tap position for forward power flow

The graph in Figure 7-7 below shows the tap position of each transformer during the simulation. The initial tap position for all transformers is 12. From Figure 7-6 above, the voltage at bus 13 dropped below 0.95pu at t = 51.72 seconds. However, the first tap action is taken only at 101.72 seconds. More tap actions follow until all transformers are on tap 24 at 218.80 seconds corresponding to the voltage at bus 13 being just above 0.975pu.

The controllers are designed to work with all kinds of tap changers. From split seconds solid state tap changers to ancient mechanical types. The time between two consecutive tap actions of the same transformer is a user-defined setting. For this simulation, the time is set to a minimum of 3 seconds and a maximum of 10second. Should the tap fail to change within 10 seconds, a blocking signal should be issued to prevent further automatic tap action.

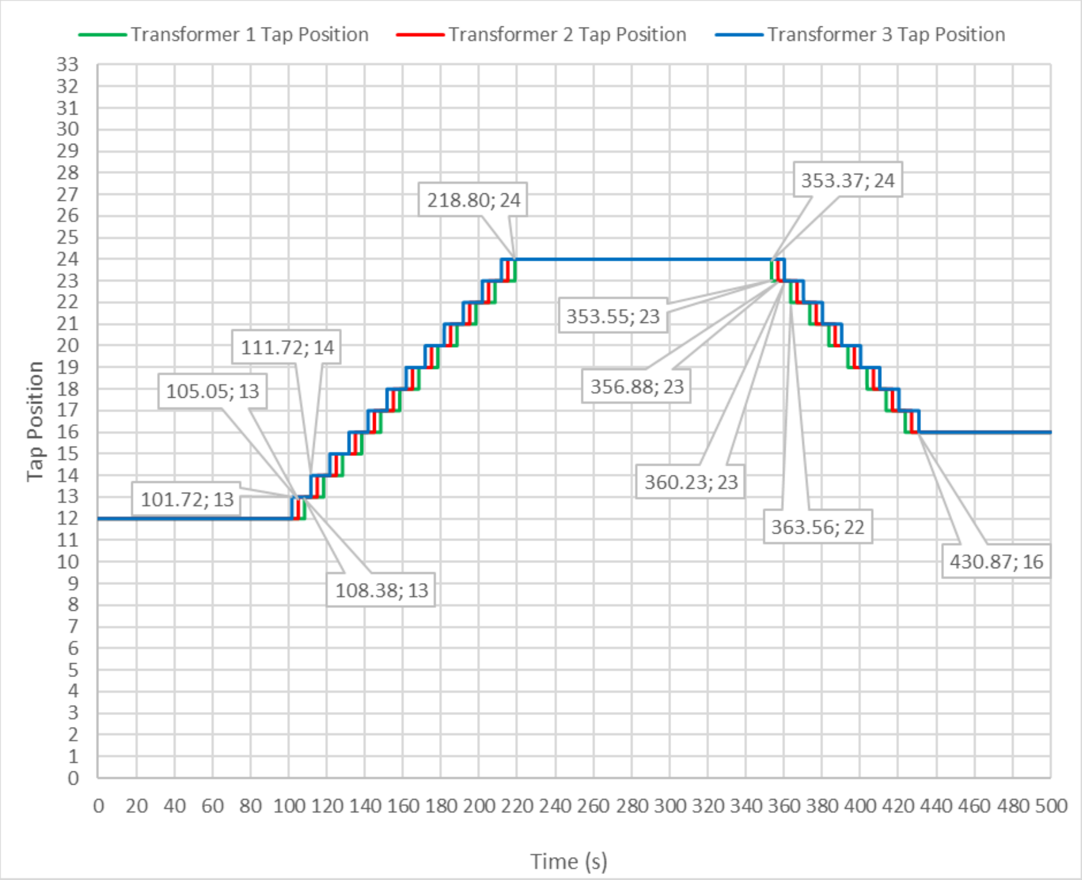


Figure 7-7: Case Study 1 - Tap Positions

At 353,37 seconds the tap position start dropping from position 24 to 16 at t= 430,87 seconds. This time corresponds to the time the voltage at bus 13 is being brought to the acceptable range.

7.5.5.1 Computation of circulating current during forward power flow

The controllers rely on the calculated circulating current contribution to decide on the next transformer to raise or lower the tap. The graph in Figure 7-8 below shows the contribution of the circuiting current for each transformer during the simulation. In the forward mode, the transformer with the lower circulating current contribution is the next to lower its tap position. The next to raise the tap is the one with the higher circulating current contribution.

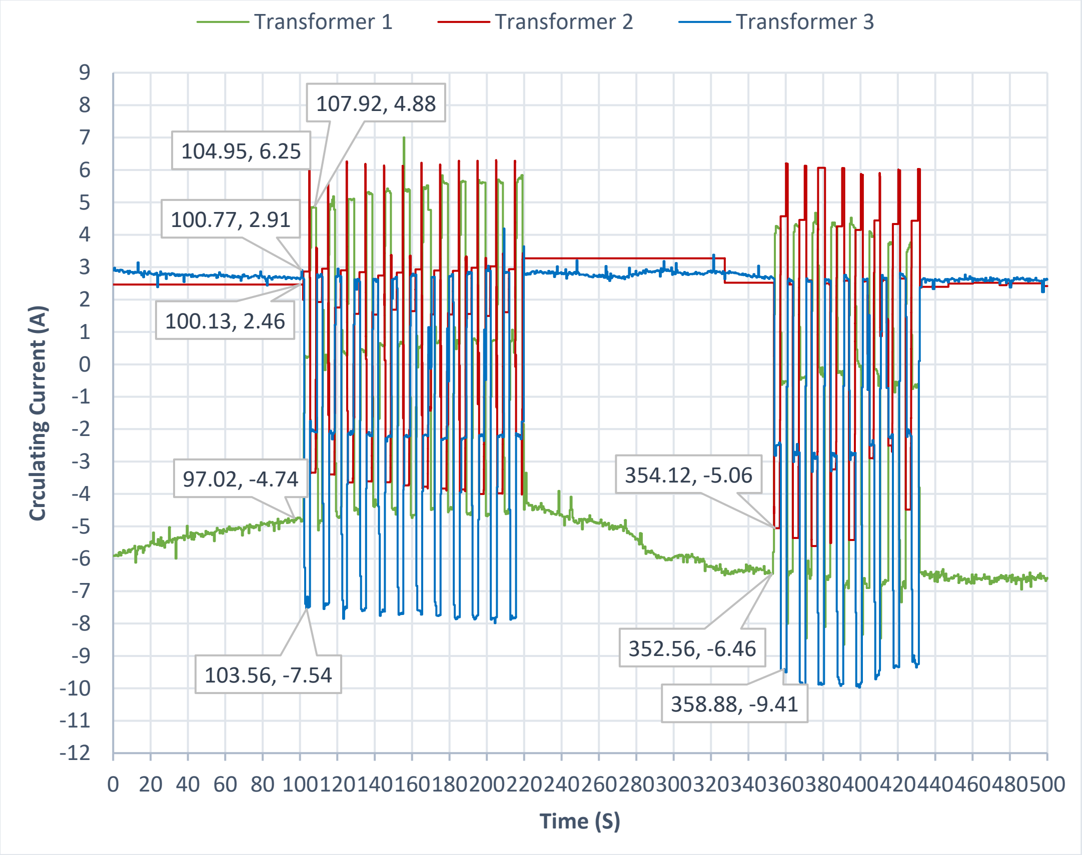


Figure 7-8: Case Study 1 - Circulating current values

The succession of transformer tap actions in Figure 7-7 below can be well understood by observing the circulating current values in Figure 7-8 above. Transformer 3 has the highest circulating current contribution at the beginning of the simulation followed by transformer 2 and then transformer 1. The pattern is repeated until the end of the simulation. Note that the power system is a dynamic system with a large number of influencing factors. Thus, in most cases, the tap changes do not follow a particular sequence as the change is purely based on circulating current contribution.

A protection feature is included in the controller to ensure that the percentile of the circulating current should not exceed 20% of the load current. Once the limit is reached, a warning should be issued. The graph in Figure 7-9 below shows the percentile of the circulating current for each transformer during the simulation. The circulating current is a function of voltage difference at the secondary side of parallel transformers and impedances of the transformers. Thus, the smaller the load current, the bigger the percentile since the voltage deviation is minimal compared to the load current change through the transformer.

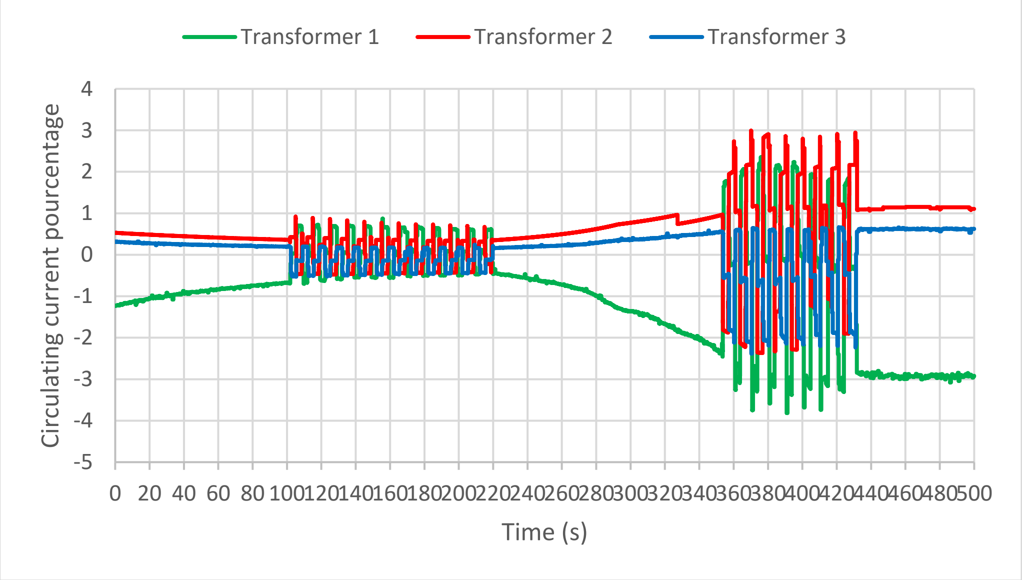
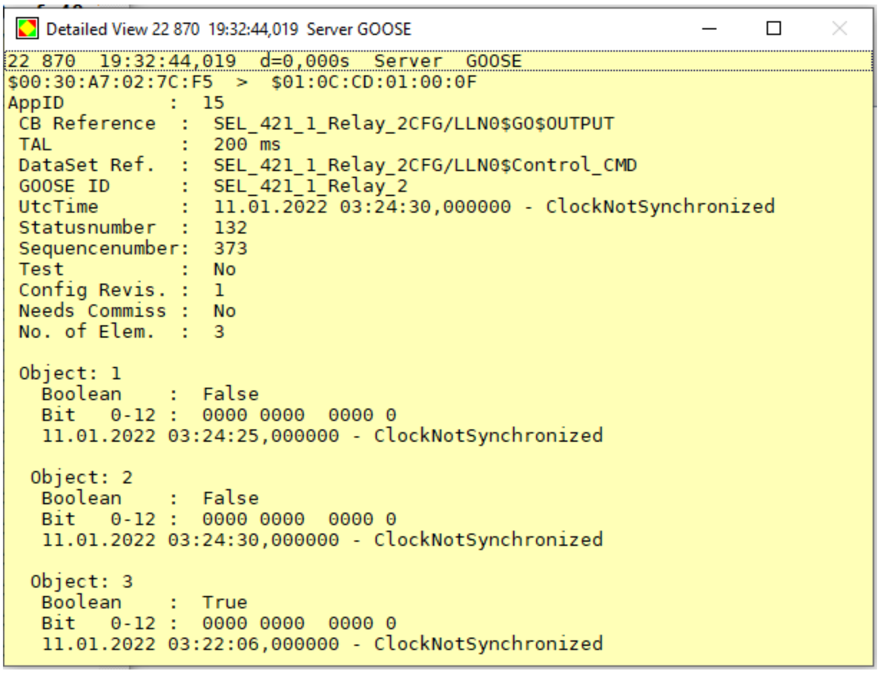


Figure 7-9: Case Study 1 - Circulating current percentile

7.5.5.2 Communications for forward power flow

Communication is the main driver behind the controller's intelligence. Information such as load current flowing through each transformer is very important for the calculation of the circulating current. The image in Figure 7-10 below shows a typical goose message captured during the simulation. These messages are broadcast for each fraction of the time. The captured is the output dataset of relay 2 (controller 2).



```
22 870  19:32:44,019  d=0,000s  Server  GOOSE
$00:30:A7:02:7C:F5  >  $01:0C:CD:01:00:0F
AppID           :  15
 CB Reference   :  SEL_421_1_Relay_2CFG/LLN0$GO$OUTPUT
 TAL            :  200 ms
 DataSet Ref.   :  SEL_421_1_Relay_2CFG/LLN0$Control_CMD
 GOOSE ID       :  SEL_421_1_Relay_2
 UtcTime        :  11.01.2022 03:24:30,000000 - ClockNotSynchronized
 Statusnumber   :  132
 Sequencenumber:  373
 Test           :  No
 Config Revis.  :  1
 Needs Commiss  :  No
 No. of Elem.   :  3

 Object: 1
   Boolean    :  False
   Bit   0-12 :  0000 0000  0000 0
   11.01.2022 03:24:25,000000 - ClockNotSynchronized

  Object: 2
   Boolean    :  False
   Bit   0-12 :  0000 0000  0000 0
   11.01.2022 03:24:30,000000 - ClockNotSynchronized

  Object: 3
   Boolean    :  True
   Bit   0-12 :  0000 0000  0000 0
   11.01.2022 03:22:06,000000 - ClockNotSynchronized
```

Figure 7-10: Goose Captured

The dataset in the goose captured in figure 7-10 contains three objects as follows:

- Object 1: Raise tap command. This is false because at the moment of capture, there was no need to raise the tap for transformer 2.
- Object 2: Lower tap command. This is false for the same reason as object 1.
- Object 3: Alarm output. There is a warning on the screen of the controller at the moment of capture. The alarm output is asserted because the voltage is out of the acceptable boundaries.

7.5.5.3 Conclusion

The aim and objectives of this case study have been met. The voltage on the controlled bus 13 is at all times of the simulation kept between 0.95pu and 1.05pu. The initial tap action is given a 50 seconds user-defined time delay and tap actions are harmonised with the equal time between consecutive tap actions. The circulating current percentile is always kept below 20%.

7.6 CASE STUDY NO 2: REVERSE POWER FLOW OPERATION

This case study aims to investigate and validate the reverse operation of developed controllers by achieving the following objectives:

v. Detect the direction of power flow in the controlled transformers.
vi. Maintaining the voltage at bus 6 between 0.95pu and 1.05pu.
vii. Optimizing the operation of the tap changer by allowing a larger time delay for the initial tap command then reduces the time delay between taps operation for a fast voltage recovery.
viii. Optimized tap operation by restoring over-voltage and under-voltage to a recovery point of approximately 1.25pu and 0.975pu respectively.

7.6.1 Simulation Setup

The setup for this case study is identical to the one in case study 1. However, the generator on the primary side of the transformers will be isolated from the network. The one on the secondary side of the transformer will be active to generate reverse power flow.

7.6.2 Load Profile for reverse power flow operation

To favour reverse power flow through the parallel transformers, Load at bus 4 is modelled as illustrated in Figure 7-11 below. The load start by decreasing to

200MVA then increase to 640MVA. The variation is sufficient to create the required voltage drop across the transformer's terminals.

