UPGRADING EXISTING POWER SUPPLY AT THE PORT OF DURBAN

By

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A dissertation submitted in partial fulfillment of the requirements for the degree

Of

Master of Science in Electrical Engineering

College of Agriculture, Engineering and Science, University of KwaZulu-Natal

November 2019

UNIVERSITY OF KWAZULU-NATAL

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DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication)

Publication 1

S. Mnukwa and A.K. Saha, “Implementation of Substation SCADA and Automation Systems in the Port of Durban”, 2018 IEEE PES/IAS Power Africa Conference, pp 214 – 219, 26 – 29 June 2018, Cape Town, South Africa.

Publication 2

S. Mnukwa and A.K. Saha, "Electrical Load Flow Analysis of 132/33/11 kV Port of Durban’s Substation”, Journal under review on Scientific.net, 2019.

Publication 3

S. Mnukwa and A.K. Saha, “SCADA and Substation Automation Systems for the Port of Durban Power Supply Upgrade”, submitted for publication to SAUPEC/RobMech/PRASA 2020, Cape Town, South Africa.

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DEDICATION

To My Son Ntsikelelo Dumakude, for always inspiring me to do my best. Thank you for being understanding when I could not be at home to spend time or watch cartoons with you. I love you dearly son, my number one supporter.

Philippians 4:13 "I can do all things through Christ who strengthens me"

ACKNOWLEDGEMENTS

Firstly, I would like to give God the Almighty all the glory and praise for granting me the divine wisdom, strength and opportunity for Education. If it was not for the Lord I would not have made it this far.

My heartfelt appreciation goes to my supervisor Professor Akshay Kumar Saha for his supervision, assistance, leadership and invaluable contribution towards my dissertation. Your advice, encouragement and efforts in comments and corrections of this dissertation are highly appreciated. Thank you for ensuring that all the equipment required for my research was available.

I would like to thank Transnet National Ports Authority: Port of Durban for allowing me the opportunity to do my masters and for assisting by providing the equipment and resources I required for my research. Special thanks goes to Mr. Akash Tulsie, Mr. Johan Sauerman and Mr. Tony Francis for always supporting my career aspirations and engineering dreams.

Further thanks to my family for your constant support, motivation and always believing in me. A special thanks to my mother Nomonde Mnukwa who never cease to pray for me. Thank you for playing a mother's role to my son when I was academically committed. To Wiseman Dumakude my life partner, thank you for your moral support and encouragement at all times.

Final acknowledgement goes to the University of KwaZulu-Natal, School of Engineering, for providing facilities and infrastructure required for my research.

ABSTRACT

The Port of Durban's (PoD's) power supply is from EThekwini Electricity (EE) at a supply voltage of 33 kV via two main intake substations that is Stanger Street Substation (STS) and Durban Harbour Intake (DHI) Substation. The supplied power in the Port is stepped down from 33 kV to 11/6.6 kV electrical network. The firm supply capacity for each of these substations is limited to 17 MVA, which is no longer sufficient to supply the PoD because EE's 33 kV electrical infrastructure and supply cables have reached the end of their design lifespan. The existing power supply capacity limit is under threat due to that; it will not be able to meet the additional load required for the planned developments and expansion plans in the Port. System strengthening and enhancements are required in order to improve the reliability of the electrical network. Increasing the electrical supply to and within the Port will ensure a stable and reliable electrical supply.

This research is based on the increase of power supply in the PoD to 132 kV electrical network based on the projected load requirements for planned developments in order to strengthen and increase reliability of the network. The 132 kV electrical network was implemented in PowaMaster software to perform the load flow analyses. Various load flow scenarios were investigated and from the results obtained it was evident that 2 x 132 kV 40 MVA transformers will be capable to carry the total projected Port load reliably and the electrical network will be stable. Detailed analysis and results of different scenarios investigated is contained in this dissertation. An automatic and interactive SCADA model of the physical power systems electrical reticulation network was developed using Schneider CitectSCADA Software. The implemented 132/33 kV substation network model together with the hardware IEDs i.e. VAMP 255, VAMP 259, MiCOM P122 and GE F35 Feeder management protection relays provided functions for control, data acquisition, monitoring, graphical displays, event capturing, alarming, trending and data storage. Communication between the implemented SCADA system and the IEDs was achieved via a communication architecture implemented that took into consideration Modbus RTU, DNP3 and IEC 81650 communications protocols. The substation model implemented was tested for operation at different operating and fault conditions. The effective operation was proven for circuit breaker operation, alarming, circuit breaker fail, overcurrent, earth fault and circuit breaker trip coil supervision under local or remote mode. Results obtained are presented and discussed.

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LIST OF ACRONYMS

AC	Alternating Current
AD	Allan Dalton Substation
AOS	Applications Object Server
CF	Coincidence Factor
CT	Current Transformer
DC	Direct Current
DF	Diversity Factor
DHI	Durban Harbour Intake Substation
DNP3	Distributed Network Protocol 3
EE	EThekwini Electricity
EI	Extremely Inverse
GR	Galaxy Repository
GS	Gauss-Seidal
HMI	Human Machine Interface
IDMT	Inverse Definite Minimum Time
IEC	International Electrotechnical Committee
IED	Intelligent Electronic Devices
IEEE	Institute of Electrical and Electronic Engineers
kVA	Kilo Volt Amperes
kV	Kilo Volt
LAN	Local Area Network
LNs	Logic Nodes
MVA	Mega Volt Amperes
NR	Newton-Raphson
NRS	National Rationalized Specification
PoD	Port of Durban
RTU	Remote Terminal Unit
SANS	South African National Standards
SAS	Substation Automation Systems
SCADA	Supervisory Control and Data Acquisition
SCL	Substation Configuration Language
SI	Standard Inverse
SSD	Specification
STS	Stanger Street Substation
TMS	Time Multiplier Settings
TNPA	Transnet National Ports Authority
VD	Voltage Drop
VI	Very Inverse
VT	Voltage Transformer

CHAPTER 1: INTRODUCTION

Power systems planning and design is one of the key aspects that needs to be considered for power supply capacity upgrade for distributed networks. The planning and design ensures compliance with forecasted load demands and ensuring a reliable robust electrical network and maintaining the voltage limits [1].