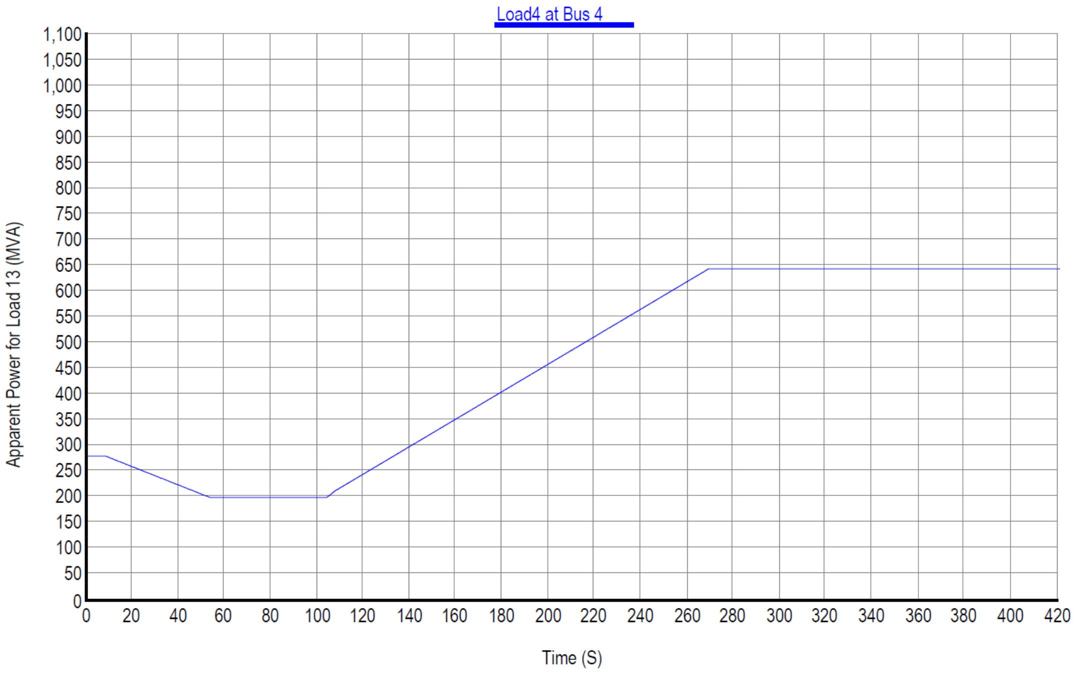


Figure 7-11: Case Study 2 - Load Profile

7.6.3 Simulation Results for reverse power flow operation

The results hereunder were recorded when performing the hardware in the loop simulation of the developed controllers for a reverse power flow scenario. The simulation ran for quite a long duration. However, only 420 significant seconds are recorded in this document.

As was the case in the first case, the controllers start by detecting the direction of power flow to determine the controlled bus. In this case, the power is flowing in the reverse direction. Thus, the controlled bus is bus 6. The direction is indicated via a target LED on the IED, this can also be viewed from the SCADA screen.

7.6.3.1 Voltage profile for reverse power flow operation

The controllers are expected to keep the voltage at bus 6 within the acceptable range. Once the voltage degrades behind the limits, an initial time delay of 50 seconds should be observed then corrective measures taken.

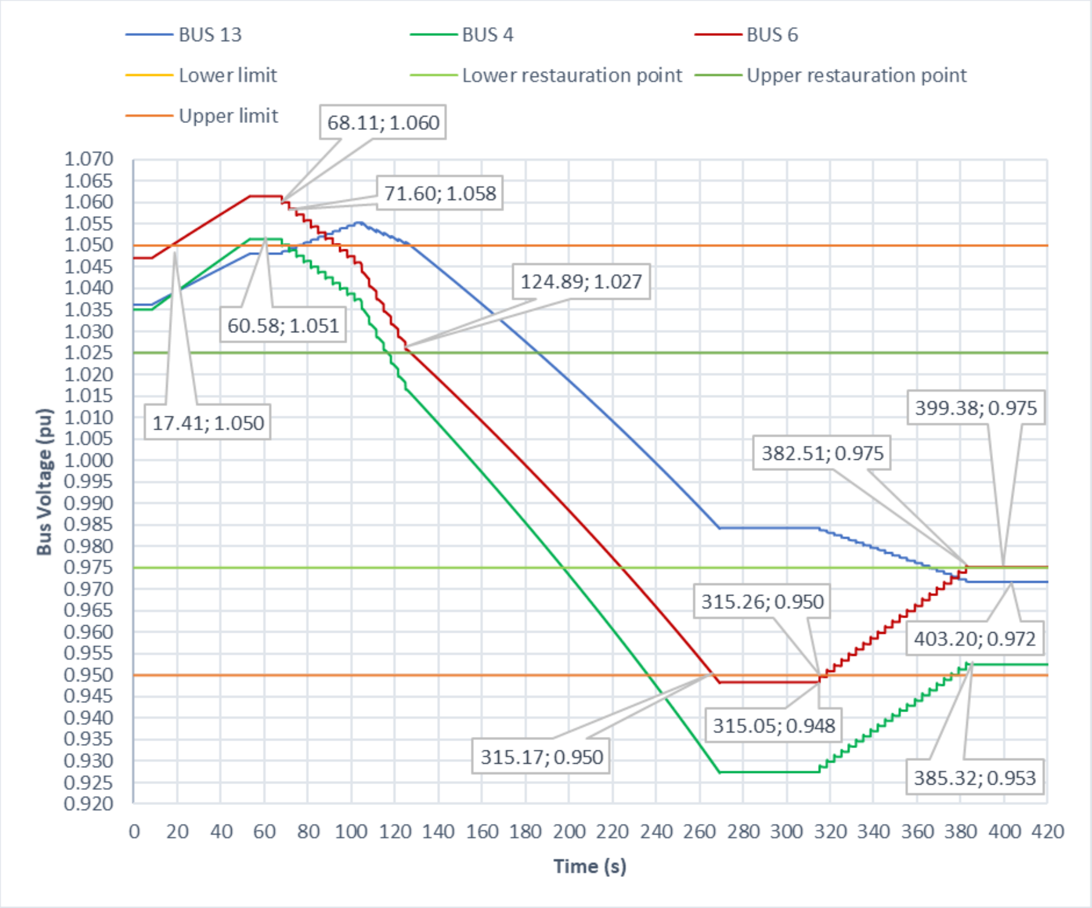


Figure 7-12: Case Study 2 - Voltage profile

From Figure 7-12 above, it can be seen that the voltage at the controlled bus 6 exceeded the upper limit of 1.050pu just after 17.41 seconds of the simulation. The voltage starts decreasing after 50 seconds, and the ramp down continues until the voltage reaches 0.948pu. In the first portion, the voltage decreases in steps from the top value to 0.975pu. This first section is due to tap changes and the increase in voltage drop across the transformers as the current through each transformer rises. The second portion is like a linear decrease with a slop similar to the inverse of the one of the loads as shown in Figure 7-11 above.

After 315 seconds the voltage at the controlled bus drops below the allowed minimum, a 50 seconds time delay is observed then corrective measure is taken. The voltage is brought to 0.975pu. It can be seen in Figure 7-12 above that the corrective measures taken to control the voltage at bus 6 also improved the quality of the voltage at bus 4 too.

7.6.3.2 Tap position for reverse power flow operation

Figure 7-13 below shows the position of taps during the simulation. The initial tap position for all transformers is 15. Reading the graph in Figure 7-13 below in conjunction with the one in Figure 7-12 above, it can be seen that the first tap raise command is issued at 68.08 seconds, 50 seconds after the voltage has depleted behind the acceptable range. The tap actions continue until tap 21 is reached. At this point, the voltage value at bus 6 is restored to 1.025pu. Since power is flowing in reverse mode, tap rising corresponds to voltage decreases.

At 315.16 seconds, we can observe further tap actions. These decreasing actions correspond to 50 seconds after the voltage at bus 6 has dropped below the allowed 0,95pu. The tap lowering actions improve the voltage at bus 6 and bus 4. The tap lowering actions stop at 382.46 seconds. The taps are all at position 14 corresponding to both voltages at bus 6 and at bus 4 being within an acceptable region.

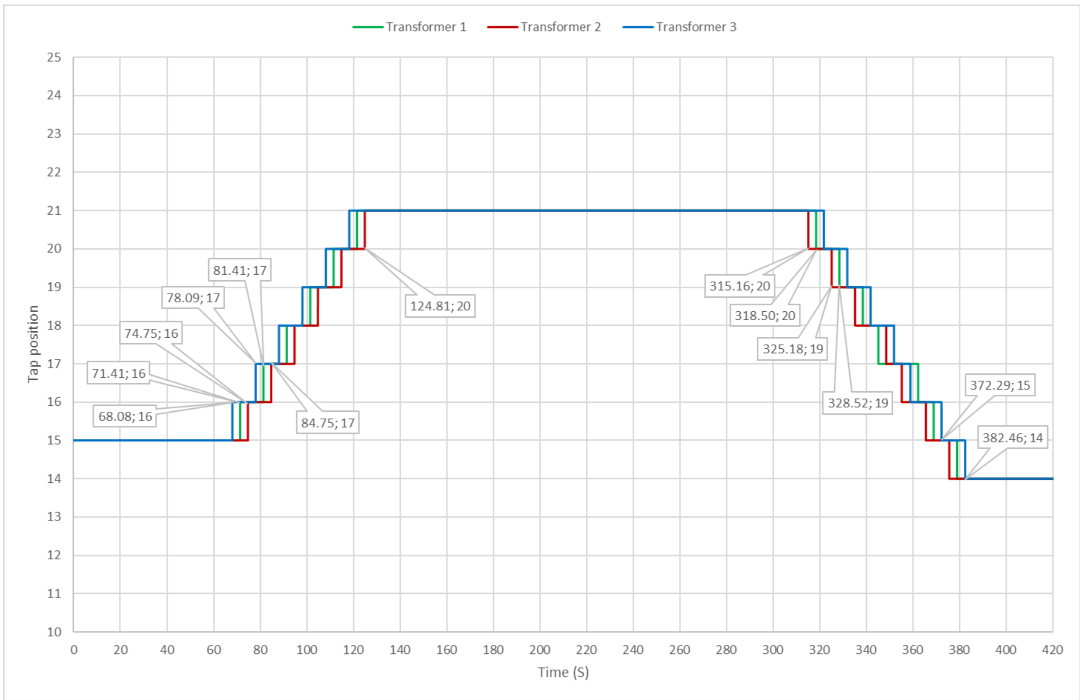


Figure 7-13: Case Study 2 - Transformer tap positions

7.6.3.3 Circulating current for reverse power flow operation

Circulating current is the key information required by the controller to generate a decision. For this case, the transformer presenting the highest circulating current contribution is the next to lower its tap position. The one with the lower contribution is the next to raise its tap position.

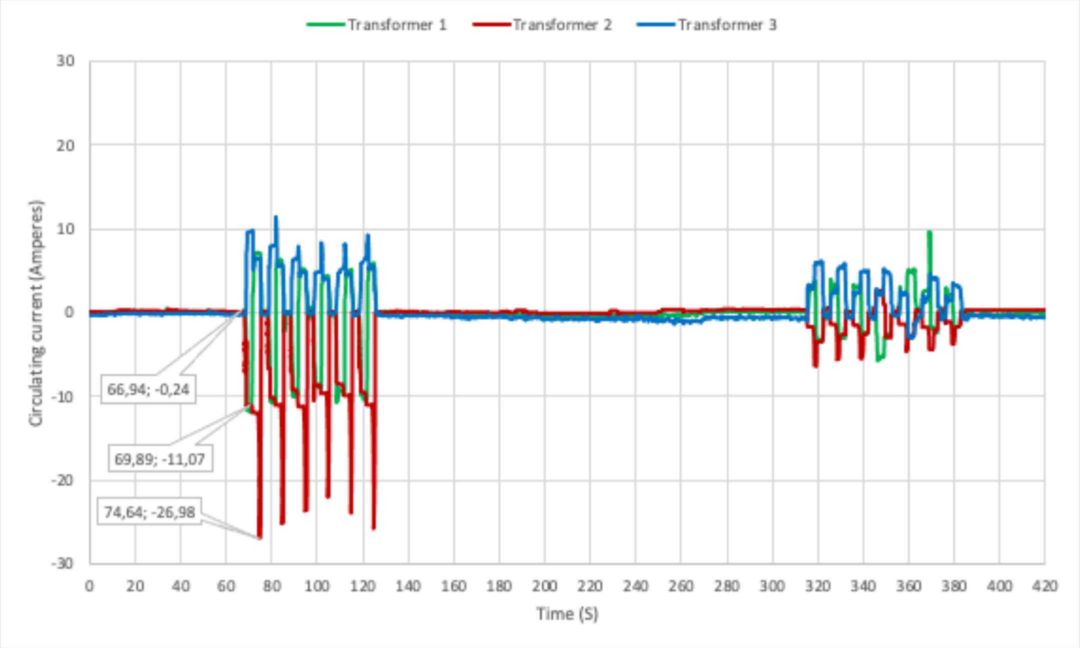


Figure 7-14: Case study 2 - Circulating current Values

The circulating current observed in Figure 7-14 above is expressed in amperes. The bleu represents the circulating current contribution of transformer 3, the red is for transformer 2 and the green is for transformer 1. As soon as the tap changes, the contribution changes too.

7.6.3.4 Discussion for reverse power flow operation

The controllers in this case study have worked accurately, the voltage is always between 0.95 and 1.05. The prescribed initial 50 seconds delay was observed, and the taps changed as dictated by the voltage deviation and circulating current contribution.

7.7 CASE STUDY NO 3: FAULT CONDITIONS

7.7.1 Introduction

This case study aims to investigate and validate the operation of developed controllers under fault conditions by achieving the following objectives:

i. Detect the direction of power flow in the controlled transformers.

ii. Maintaining the voltage at bus 6 and bus 13 between 0.95pu and 1.05pu in forward and reverse mode respectively.
iii. Optimizing the operation of the tap changer by allowing a larger time delay for the initial tap command then reduces the tap delay between taps operation for a fast voltage recovery.
iv. Optimized tap operation by restoring overvoltage and under-voltage to a recovery point of approximately 1.25pu and 0.975pu respectively.
v. Synchronise the operation of the tap changer once a transformer with a large tap position gape is added to the series set.

7.7.2 Simulation setup for fault conditions

The setup for this case study is a combination of the two previous cases. Power will flow in the reverse direction and change direction mid-simulations. Moreover, the simulation starts with transformer 2 disconnected, it will be reconnected with its initial tap position while other transformers are in the process of changing taps.

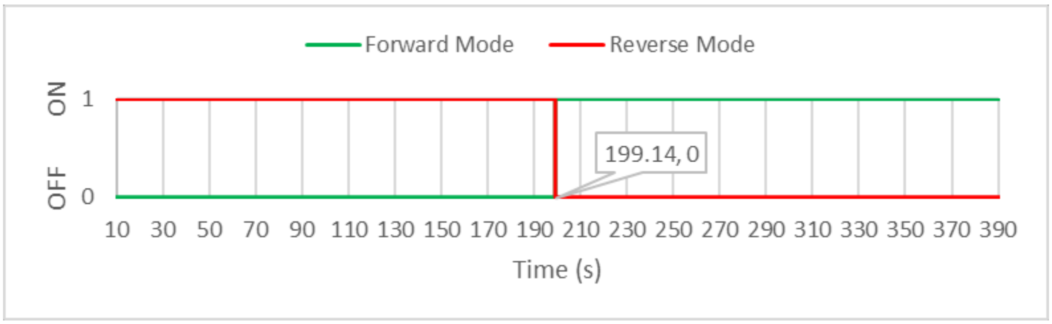


Figure 7-15: Case study 3: Power flow direction

7.7.3 Load profile for fault conditions

The load in this case study will be more stable as opposed to one in previous cases. The dynamic load will be modelled at bus 13 with an initial load of 798 MVA. The load will gradually increase to a maximum of 1065MVA and then remain at this level for the remainder of the simulation as indicated in Figure 7-16 below.

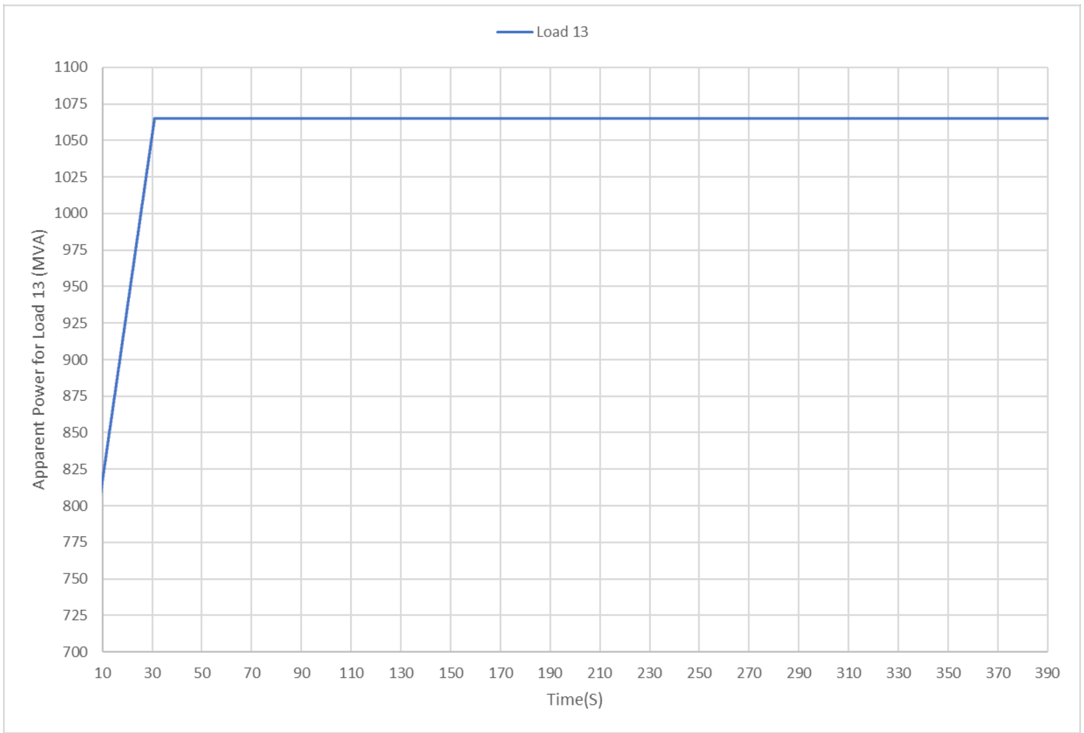


Figure 7-16: Case study number 3 load profile

7.7.4 Simulation results for fault conditions

Results for this case study are captured for 400 significant seconds. All the graphs given for various quantities are to be read in conjunction with each other and the load profile in Figure 7-16 above.

7.7.4.1 Voltage profile for fault conditions

Figure 7-17 below shows the RMS voltage for bus 6 and bus 13 in blue and red, respectively. The controlled bus changes according to the power flow direction.

We can see that bus 6 voltage dropped below 0.97pu at about 22.06 seconds of the simulation. At 71.81 seconds, the voltage starts increasing in steps until the reaches 0.974pu. At this point, the voltage stabilises until 198.40 seconds after which, the voltage at bus 6 increases to 1.022pu due to the change in the power flow direction. The voltage at bus 13 drops below 0.950. With the change in direction, the controlled bus is assigned to bus 13. Corrective measures are then taken 50 seconds later at this bus in steps until it reaches 0.976pu at 296.19 seconds.

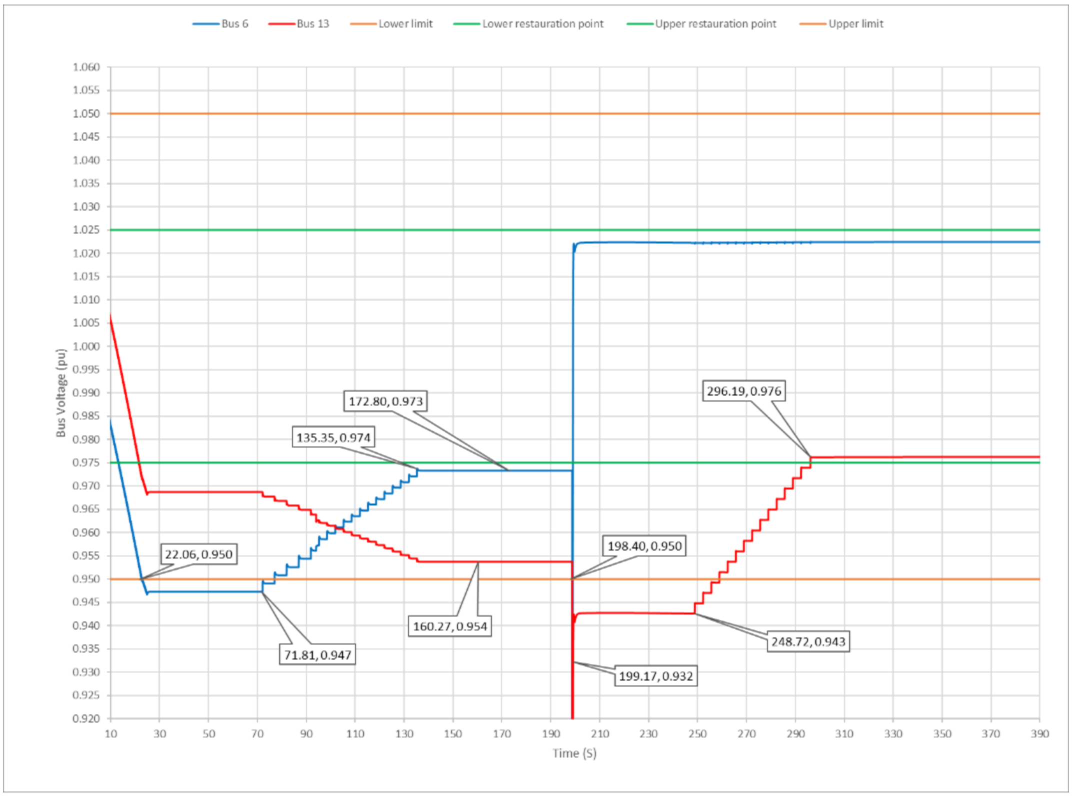


Figure 7-17: Case study number 3: Voltage profile

7.7.4.2 Tap Positions for fault conditions

The graph in Figure 7-18 below shows the tap positions of the three transformers during the simulation. The first tap change is issued to transformer 1 then transformer 3. For a short duration, we can observe transformer 2 not changing taps while the others are. At 91.87 seconds, transformer 1 tap is at position 14, transformer 3 at position 15 but transformer 2 is still at position 17. The first transformer 2 tap action is taken at 92.21 seconds, then carries on until position 14 after which the three transformers change taps in harmony till tap 11.

At 248.88, the tap positions of the three transformers start changing in harmony until all reach position 16.

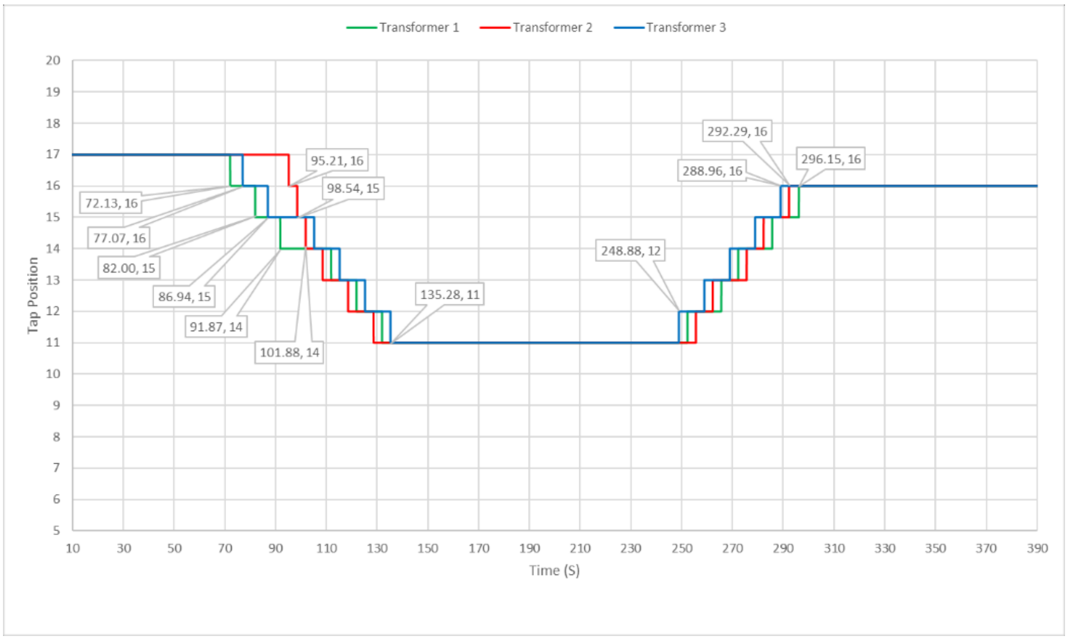


Figure 7-18:Case Study number 3: Transformer tap positions

7.7.4.3 Circulating current & transformer operations

The circulating current is the key to the operation and accuracy of the developed scheme. However, since the principle remains the same as in other case studies, only the current contribution is displayed in Figure 7-19 hereunder.

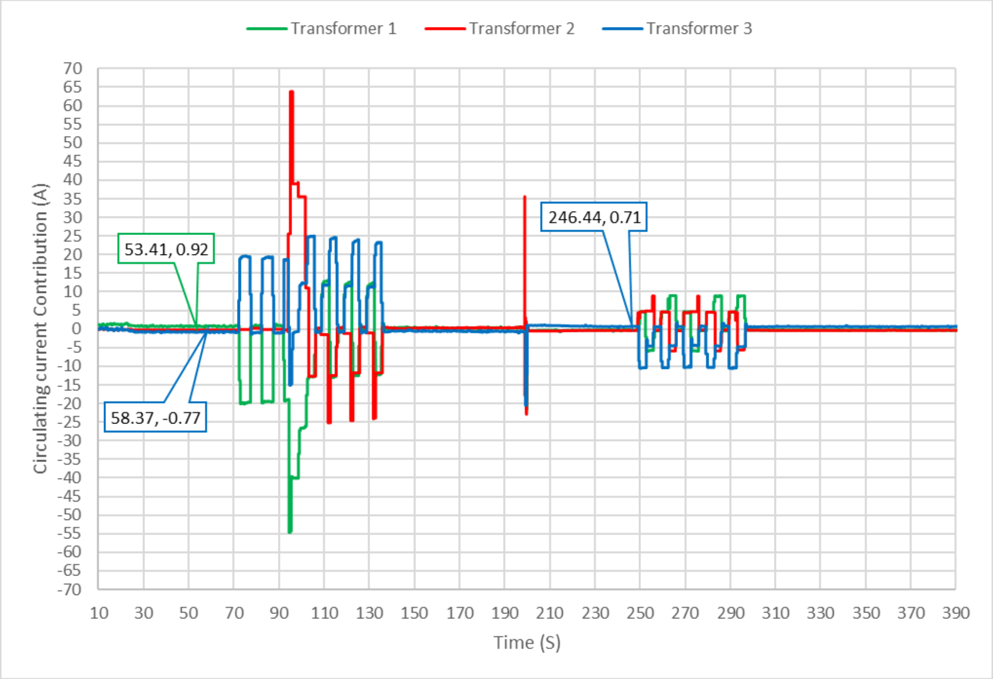


Figure 7-19: Case study number 3: circulating current contribution

The aim of the case study is the investigation of the controllers under abnormal conditions, Figure 7-20 below shows the load current flowing in each transformer during the simulation

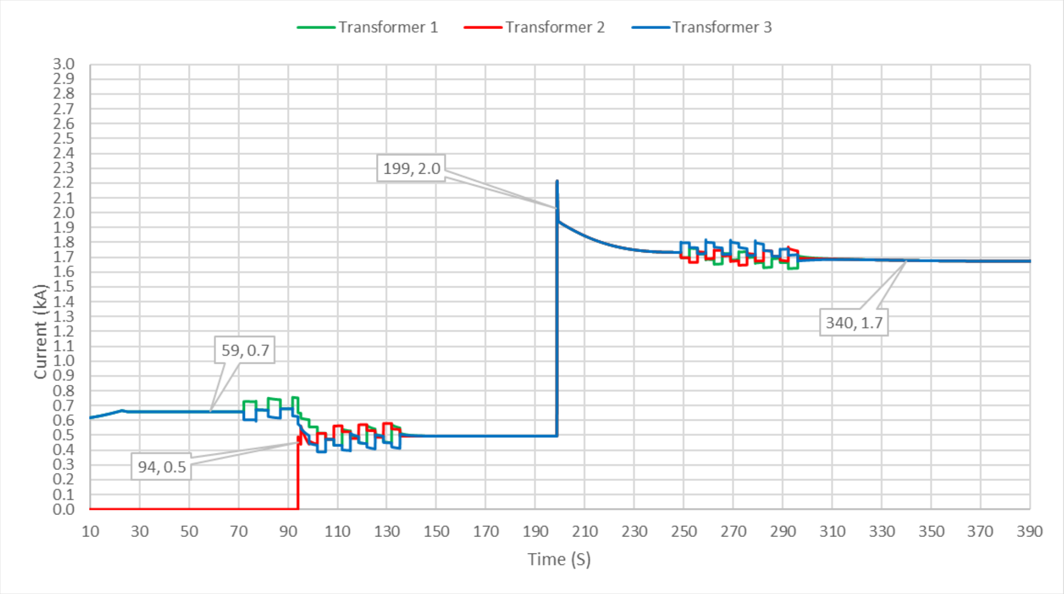


Figure 7-20: Case study 3 – Load current

It can be seen that there is no current flowing in transformer 2 until the 94th second of the simulation. At this instance, the other two transformers were performing tap changing activities.

As soon as transformer 2 is back online, the necessity to change the tap is detected. The gap between tap positions with other transformers is detected, blocking signal is issued to block the automatic tap changes. The blocking signal is withdrawn a couple of milliseconds later as the controllers foresee no risks. Transformer 2 tap position is brought up to speed tap positions are harmonised. The breaker status of each transformer during the simulation and blocking the automatic tap changing signal is shown in Figures 7-21, 7-22 and 7-23 below respectively.

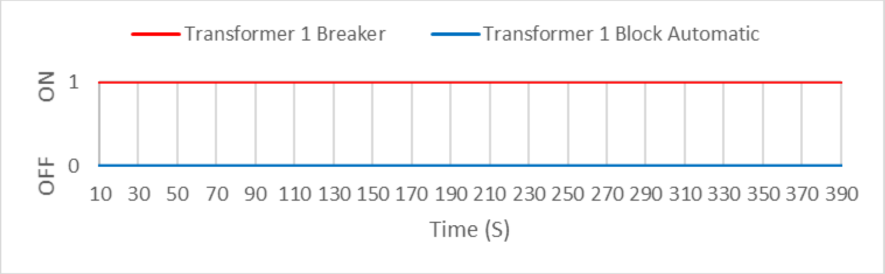


Figure 7-21: Case study 3: Transformer 1 status

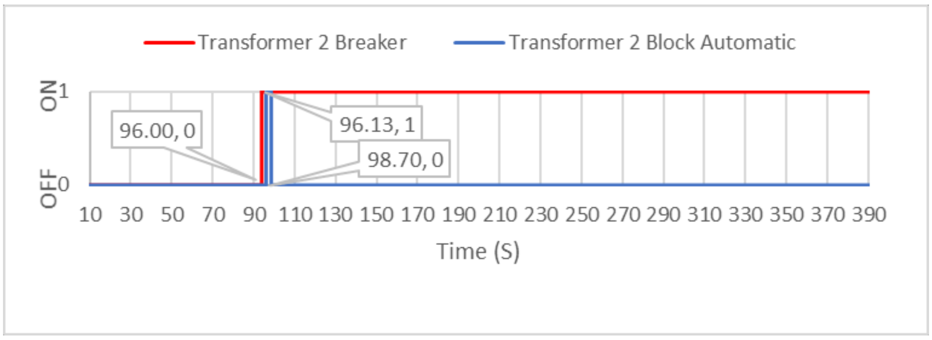


Figure 7-22: Case study 3: Transformer 2 status

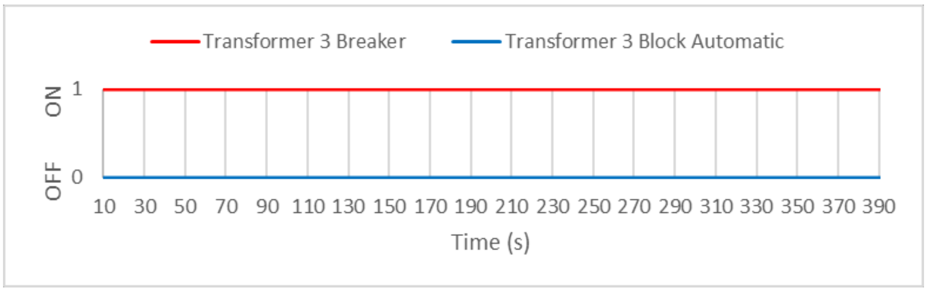


Figure 7-23: Case study 3: Transformer 3 status

7.7.4.4 Discussion

This case study aimed to validate the operation of the controllers under fault conditions. The objectives have been met; the controllers' operations were satisfactory.

7.8 CASE STUDY NO 4: OPERATIONS OF A PARALLEL GROUP OF TRANSFORMERS WITH DIFFERENT IMPEDANCE

The general requirements for transformers operating in parallel, as described in IEEE standards, allow parallel operation of transformers with different impedance values. However, the following conditions must be observed:

- All transformers must have equal turn ratio
- All transformers must impedance ratio and percentage impedance.
- All transformers should have same windings polarity and same phase rotation

This case study aims to investigate parallel operation of such transformers. To achieve this, the simulation conditions of case study 3 are duplicated for this case study. In addition, the transformer impedances are different but meeting the general requirements.

7.8.1 Simulation setup for the operation of transformers with different impedance

The setup for this case study is typical of the one of case study number 3. Power flows in reverse then changes to forward direction as can be seen in Figure 7-24 below.

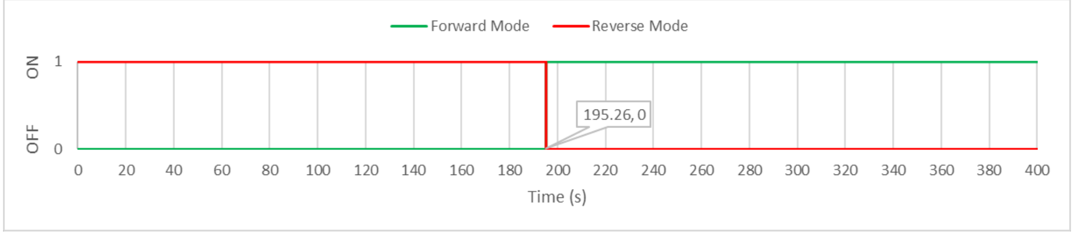


Figure 7-24: Case study 4 - Power flow direction

7.8.2 Load profile for the operation of transformers with different impedance

The load in this case study is modelled identically to the one in case study 3 as illustrated in Figure 7-25 below.

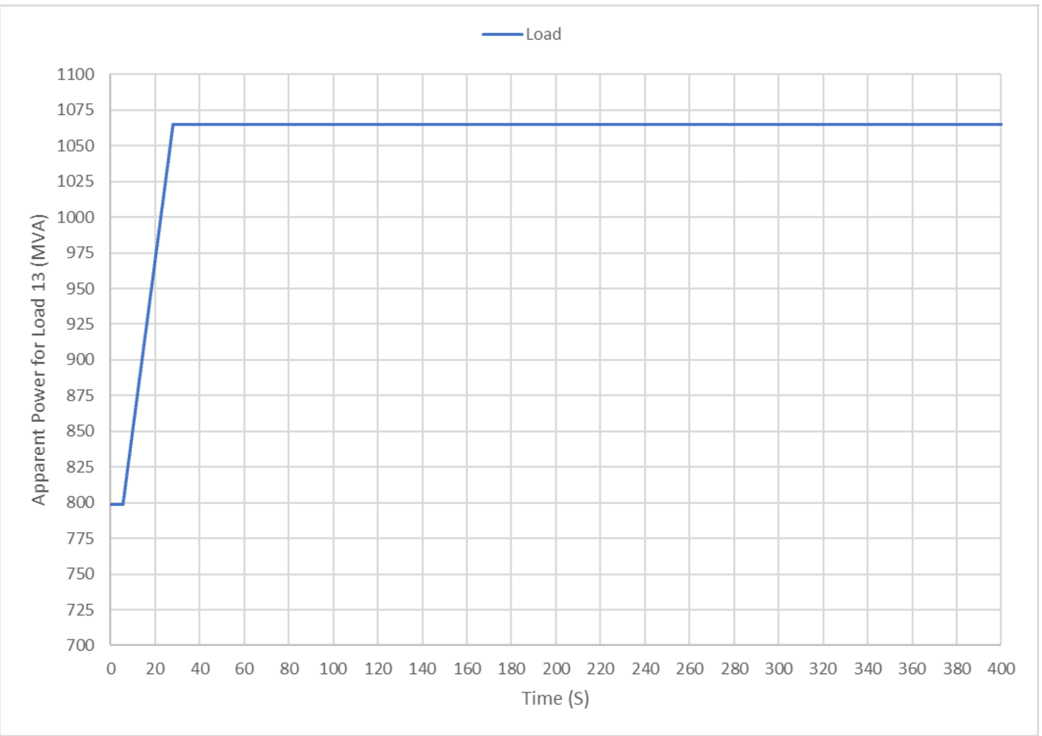


Figure 7-25: Case study 4 - load profile

1.1.1.1 Simulation results for the operation of transformers with different impedance

Results for this case study are captured for 400 significant seconds. All the graphs given for various quantities are to be read in conjunction with each other and the load profile in Figure 7-25 above.

7.8.2.1 Voltage profile for the operation of transformers with different impedance

The graph Figure 7-26 below shows the RMS voltage for bus 6 and bus 13 in green and red, respectively. The controlled bus changes according to the power flow direction.

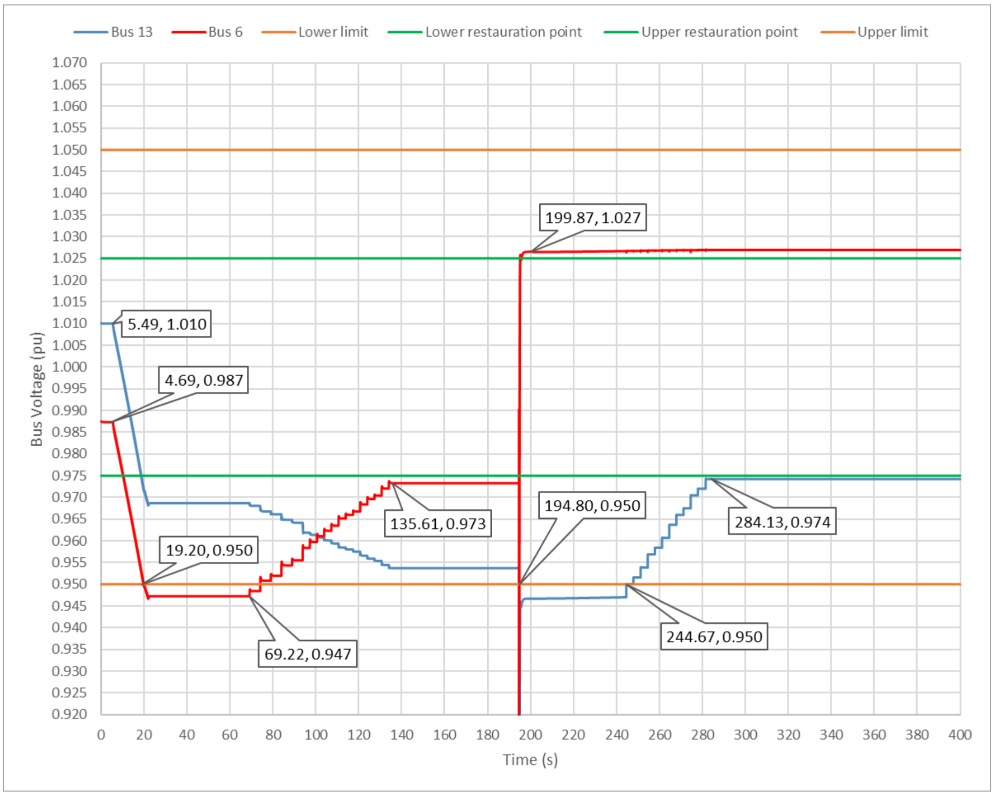


Figure 7-26: Case study number 4: Voltage profile

It can be seen that bus 6 voltage dropped below 0.95pu at about 19.20 seconds of the simulation. At 69.22 seconds, the voltage starts increasing in steps until the reaches 0.973pus. At this point, the voltage stabilises until 194.80 seconds then shoots to 1.027pu due to the change in the power flow direction. The voltage at bus 13 drops below 0.95, the bus being the controlled bus, corrective measures are then taken 50 seconds later in steps until it reaches 0.974pu at 284.13 seconds.

7.8.2.2 Tap Positions for the operation of transformers with different impedance

The graph in Figure 7-27 below shows the tap positions of the three transformers during the simulation process. The tap actions are similar to the ones in the previous case study.

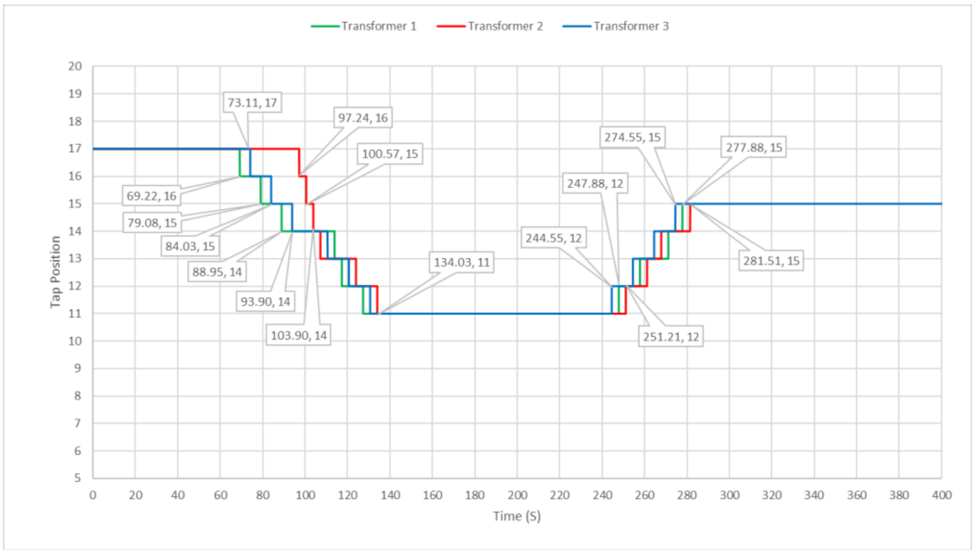


Figure 7-27: Case Study number 4: Transformer tap positions

7.8.2.3 Measurement of circulating current & transformer operations

The circulating current contributions are indicated in the graph in Figure 7-28 below. The current contribution is identical to the ones for previous cases.

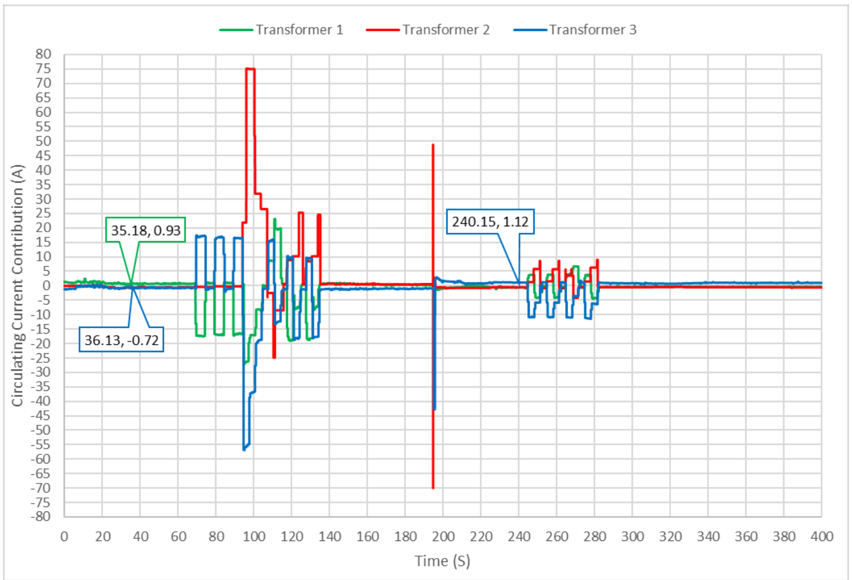


Figure 7-28: Case study number 4: circulating current

Figure 7-29 below show the load current flowing in each transformer during the simulation. The inequality observed is due to the fact that these transformers have unidentical power ratings.

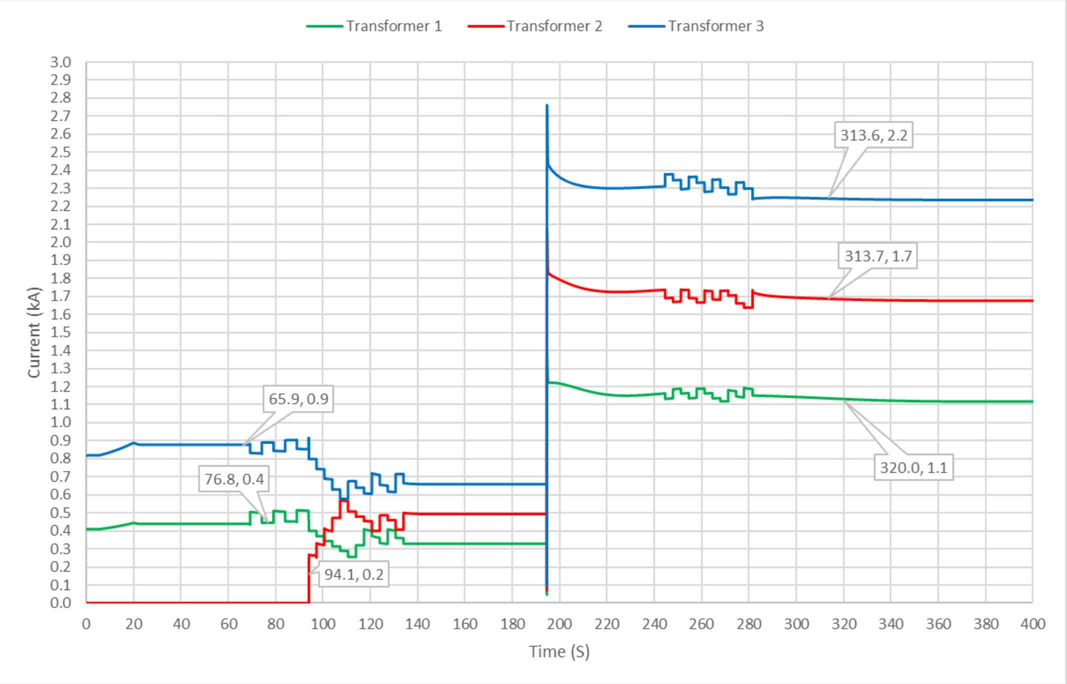


Figure 7-29: Case study number 4 - Transformer load current

Figures 7-30, 7-301 and 7-32 below show the status of the controller at each transformer during the simulation. It is observed that the operation is identical to the one in case study 3.

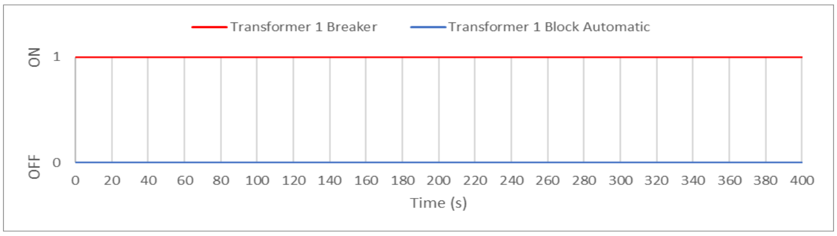


Figure 7-30: Case study 4: Transformer 1 status

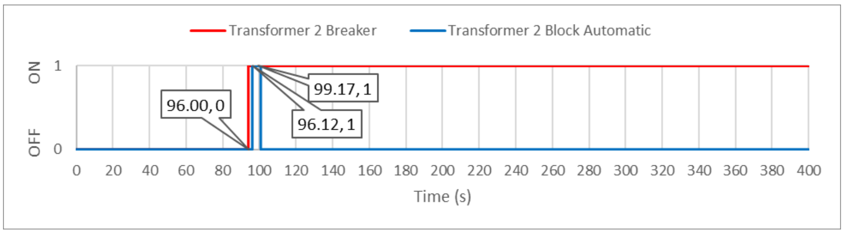


Figure 7-31: Case study 4: Transformer 2 status

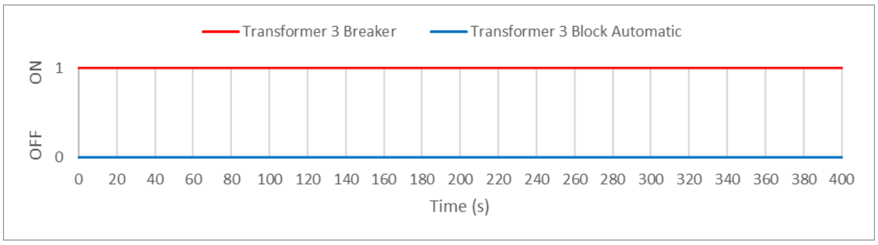


Figure 7-32: Case study 4: Transformer 3 status

7.8.2.4 Discussion for the operation of transformers with different impedance

Transformer 2 is brought back online with the tap position being different to the others. Despite the difference in tap positions and the electrical properties, the controllers assessed the circulating current contribution of each transformer in the parallel group and performed the necessary operation.

7.9 DISCUSSION

Ideally, to investigate the operation of transformer on-load tap changer controllers, a set of transformer tests would have to be performed. In this work, a different approach is taken, and the controllers are subjected to more adverse conditions. For each of the conditions, the controller operated successfully. The operation of the controllers is only based on locally measured values and shared through IEC61850. The automatic operation is fully decentralised. All case studies have indicated that the employment of the controllers has contributed significantly to improving the stability of system voltage.

7.10 CONCLUSION

This chapter aimed to evaluate the performance of the developed controllers utilizing hardware-in-the-loop simulation. The task was subdivided into four case studies as summarised in table 7-1 below

Table 7-1: Case studies summary

Case study	Aim	Objectives	Status
1. Forward mode	Evaluate forward mode operation	• Power direction detection • Optimisation of tap action • Voltage control	Achieved
2. Reverse mode	Evaluate Reverse mode operation	• Power direction detection • Optimisation of tap action	Achieved

		- Voltage control	
3. Combined mode & disturbance	Evaluate the combination of both mode and operation under disturbance	- Power direction detection - Optimisation of tap action - Voltage control	Achieved
4. Combine mode, Disturbance and operation of different transformers	Evaluate the operation for different transformers	- Power direction detection - Optimisation of tap action - Voltage control	Achieved

With the aims and objectives of each case study achieved, it can be confidently concluded that the controllers have performed as per objectives.

The following chapter will give a comprehensive conclusion on the entire work the main contribution of this work to the literature will be alighted. Future development will be enumerated.

CHAPTER 8
CONCLUSION

8.1 INTRODUCTION

Voltage regulation utilizing an on-load tap changer is one of the methods commonly used in the power system to enhance voltage stability. Traditionally, the on-load tap changers are controlled using a designated device. This often leads to the requirement of additional space and exorbitant costs. In other cases, the tap changer is controlled from the control centre resulting in dependability. The traditional controllers are designed to operate in unidirectional power flow. When two or more transformers are connected in parallel, the control of the group becomes a challenging. There are three principal methods of controlling the parallel operation.

- Master-slave,
- Circulating current,
- Negative reactance.

The master-slave method is the most used throughout the globe owing to its simplicity in operation and implementation. The circulating method is the second widely used method. The negative reactance method is the least used of the methods. The two methods first methods require communication between controllers operating in parallel. Depending on the amount features embedded into the controllers, the communication cables can range from a couple of cables to a cluster of communication cables.

This research project focused on the design of on-load tap changer controllers using the circulating current methods. Unlike the majority of researches on this method, the developed controller does not only use the angle of currents to decide on the next tap to operate but also the magnitude of the current. The research intent was also to utilise the IEC 61850 Standards for communication between controllers and the control centre.

The first object of the project was to review approaches for the design and execution of transformer tap changer controllers. Literature consultation showed that the most common method used is controlling utilizing the designated device. The technique employed is usually the master-slave technique. A master controller is selected and the rest of the controllers, slaves, follow all commands issued by the master. Should the master be unable to be in service, another controller is selected as the master. The drawback of this method is that it is only effective for identical transformers. The circulating current method is the second most commonly used method. The principle used in this technique shows that the method can work for transformers with different electrical properties. The method relies on the comparison of the circulating current contribution of each transformer in the parallel group to decide on which would be the next to operate. Although this is the intent of the method, in most cases where this method is utilised, only the angles current flowing through each transformer are compared. In the negative reactance method, the least employed make use of line drop compassion to evaluate the need to operate the transformer tap changer. This method does not necessarily require communication between the controllers involved.

The second objective of the research was to do an overview and application of the IEC61850 standard for the implementation of the transformer tap changer controllers. Whether circulating current or master-slave controlling technique is employed, the communication between each controller and to the control centre remains of high importance. The standard reduces all the communication cables, including wiring from instrument transformers to a single fibre or Ethernet cable. Voltage and current are communicated using parts 9-1 and 9-2 of IEC61850 standards.

The third objective was to model a system of parallel transformers in the software environment of RSCAD and simulate the system behaviours under various disturbances and operational requirements. The 12 bus IEEE network was modified to accommodate the parallel operation of transformers. The modification was purely the replacement of a transformer with 3 equal ratings in total. and an addition of a load.

The fourth objective was to design fully decentralised and hierarchal controllers for the tap changer of the system of the parallel transformers. The selected method of controlling was circulating current. The proposed algorithm makes use of the magnitude of the circulating current contribution of the transformer in the parallel group. The methods were developed based on the calculation of the circulating current as follows:

- The algebraic sum of circulating current contributions for a group of parallel transformers is equal to 0
- The current flowing in each transformer is made of the current being drawn by the load plus or minus the circulating current contribution.
- The sum of current flowing in a group of transformers in parallel is equal to the maximum current being drawn by the load
- The active component of the circulating current is several times smaller compared to its reactive component. Thus, the active component can be ignored in the calculations.

Based on the above, a formula was developed to extract the circulating current contribution for each transformer in the parallel group. The formula was then exploited to compare the circulating current contribution among the transformer. High circulating current contribution can be interpreted as lower secondary voltage. Thus, the next transformer to raise the tap would be the one presenting the high contribution of circulating current. Not that this is only true when power is flowing in the forward direction. For the reverse direction, the principle is still the same. However, the transformer with a high circulating current contribution would be the one to lower its tap position. The controller was designed using AcSELarator QuickSet and implemented in SEL Protection Automation Control relays.

The Fifth objective was to implement the developed controllers in the software environment of RSCAD and simulate the obtained control system under various operating conditions and disturbances. Due to the lack of some trigonometric function blocks in the RSCAD libraries, the controller design was not duplicated in RSCAD. The controllers were instead tested in Hardware in the loop simulation setup.

The sixth and last objective of the research was to perform a hardware-in-the-loop simulation of the developed controllers for parallel transformer tap changers and to investigate behaviour for different operating conditions and disturbances. The test was subdivided into four case studies:

- The first case study aims to evaluate the forward operation of the controllers.
- The second case study aims to evaluate the reverse operation of the controllers
- The third case study aimed to evaluate the operation of the system under disturbances.
- The fourth case study was aiming to investigate the operation of the controller when used with transformers presenting unequal electrical properties.

With all six objectives achieved, it safe to conclude that the aim of the research project has been reached. Subsequently, the proposed controller has evidently performed as intended and can therefore be implemented in real life power system.

8.2 THESIS DELIVERABLES

The research project has generated the following deliverables

8.2.1 Literature review

The review of the literature is detailed in chapter two. The review started with power quality in the power system. Current and traditional methods used to enhance power quality in power systems were detailed. The chapter focused on the automatic voltage regulation using on-load tap changers. Moreover, the application of IEC61850 standards for tap changers was reviewed. The chapter also reviewed prior work on real-time digital simulation and its applications.

8.2.2 Theoretical aspects of transformer in power system

The theoretical aspects of transformers in power systems are presented in chapter three. The construction, application and type of transformer are given the historical background of the transformer tap changer is also given in this chapter. All the types of tap changers, their constructions, strength and weakness are also given in detail.

The chapter also describes the effects of transformers equipped with an on-load tap changer in the power system.

8.2.3 A modified model of the IEEE 12 bus test power system in RTDS/RSCAD

The modelling of the 12 bus IEEE power network is detailed in Chapter 5. The modelling and configuration of each of the major components of the power system are detailed. The system was modified to allow for reverse power flow and accommodate the parallel operation of transformers.

8.2.4 On-load tap changer controllers for parallel operation of transformers

The steps involved in the development of the proposed controllers are detailed in Chapter 6. The design is based on the theoretical aspects of the transformer presented in chapter three as well as the communications standards as per chapter four.

8.2.5 Application of IEC61850 standards in the development of tap changer controllers

The development of the proposed controllers relies on several data exchanges between participating devices. The exchange is facilitated by IEC61850 standards. The communication between Controllers uses IEC61850 GOOSE messages. The object and data are modelled according to IEC61850 standards.

8.2.6 Hardware in the loop simulation

The performance of hardware in the loop simulation is presented in Chapter 7. The developed controllers are tested in real-time using real-time digital simulation. The advantage of the HIL is that since real current and voltage (analogue signals) are input to the IED’s, should the controllers work in HIL, they will work in a real power system.

8.2.7 Software used for the design, implementation of the proposed controllers

The below table list all software used to complete this research project. The objective of using each is indicated next to the software.

Table 8-1: List of Software

Software Package	Application
AcSELerator Quickset	IED's Configuration Controller's logic building
AcSELerator Architect	IEC 61850 data modelling IEC 61850 data mapping
RTDS/RSCAD	Power system modelling Power system simulation IEC 61850 data modelling IEC 61850 data mapping
Wireshark	GOOSE monitoring
GOOSE inspector	GOOSE monitoring
Autodesk AutoCAD	Illustration creation

8.3 APPLICATION TO ACADEMIA

This research project presents a whole way of approaching the circulating current method for transformer tap changers in parallel applications. Most research only considers the angle of the current to make the decision. In this work, the magnitudes have been considered. Moreover, this research is a good example and a guideline for creating customised protection automation or monitoring systems.

Only a limited number of researchers chose real-time digital simulation to validate the findings of their research. Accumulated knowledge from developing this research project will be utilised in future research and will be transferred to researchers and students through this document or any other form of presenting the content of this document.

8.4 POSSIBLE FUTURE RESEARCH WORK

The work presented in this document was developed assuming that the other protection and automation schemes including their backup are configured and coordinated. Moreover, the defined time delays are set sufficiently selected to take care of discrimination and hierarchy. Future work may involve the interconnectivity of all automation schemes involved in voltage support and correction in such a way that time delays are dynamic and computed based on the actual situation. Furthermore, machine learning can be introduced to generate more accurate predictions of the operations and raise alarm should the system deviate from the prediction at a large scale.

System performance is not the only concern in today's society. With the application of large-area automation or protection comes the threat of cyber-attacks. Further work would involve cyber security to enhance the reliability of the system.

8.5 PUBLICATIONS

1. C. Lubamba Ntambwe, R. Ratshitanga and M. Elvis Siyanda Mnguni, 2022. IEC6 IEC61850 standard-based bi-directional transformer tap changer control for power system stability. Submitted to the SAIEE Africa Research Journal, pp. 1-10

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2. Adewole, A. C., Tzoneva, R. and Apostolov, A. (2016) ‘Real-time underload tap-changer control based on synchrophasor measurements’, *Revue Roumaine des Sciences Techniques Serie Electrotechnique et Energetique*, 61(4), pp. 343–348. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85019293466&partnerID=40&md5=834e80f97e540d36bf15c5ea914b8ba0.
3. Apostolov, A. P. (2005) ‘IEC 61850 distributed analog values applications in substation automation systems’, *2005 IEEE Power Engineering Society General Meeting*, 2, pp. 1155–1162. doi: 10.1109/pes.2005.1489748.
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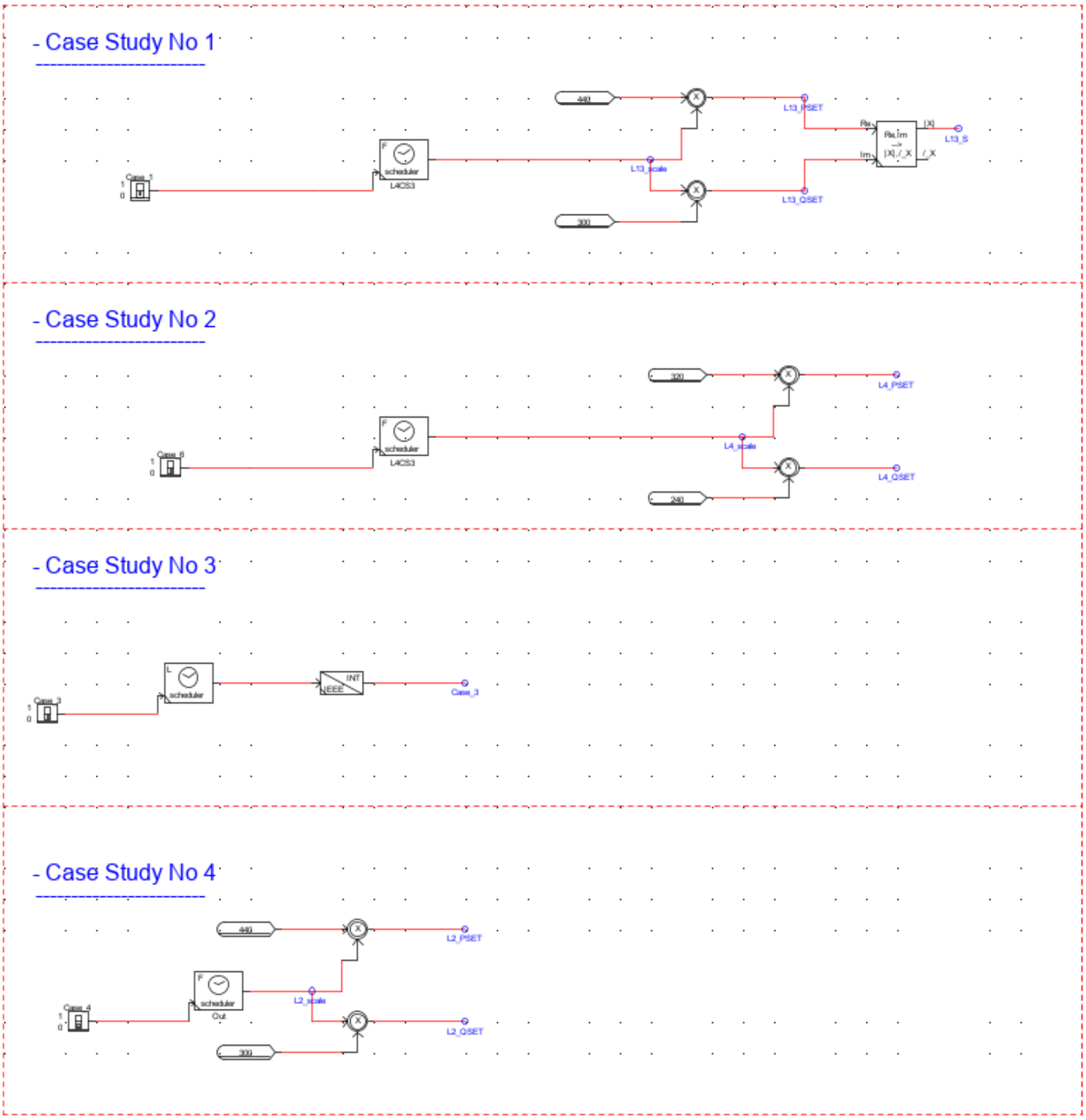
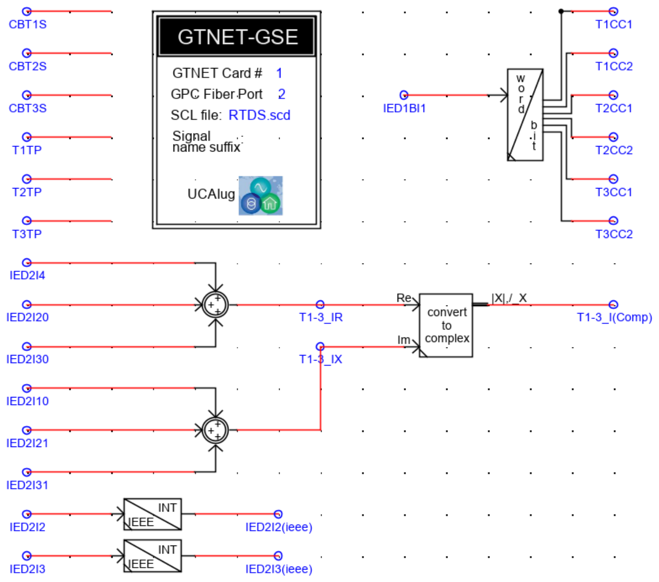
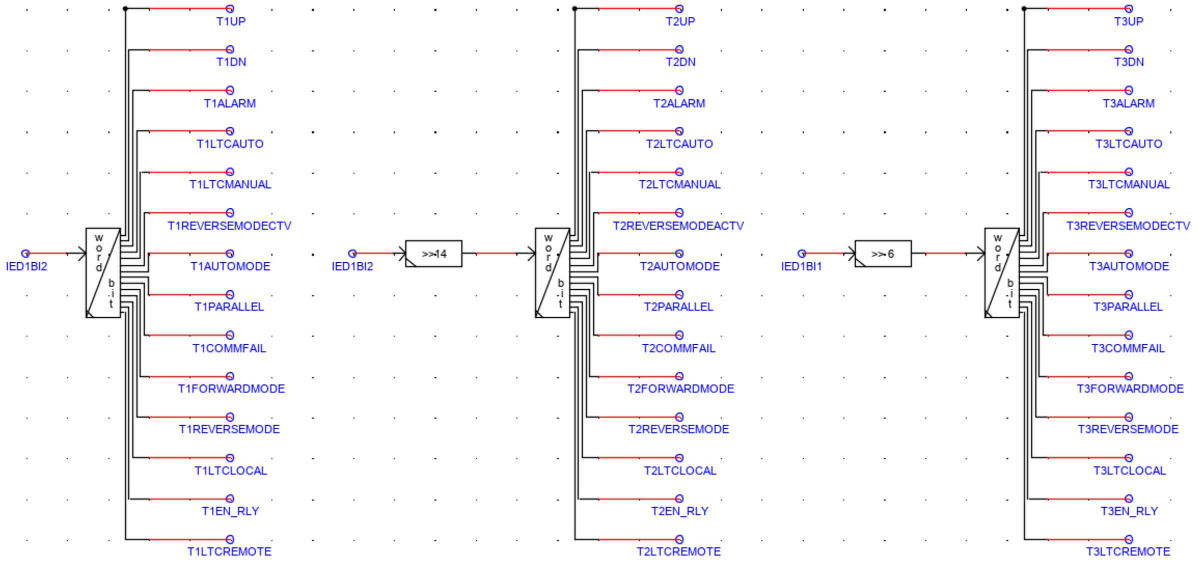
APPENDIX

A. Case studies control

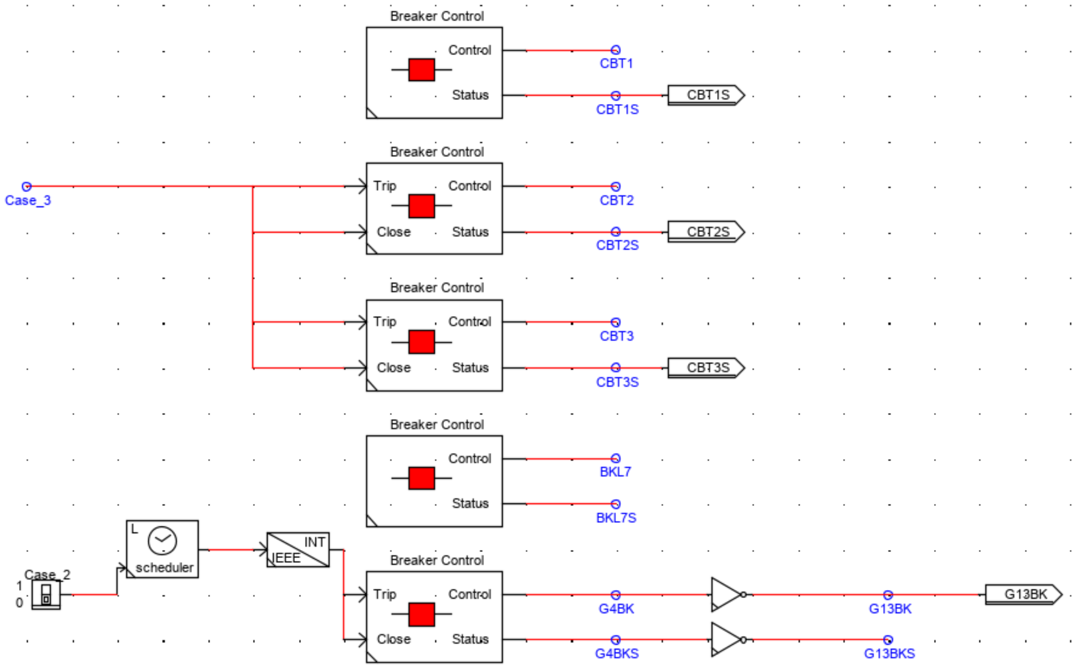


B. GTNET Solution

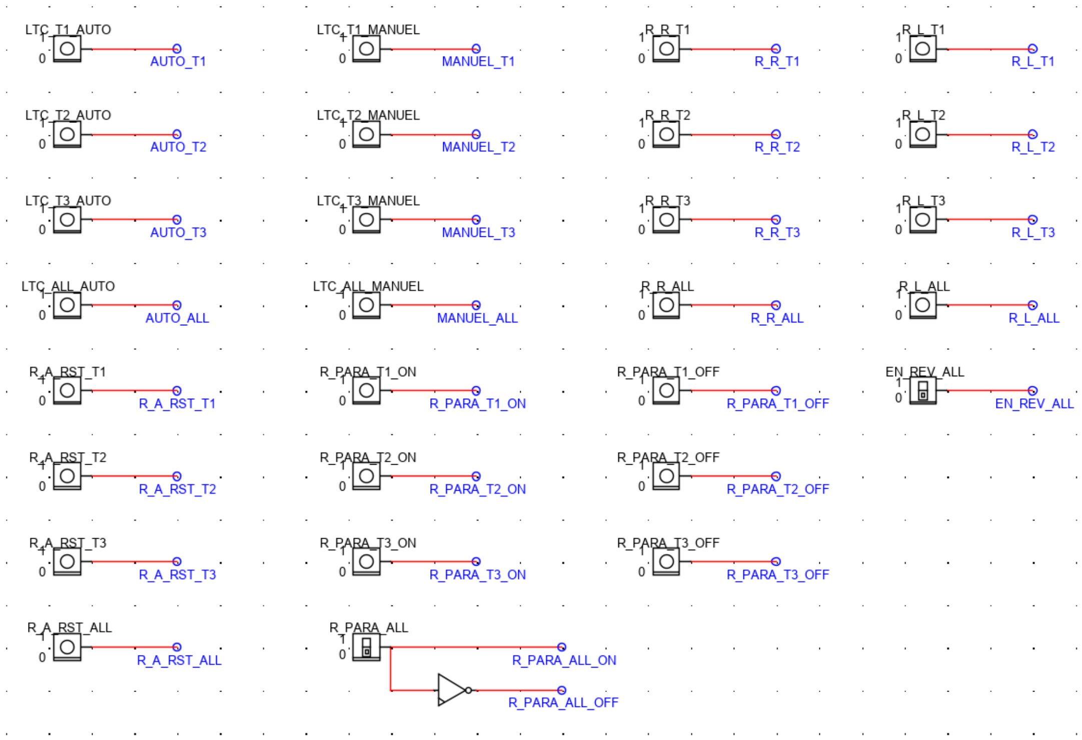




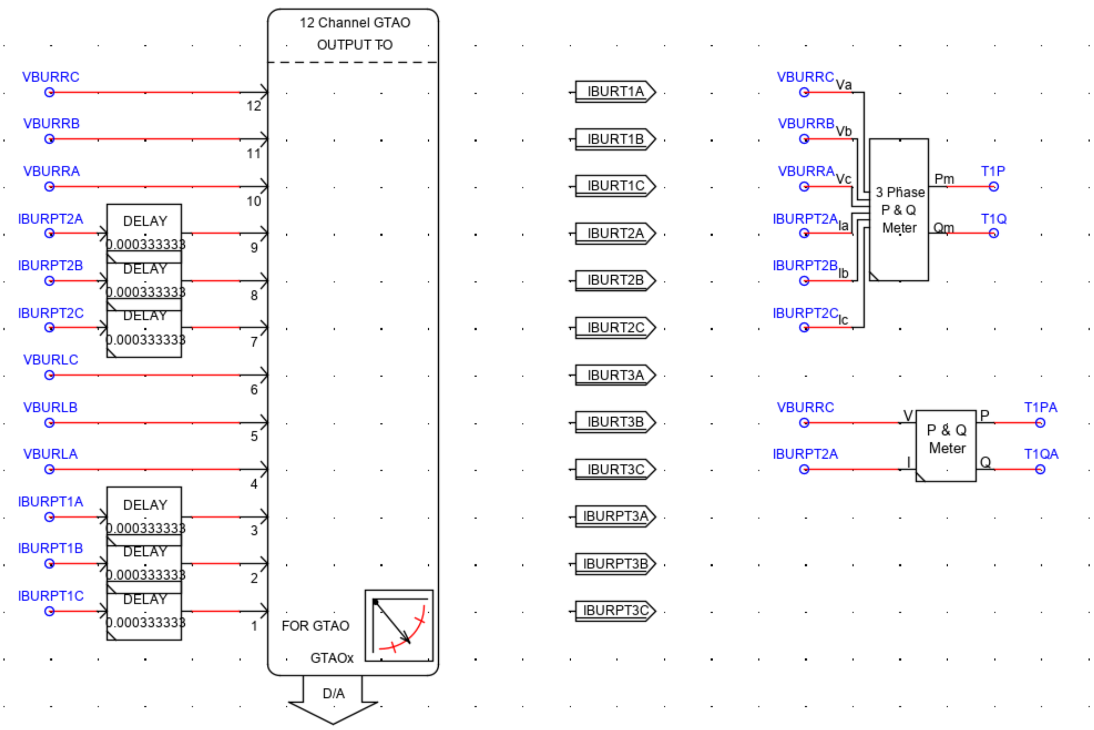
C. Breaker Control

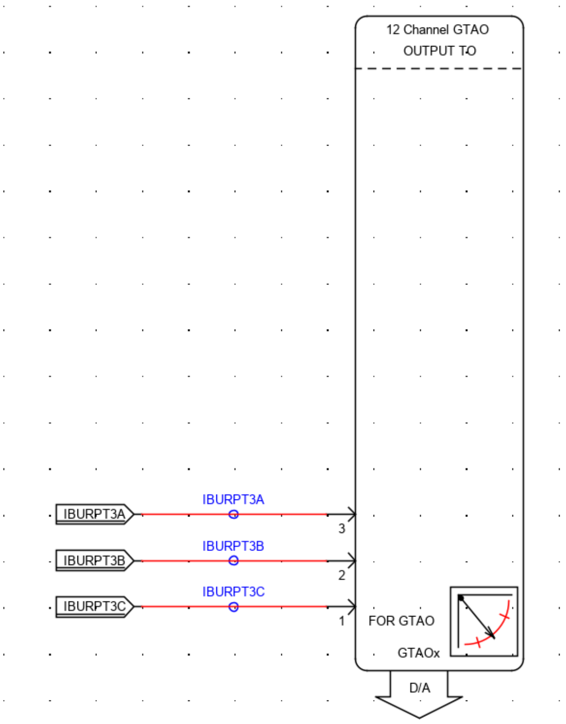


D. Runtime controls



E. Analogue outputs





F. Goose messages data mapping

Subscriber IED	intAddr	Publisher IED	Source data item
SEL_487V_1_Relay_1	VB001	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO7.Ind.stVal
SEL_487V_1_Relay_1	VB002	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO11.Ind.stVal
SEL_487V_1_Relay_1	VB003	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO15.Ind.stVal
SEL_487V_1_Relay_1	VB004	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO19.Ind.stVal
SEL_487V_1_Relay_1	VB005	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO18.Ind.stVal
SEL_487V_1_Relay_1	VB006	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO22.Ind.stVal
SEL_487V_1_Relay_1	VB007	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind13.stVal
SEL_487V_1_Relay_1	VB008	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind13.stVal
SEL_487V_1_Relay_1	VB009	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO23.Ind.stVal
SEL_487V_1_Relay_1	VB010	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO26.Ind.stVal
SEL_487V_1_Relay_1	VB011	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/OUTPUT.ANN.OUT1GGIO17.Ind01.stVal
SEL_487V_1_Relay_1	VB012	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind01.stVal
SEL_487V_1_Relay_1	VB014	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO27.Ind.stVal
SEL_487V_1_Relay_1	VB015	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO31.Ind.stVal
SEL_487V_1_Relay_1	VB017	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO10.Ind.stVal
SEL_487V_1_Relay_1	VB018	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO14.Ind.stVal
SEL_487V_1_Relay_1	VB019	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO30.Ind.stVal
SEL_487V_1_Relay_1	VB020	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO34.Ind.stVal
SEL_487V_1_Relay_1	VB021	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/OUTPUT.ANN.OUT1GGIO17.Ind02.stVal
SEL_487V_1_Relay_1	VB022	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind02.stVal
SEL_487V_1_Relay_1	VB031	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind12.stVal
SEL_487V_1_Relay_1	VB032	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind12.stVal
SEL_487V_1_Relay_1	VB042	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind50.stVal
SEL_487V_1_Relay_1	VB043	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind51.stVal
SEL_487V_1_Relay_1	VB044	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind50.stVal
SEL_487V_1_Relay_1	VB045	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind51.stVal
SEL_487V_1_Relay_1	VB050	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind06.stVal
SEL_487V_1_Relay_1	VB051	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind07.stVal
SEL_487V_1_Relay_1	VB052	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind06.stVal
SEL_487V_1_Relay_1	VB053	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind07.stVal
SEL_487V_1_Relay_1	VB061	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/OUTPUT.ANN.OUT1GGIO17.Ind03.stVal
SEL_487V_1_Relay_1	VB062	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind03.stVal
SEL_487V_1_Relay_1	VB070	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO1.Ind.stVal
SEL_487V_1_Relay_1	VB071	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO35.Ind.stVal
SEL_487V_1_Relay_1	VB081	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind10.stVal

Subscriber IED	intAddr	Publisher IED	Source data item
SEL_487V_1_Relay_1	VB082	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind10.stVal
SEL_487V_1_Relay_1	VB091	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PLTGGIO2.Ind12.stVal
SEL_487V_1_Relay_1	VB092	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PLTGGIO1.Ind12.stVal
SEL_487V_1_Relay_1	VB093	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind39.stVal
SEL_487V_1_Relay_1	VB094	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind39.stVal
SEL_487V_1_Relay_1	VB102	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind40.stVal
SEL_487V_1_Relay_1	VB103	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind40.stVal
SEL_487V_1_Relay_1	VB112	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind41.stVal
SEL_487V_1_Relay_1	VB113	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind41.stVal
SEL_487V_1_Relay_1	RA017	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO2.AnIn.mag.f
SEL_487V_1_Relay_1	RA020	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao10.mag.f
SEL_487V_1_Relay_1	RA021	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao11.mag.f
SEL_487V_1_Relay_1	RA022	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao12.mag.f
SEL_487V_1_Relay_1	RA023	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao13.mag.f
SEL_487V_1_Relay_1	RA024	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao14.mag.f
SEL_487V_1_Relay_1	RA025	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao15.mag.f
SEL_487V_1_Relay_1	RA026	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Circulating_C.ANN.RAOGGIO1.Rao16.instMag.f
SEL_487V_1_Relay_1	RA027	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Circulating_C.ANN.RAGGIO1.Ra017.instMag.f
SEL_487V_1_Relay_1	RA030	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao10.mag.f
SEL_487V_1_Relay_1	RA031	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao11.mag.f
SEL_487V_1_Relay_1	RA032	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao12.mag.f
SEL_487V_1_Relay_1	RA033	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao13.mag.f
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SEL_487V_1_Relay_1	RA035	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao15.mag.f
SEL_487V_1_Relay_1	RA036	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Circulating_C.ANN.RAOGGIO1.Rao16.instMag.f
SEL_487V_1_Relay_1	RA037	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Circulating_C.ANN.RAGGIO1.Ra017.instMag.f
SEL_487V_1_Relay_1	RA052	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Current_T_W.MET.METMMXU1.A1.phsA.instCVal.mag.f
SEL_487V_1_Relay_1	RA053	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Current_T_W.MET.METMMXU1.A1.phsA.instCVal.ang.f
SEL_487V_1_Relay_1	RA062	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Current_T_W.MET.METWMMXU1.A1.phsA.instCVal.mag.f
SEL_487V_1_Relay_1	RA063	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Current_T_W.MET.METWMMXU1.A1.phsA.instCVal.ang.f
SEL_421_1_Relay_2	VB001	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO8.Ind.stVal
SEL_421_1_Relay_2	VB002	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO12.Ind.stVal
SEL_421_1_Relay_2	VB003	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO16.Ind.stVal
SEL_421_1_Relay_2	VB004	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO20.Ind.stVal
SEL_421_1_Relay_2	VB005	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO18.Ind.stVal
SEL_421_1_Relay_2	VB006	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO22.Ind.stVal
SEL_421_1_Relay_2	VB007	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind13.stVal
SEL_421_1_Relay_2	VB008	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind13.stVal
SEL_421_1_Relay_2	VB009	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO23.Ind.stVal

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SEL_421_1_Relay_2	VB010	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO26.Ind.stVal
SEL_421_1_Relay_2	VB011	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind01.stVal
SEL_421_1_Relay_2	VB012	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind01.stVal
SEL_421_1_Relay_2	VB014	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO28.Ind.stVal
SEL_421_1_Relay_2	VB015	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO32.Ind.stVal
SEL_421_1_Relay_2	VB017	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO10.Ind.stVal
SEL_421_1_Relay_2	VB018	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO14.Ind.stVal
SEL_421_1_Relay_2	VB019	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO30.Ind.stVal
SEL_421_1_Relay_2	VB020	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO34.Ind.stVal
SEL_421_1_Relay_2	VB021	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind02.stVal
SEL_421_1_Relay_2	VB022	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind02.stVal
SEL_421_1_Relay_2	VB031	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind12.stVal
SEL_421_1_Relay_2	VB032	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind12.stVal
SEL_421_1_Relay_2	VB042	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind50.stVal
SEL_421_1_Relay_2	VB043	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind51.stVal
SEL_421_1_Relay_2	VB044	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind50.stVal
SEL_421_1_Relay_2	VB045	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind51.stVal
SEL_421_1_Relay_2	VB050	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind06.stVal
SEL_421_1_Relay_2	VB051	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind07.stVal
SEL_421_1_Relay_2	VB052	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind06.stVal
SEL_421_1_Relay_2	VB053	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind07.stVal
SEL_421_1_Relay_2	VB061	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind03.stVal
SEL_421_1_Relay_2	VB062	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind03.stVal
SEL_421_1_Relay_2	VB070	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO3.Ind.stVal
SEL_421_1_Relay_2	VB071	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO35.Ind.stVal
SEL_421_1_Relay_2	VB081	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind10.stVal
SEL_421_1_Relay_2	VB082	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind10.stVal
SEL_421_1_Relay_2	VB091	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PLTGGIO1.Ind12.stVal
SEL_421_1_Relay_2	VB092	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PLTGGIO1.Ind12.stVal
SEL_421_1_Relay_2	VB093	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind39.stVal
SEL_421_1_Relay_2	VB094	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind39.stVal
SEL_421_1_Relay_2	VB102	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind40.stVal
SEL_421_1_Relay_2	VB103	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind40.stVal
SEL_421_1_Relay_2	VB112	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind41.stVal
SEL_421_1_Relay_2	VB113	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Status.ANN.PSVGGIO1.Ind41.stVal
SEL_421_1_Relay_2	RA017	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO4.AnIn.mag.f
SEL_421_1_Relay_2	RA020	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao10.mag.f
SEL_421_1_Relay_2	RA021	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao11.mag.f
SEL_421_1_Relay_2	RA022	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao12.mag.f

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SEL_421_1_Relay_2	RA023	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao13.mag.f
SEL_421_1_Relay_2	RA024	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao14.mag.f
SEL_421_1_Relay_2	RA025	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao15.mag.f
SEL_421_1_Relay_2	RA026	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Circulating_C.ANN.RAOGGIO1.Rao16.instMag.f
SEL_421_1_Relay_2	RA027	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Circulating_C.ANN.RAGGIO1.Ra017.instMag.f
SEL_421_1_Relay_2	RA030	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao10.mag.f
SEL_421_1_Relay_2	RA031	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao11.mag.f
SEL_421_1_Relay_2	RA032	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao12.mag.f
SEL_421_1_Relay_2	RA033	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao13.mag.f
SEL_421_1_Relay_2	RA034	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao14.mag.f
SEL_421_1_Relay_2	RA035	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao15.mag.f
SEL_421_1_Relay_2	RA036	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Circulating_C.ANN.RAOGGIO1.Rao16.instMag.f
SEL_421_1_Relay_2	RA037	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Circulating_C.ANN.RAGGIO1.Ra017.instMag.f
SEL_421_1_Relay_2	RA052	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Terminal_W_Cur.MET.METWMMXU1.A1.phsA.instCVal.mag.f
SEL_421_1_Relay_2	RA053	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Terminal_W_Cur.MET.METWMMXU1.A1.phsA.instCVal.ang.f
SEL_421_1_Relay_2	RA062	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Current_T_W.MET.METWMMXU1.A1.phsA.instCVal.mag.f
SEL_421_1_Relay_2	RA063	SEL_487V_1_Relay_3	SEL_487V_1_Relay_3/CFG/LLN0/Current_T_W.MET.METWMMXU1.A1.phsA.instCVal.ang.f
SEL_487V_1_Relay_3	VB001	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO9.Ind.stVal
SEL_487V_1_Relay_3	VB002	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO13.Ind.stVal
SEL_487V_1_Relay_3	VB003	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO17.Ind.stVal
SEL_487V_1_Relay_3	VB004	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO21.Ind.stVal
SEL_487V_1_Relay_3	VB005	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO18.Ind.stVal
SEL_487V_1_Relay_3	VB006	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO22.Ind.stVal
SEL_487V_1_Relay_3	VB007	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind13.stVal
SEL_487V_1_Relay_3	VB008	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind13.stVal
SEL_487V_1_Relay_3	VB009	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO23.Ind.stVal
SEL_487V_1_Relay_3	VB010	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO26.Ind.stVal
SEL_487V_1_Relay_3	VB011	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind01.stVal
SEL_487V_1_Relay_3	VB012	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/OUTPUT.ANN.OUT1GGIO17.Ind01.stVal
SEL_487V_1_Relay_3	VB014	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO29.Ind.stVal
SEL_487V_1_Relay_3	VB015	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO33.Ind.stVal
SEL_487V_1_Relay_3	VB017	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO10.Ind.stVal
SEL_487V_1_Relay_3	VB018	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO14.Ind.stVal
SEL_487V_1_Relay_3	VB019	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO30.Ind.stVal
SEL_487V_1_Relay_3	VB020	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO34.Ind.stVal
SEL_487V_1_Relay_3	VB021	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind02.stVal
SEL_487V_1_Relay_3	VB022	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/OUTPUT.ANN.OUT1GGIO17.Ind02.stVal
SEL_487V_1_Relay_3	VB031	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind12.stVal
SEL_487V_1_Relay_3	VB032	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind12.stVal

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SEL_487V_1_Relay_3	VB042	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind50.stVal
SEL_487V_1_Relay_3	VB043	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind51.stVal
SEL_487V_1_Relay_3	VB044	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind50.stVal
SEL_487V_1_Relay_3	VB045	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind51.stVal
SEL_487V_1_Relay_3	VB050	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind06.stVal
SEL_487V_1_Relay_3	VB051	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind07.stVal
SEL_487V_1_Relay_3	VB052	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind06.stVal
SEL_487V_1_Relay_3	VB053	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind07.stVal
SEL_487V_1_Relay_3	VB061	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/OUTPUT.ANN.OUTGGIO1.Ind03.stVal
SEL_487V_1_Relay_3	VB062	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/OUTPUT.ANN.OUT1GGIO17.Ind03.stVal
SEL_487V_1_Relay_3	VB070	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO5.Ind.stVal
SEL_487V_1_Relay_3	VB071	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO35.Ind.stVal
SEL_487V_1_Relay_3	VB081	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind10.stVal
SEL_487V_1_Relay_3	VB082	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind10.stVal
SEL_487V_1_Relay_3	VB091	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PLTGGIO1.Ind12.stVal
SEL_487V_1_Relay_3	VB092	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PLTGGIO2.Ind12.stVal
SEL_487V_1_Relay_3	VB093	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind39.stVal
SEL_487V_1_Relay_3	VB094	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind39.stVal
SEL_487V_1_Relay_3	VB102	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind40.stVal
SEL_487V_1_Relay_3	VB103	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind40.stVal
SEL_487V_1_Relay_3	VB112	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Status.ANN.PSVGGIO1.Ind41.stVal
SEL_487V_1_Relay_3	VB113	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Status.ANN.PSVGGIO1.Ind41.stVal
SEL_487V_1_Relay_3	RA017	RSCAD	RSCAD/RTDS/LLN0/Gcb01.RTDS.OUT_GGIO6.AnIn.mag.f
SEL_487V_1_Relay_3	RA020	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao10.mag.f
SEL_487V_1_Relay_3	RA021	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao11.mag.f
SEL_487V_1_Relay_3	RA022	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao12.mag.f
SEL_487V_1_Relay_3	RA023	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao13.mag.f
SEL_487V_1_Relay_3	RA024	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao14.mag.f
SEL_487V_1_Relay_3	RA025	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao15.mag.f
SEL_487V_1_Relay_3	RA026	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Circulating_C.ANN.RAOGGIO1.Rao16.instMag.f
SEL_487V_1_Relay_3	RA027	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Circulating_C.ANN.RAGGIO1.Ra017.instMag.f
SEL_487V_1_Relay_3	RA030	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao10.mag.f
SEL_487V_1_Relay_3	RA031	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao11.mag.f
SEL_487V_1_Relay_3	RA032	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao12.mag.f
SEL_487V_1_Relay_3	RA033	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao13.mag.f
SEL_487V_1_Relay_3	RA034	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao14.mag.f
SEL_487V_1_Relay_3	RA035	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Complex_Current.ANN.RAOGGIO1.Rao15.mag.f
SEL_487V_1_Relay_3	RA036	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Circulating_C.ANN.RAOGGIO1.Rao16.instMag.f
SEL_487V_1_Relay_3	RA037	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Circulating_C.ANN.RAGGIO1.Ra017.instMag.f

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SEL_487V_1_Relay_3	RA052	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Terminal_W_Cur.MET.METWMMXU1.A1.phsA.instCVal.mag.f
SEL_487V_1_Relay_3	RA053	SEL_487V_1_Relay_1	SEL_487V_1_Relay_1/CFG/LLN0/Terminal_W_Cur.MET.METWMMXU1.A1.phsA.instCVal.ang.f
SEL_487V_1_Relay_3	RA062	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Current_T_W.MET.METMMXU1.A1.phsA.instCVal.mag.f
SEL_487V_1_Relay_3	RA063	SEL_421_1_Relay_2	SEL_421_1_Relay_2/CFG/LLN0/Current_T_W.MET.METMMXU1.A1.phsA.instCVal.ang.f

G. Controllers code

- PLT01S := NOT PLT01 AND PB2_PUL
- PLT01R := PB2_PUL AND PLT01
- PLT02S := NOT PLT02 AND (R_TRIG PSV42 AND PLT01 OR NOT PLT01 AND PB1_PUL)
- PLT02R := (NOT PLT01 AND PB1_PUL OR R_TRIG PSV43 AND PLT01 OR PCT18Q) AND PLT02
- PSV01 := PLT02
- PSV02 := NOT PLT02
- PMV02 := PMV53 + PMV54 + PMV55
- PMV03 := PMV50 + PMV51 + PMV52
- PMV04 := PMV03 / PMV02
- PMV05 := SQRT(PMV03 * PMV03 + PMV02 * PMV02)
- PLT04S := PSV07 AND PSV18 OR PSV06 AND PSV19
- PLT04R := NOT (PSV07 AND PSV18 OR PSV06 AND PSV19)
- PLT05S := PLT04 AND NOT (VB102 AND VB094 OR VB103 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12
- PLT05R := NOT (PLT04 AND NOT (VB102 AND VB094 OR VB103 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12) OR PCT06Q OR PCT07Q OR PCT18Q OR NOT PLT04
- PLT06S := PLT07 AND NOT (VB112 AND VB094 OR VB113 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12
- PLT06R := NOT (PLT07 AND NOT (VB112 AND VB094 OR VB113 AND VB093) AND NOT (PCT06Q OR PCT07Q) AND PSV12) OR PCT06Q OR PCT07Q OR PCT18Q OR NOT PLT07
- PSV17 := NOT PSV01 AND (PB3 AND NOT PLT01 OR R_TRIG PSV36 AND PLT01)
- PCT06PU := 0.000000
- PCT06DO := 0.000000
- PCT06IN := PSV09 OR VB011 AND VB094 OR VB012 AND VB093
- PCT07PU := 0.000000
- PCT07DO := 0.000000
- PCT07IN := PLT09 OR VB021 AND VB094 OR VB022 AND VB093
- PCT09PU := 1.000000
- PCT09DO := 0.000000
- PCT09IN := PCT11Q AND PCT20Q AND NOT PCT12Q AND NOT PSV12 OR PSV12 AND PLT05 AND PCT11Q AND PCT10Q AND PCT21Q
- PCT10PU := 0.000000
- PCT10DO := 800.000000
- PCT10IN := PCT06Q
- PCT11PU := 1.000000
- PCT11DO := 0.000000
- PCT11IN := NOT PSV15 AND PSV01 AND PLT08 AND (PLT05 OR T1_ON AND NOT PLT12)
- PSV09 := PCT12Q AND PSV12
- PCT12PU := 0.000000
- PCT12DO := 5.000000

- PCT12IN := ((PCT11Q AND PCT20Q OR R_TRIG PCT09Q) AND NOT PSV15 OR R_TRIG PSV17 OR R_TRIG PCT05Q AND NOT PSV25) AND NOT PCT15Q AND NOT PLT13
- PCT13PU := 0.000000
- PCT13DO := 800.000000
- PCT13IN := PCT07Q
- PCT14PU := 1.000000
- PCT14DO := 0.000000
- PCT14IN := PSV04
- PCT19PU := 1.000000
- PCT19DO := 0.000000
- PCT19IN := PCT14Q AND PCT20Q AND NOT PCT15Q AND NOT PSV12 OR PSV12 AND PLT06 AND PCT14Q AND PCT21Q AND PCT13Q
- PCT15PU := 0.000000
- PCT15DO := 5.000000
- PCT15IN := (PSV31 OR R_TRIG PSV26 OR R_TRIG PCT08Q AND NOT PSV25) AND NOT PCT12Q AND NOT PLT16
- PLT08S := PMV12 > PMV15 AND ASV002 AND PSV19 OR PMV11 < PMV16 AND ASV001 AND PSV18
- PLT08R := NOT ASV002 AND PSV19 OR NOT ASV001 AND PSV18 OR PMV12 < PMV16 AND PSV19 OR PMV11 > PMV15 AND PSV18
- PCT18PU := 50.000000
- PCT18DO := 0.000000
- PCT18IN := LB03
- PSV10 := PSV01 AND (PSV11 AND PSV12 OR NOT PLT12 AND T1_ON)
- PSV11 := (VB031 OR VB032) AND (NOT VB091 OR VB031 AND VB081 OR NOT VB094) AND (NOT VB092 OR VB032 AND VB082 OR NOT VB094) # AUTO_PERM
- PLT09S := PCT15Q AND PSV12
- PLT09R := NOT (PCT15Q AND PSV12)
- PSV12 := T1_ON AND PLT12
- PLT12S := NOT PLT12 AND NOT PLT01 AND LB02 OR R_TRIG PSV44 AND PLT01
- PLT12R := R_TRIG PSV45 AND PLT01 OR NOT LB02 AND NOT PLT01 AND PLT12 OR PCT18Q OR IN102
- PSV13 := (VB007 AND VB094 OR VB008 AND VB093) AND PSV12
- PCT16PU := 50.000000
- PCT16DO := 25.000000
- PCT16IN := NOT PCT16Q
- PMV13 := TP_L
- PCT17PU := 25.000000
- PCT17DO := 50.000000
- PCT17IN := TP_L > 33.000000 OR TP_L < 1.000000 OR PSV24
- PMV15 := PMV14 + 0.562500 * PSV18 + 0.562500 * PSV19
- PMV16 := PMV14 - (0.562500 * PSV18 + 0.562500 * PSV19)
- PMV14 := 120.000000 * PSV18 + PSV19 * 120.000000
- PSV14 := (PCT01Q OR PCT02Q OR PCT03Q OR HALARM OR NOT (PSV18 OR PSV19)) AND PSV12
- PSV15 := PCT01Q OR PCT02Q OR PCT03Q OR HALARM OR NOT (PSV18 OR PSV19) OR VB094 AND VB061 OR VB093 AND VB062 OR PSV13
- PCT01PU := 25.000000
- PCT01DO := 50.000000
- PCT01IN := IAWFM > 1800.000000 OR IBWFM > 1800.000000 OR ICWFM > 1800.000000
- PCT02PU := 25.000000
- PCT02DO := 50.000000
- PCT02IN := PMV26 < 96.000000 OR PMV26 > 144.000000
- PCT03PU := 25.000000
- PCT03DO := 50.000000
- PCT03IN := PMV26 < 96.000000 OR PMV26 > 144.000000

- PCT04PU := 100.000000
- PCT04DO := 0.000000
- PCT04IN := PSV16
- PLT13S := TP_L >= 33.000000
- PLT13R := TP_L < 33.000000
- PSV16 := PMV20 >= 0.200000
- PLT14S := PCT04Q
- PLT14R := PSV32
- PLT15S := PCT17Q AND PSV24
- PLT15R := NOT (PCT17Q AND PSV24)
- PSV20 := PMV25 > PMV15 AND NOT PSV15 AND PSV18 AND ASV002
- PSV21 := NOT (ASV001 OR ASV002) AND NOT PSV15 AND ASV003 AND PMV24 > 60.000000
- PSV22 := OUT102 AND NOT LB01 OR LB01 AND PCT16Q
- PSV23 := PMV24 < PMV16 AND NOT PSV15 AND ASV001
- PSV26 := NOT PSV01 AND (PB9 AND NOT PLT01 OR R_TRIG PSV37 AND PLT01)
- PSV27 := PSV26
- PSV28 := PSV31 OR R_TRIG PSV26 OR R_TRIG PCT08Q AND NOT PSV25
- PMV01 := RA037 * VB093
- PMV17 := RA027 * VB094
- PMV20 := ICC_L / IAWFMC
- PMV21 := EXP(TP_L - PMV17)
- PMV22 := EXP(TP_L - PMV01)
- ICC_L := PMV38 - IAWFMC * (PMV27 / SQRT(PMV27 * PMV27 + PMV28 * PMV28))
- PMV24 := PMV11 * PSV18 + PMV12 * PSV19
- PMV25 := PMV11 * PSV18 + PMV12 * PSV19
- PSV04 := NOT PSV15 AND PSV01 AND (PLT06 OR T1_ON AND NOT PLT12) AND PLT19
- PSV05 := PSV31
- PSV31 := (PCT14Q AND PCT20Q OR R_TRIG PCT19Q) AND NOT PSV15
- PSV32 := NOT PSV16 OR R_TRIG PSV33
- PSV33 := R_TRIG PSV35 OR PCT18Q OR R_TRIG TRGTR
- PLT16S := TP_L <= 1.000000
- PLT16R := TP_L > 1.000000
- PMV11 := VAZFM * SQRT(3.000000)
- PMV12 := SQRT(3.000000) * VAYFM
- PSV40 := PLT05
- PSV41 := PLT06
- T1_ON := EN AND VB070
- PSV08 := (PCT11Q AND PCT20Q OR R_TRIG PCT09Q) AND NOT PSV15 OR R_TRIG PSV17 OR R_TRIG PCT05Q AND NOT PSV25
- PSV35 := VB009 OR VB010
- PSV36 := VB003 OR VB005
- PSV37 := VB004 OR VB006
- PSV42 := VB001 OR VB017
- PSV43 := VB002 OR VB018
- PSV44 := VB014 OR VB019
- PSV45 := VB015 OR VB020
- PSV34 := NOT PLT01
- EN_RLY := EN
- PSV03 := PLT03
- PLT03S := VB071 AND PLT01 OR NOT PLT03 AND NOT PLT01 AND (VB042 AND VB094 OR VB044 AND VB093 OR PB12PUL)
- PLT03R := (VB045 AND VB093 OR VB043 AND VB094 OR PB12PUL) AND NOT PLT01 AND PLT03 OR PLT01 AND NOT VB071
- PSV50 := NOT PLT01 AND (VB071 AND PLT01 OR NOT PLT03 AND NOT PLT01 AND (VB042 AND VB094 OR VB044 AND VB093 OR PB12PUL))

- PSV51 := ((VB045 AND VB093 OR VB043 AND VB094 OR PB12PUL) AND NOT PLT01 AND PLT03 OR PLT01 AND NOT VB071) AND NOT PLT01
- PMV30 := RAO10
- PMV31 := RAO11
- PMV32 := RAO12
- PMV33 := RAO13
- PMV34 := RAO14
- PMV35 := RAO15
- PMV40 := RA020
- PMV41 := RA026
- PMV42 := RA023
- PMV45 := RA033
- PMV44 := RA036
- PMV43 := RA030
- PLT19S := PMV12 < PMV16 AND PSV19 OR PMV11 > PMV15 AND PSV18
- PLT19R := NOT ASV002 AND PSV18 OR NOT ASV001 AND PSV19 OR PMV12 > PMV15 AND ASV002 AND PSV19 OR PMV11 < PMV16 AND ASV001 AND PSV18
- PMV50 := IAWFI * 1200.000000
- PMV51 := PMV42
- PMV52 := PMV45
- PMV53 := 1200.000000 * IAWFR
- PMV54 := PMV40
- PMV55 := PMV43
- PSV60 := PMV28 > 0.000000 AND PMV27 > 0.000000
- PSV61 := PMV28 < 0.000000 AND PMV27 > 0.000000
- PSV62 := PMV28 < 0.000000 AND PMV27 < 0.000000
- PSV63 := PMV28 > 0.000000 AND PMV27 < 0.000000
- PMV27 := PMV38 + RA052 * SIN(RA053) + RA062 * SIN(RA063)
- PMV28 := PMV39 + COS(RA053) * RA052 + COS(RA063) * RA062
- PMV36 := PMV28 / SQRT(PMV27 * PMV27 + PMV28 * PMV28)
- PMV38 := IAWFMC * SIN(IAWFAC)
- PMV39 := COS(IAWFAC) * IAWFMC
- PLT07S := PSV06 AND PSV18 OR PSV07 AND PSV19
- PLT07R := NOT (PSV06 AND PSV18 OR PSV07 AND PSV19)
- PSV46 := (TP_L < RA027 OR NOT VB094 OR NOT VB031) AND (TP_L < RA037 OR NOT VB093 OR NOT VB032) AND PSV24
- PSV47 := (TP_L > RA027 OR NOT VB031 OR NOT VB094) AND (TP_L > RA037 OR NOT VB032 OR NOT VB093) AND PSV24
- PSV18 := NOT PSV03 AND PMV11 >= 60.000000 OR PMV11 >= 60.000000 AND PSV29
- PSV19 := PMV11 >= 60.000000 AND PSV30 AND PSV03
- PSV24 := VB094 AND PMV21 >= 10.000000 OR VB093 AND PMV22 > 10.000000
- PSV29 := (PSV60 OR PSV63) AND NOT (PSV61 OR PSV62)
- PSV30 := NOT (PSV60 OR PSV63) AND (PSV61 OR PSV62)
- PLT17S := PMV26 < 114.000000
- PLT17R := PMV26 >= 116.700000 OR R_TRIG PSV18 OR R_TRIG PSV19
- PLT18S := PMV26 > 126.000000
- PLT18R := PMV26 <= 123.000000 OR R_TRIG PSV18 OR R_TRIG PSV19
- PMV26 := PSV19 * PMV12 + PSV18 * PMV11
- PSV06 := (CIRC_CU < PMV41 OR NOT VB094 OR NOT VB031) AND (CIRC_CU < PMV44 OR NOT VB093 OR NOT VB032)
- PSV07 := (CIRC_CU > PMV41 OR NOT VB094 OR NOT VB031) AND (CIRC_CU > PMV44 OR NOT VB093 OR NOT VB032)
- CIRC_CU := RAO16
- PCT20PU := 2479.000000
- PCT20DO := 0.000000
- PCT20IN := PLT10
- PCT21PU := PMV19
- PCT21DO := 0.000000

- PCT21IN := PLT11
- PLT10S := PLT08 OR PLT19
- PLT10R := NOT (PLT08 OR PLT19) OR PCT06Q OR PCT07Q
- PLT11S := PCT13Q OR PCT10Q
- PLT11R := NOT (PCT13Q OR PCT10Q) OR PCT06Q OR PCT07Q
- PCT05PU := PMV19
- PCT05DO := 10.000000
- PCT05IN := PLT20
- PCT08PU := PMV19
- PCT08DO := 10.000000
- PCT08IN := PLT21
- PLT20S := (TP_L < RA027 OR NOT VB094 OR NOT VB031) AND (TP_L < RA037 OR NOT VB093 OR NOT VB032) AND ASV003 AND TAP_ADJ
- PLT20R := NOT ((TP_L < RA027 OR NOT VB094 OR NOT VB031) AND (TP_L < RA037 OR NOT VB093 OR NOT VB032) AND ASV003 AND TAP_ADJ) OR PCT06Q OR PCT05Q
- PLT21S := (TP_L > RA027 OR NOT VB031 OR NOT VB094) AND (TP_L > RA037 OR NOT VB032 OR NOT VB093) AND ASV003 AND TAP_ADJ
- PLT21R := NOT ((TP_L > RA027 OR NOT VB031 OR NOT VB094) AND (TP_L > RA037 OR NOT VB032 OR NOT VB093) AND ASV003 AND TAP_ADJ) OR PCT07Q OR PCT08Q
- PMV18 := VB094 * VB031 + VB093 * VB032 + 1.000000
- PMV19 := 479.000000 / PMV18
- PSV25 := PCT05Q AND PSV19 AND PMV18 <= 2.000000 OR PMV18 <= 2.000000 AND PCT08Q AND PSV18