The following factors influence the network design include the [1, 2]:

(a) Existing services.
(b) Geographical location.
(c) Required load or customer loads.
(d) Diversity Factor (DF) and Coincidence Factor (CF).
(e) Cable and conductor sizes and types of cable and conductor.
(f) Size, location and types of substation.
(g) Quality of supply.
(h) Voltage Drop (VD) and unbalance, within limits of design loads.
(i) Future Developments and Environmental considerations.

Power systems load flow analysis is conducted upon considering the above mentioned factors for evaluation and analysis of the electrical network design behaviour and also for verification of suitability of the selected equipment for the projected future loads and ensure optimal system loading [1, 3].

To ensure quicker returns on investment, cost effective Substation Automation Systems (SAS) are designed to operate and maintain. In order to advance the existing communications protocols for SAS, the Institute of Electrical and Electronic Engineers (IEEE) and the International Electrotechnical Committee (IEC) collaborated to develop and implement the Ethernet based IEC 61850 international standard. The IEC 61850 communications network and system in substations allows for compatibility between Intelligent Electronic Devices (IEDs) of different manufacturers [4, 5]. This standard is also equipped with descriptive object data models with standard Substation Configuration Language (SCL) and lower integration costs [6].

1.1 Background

The Port of Durban (PoD) is the busiest in South Africa and the biggest in terms of container capacity and plays a pivotal role in the South African economy. The PoD's electrical supply is integral in supporting the various Transnet facilities / terminals and revenue creating operations contained therein. The PoD's existing power supply is under threat, due to the planned developments and expansion plans requiring additional load. System strengthening and enhancements are also required. The 33 kV electrical supply to the PoD is from EThekwini Electricity (EE) via two intake Substations and the supply capacity in each of these substations is limited to 17 MVA. The supply voltage from the intake substations is redistributed and stepped down from 33 kV to 11/6.6 kV to all PoD's consumers i.e. Durban Container Terminal connected to Port electrical network [7]. The current Notified Maximum Demand according to the port billing statements is 14.63 MVA. The firm supply of 17 MVA has been exceeded in the past leaving the port with no redundant supply. The requirement to increase the container throughput capacity at Pier 1 and Pier 2 container terminals and other infrastructure development projects at the PoD will result in the firm supply of 17 MVA being exceeded [8,9].

According to eThekwini Municipal "By-Laws", large power users with maximum demand exceeding 18 MVA shall be supplied with a system voltage of 132kV. In addition, EE is phasing out all their 33kV infrastructure and cables due to the exceeded design lifespan resulting in obsolete spares for maintenance. The costs associated with the maintenance, operation and sustaining infrastructure at this voltage level far exceeds the return on investment and revenue generated for a bulk supply of this magnitude [9]. The EE system distribution voltage to large power users is 132 kV.

Based on the abovementioned facts, the PoD had to evaluate alternative sources of power supply solution, which will be able to cater for future loads and strengthen the network. This entails the new 132kV, 80 MVA supply through underground cables from the existing EE's Edwin Swales outdoor switching station to the new 132/33 kV Langeberg outdoor PoD substation.

1.2 Motivation

Electricity is the most crucial component of infrastructure affecting economic growth therefore a stable power network is very essential. Grid collapse situations are a result of overloaded electrical networks that are prone to electrical failures. It is of great importance that electrical load flow study analysis are conducted to monitor and control the load and voltage profiles in a power systems network. This ensures effective electrical network performance and reduces disruption to operations unexpectedly and savings on operating and maintenance costs [10] and loss of production. Network modelling is useful for network planners, designers and operators. Network planners are able to gather information on the status of the electrical networks and ensure that the network caters for any planned developments requiring additional load. The design engineers utilise modelling to verify if the selected equipment will be able to cater for the required load demand under normal operating conditions as well as under fault conditions. The operators use modelling to monitor and control voltages and currents keeping them within acceptable limits and ranges [11]

Load flow study analysis will be conducted to evaluate the status of the existing PoD's electrical network and future developments forecast loads will be considered to ensure that the electrical supply upgrade will take into account the projected loads. The main objectives of electrical load flow studies are the following:

(a) To analyse the status of the existing electrical network and ensure that the network is reliable and robust to cater for additional forecasted loads.
(b) To obtain information regarding system voltages, currents, active and reactive power at each point in the network and equipment percentage loading with the respect to equipment rating.
(c) To determine the best location for new substations or new lines with respect to the load centres and ensuring that there is sufficient capacity to cater for the demand.
(d) To ensure that voltages at different levels of a power system are monitored and maintained at acceptable limits.
(e) Provides information of the conductor percentage loading. This ensures that the selected conductors are not overloaded and are not operated close to their capacity limits or thermal limits.

Gauss-Seidel (GS), the Newton Raphson (NR) and Fast Decoupled are the three commonly used iterative methods to solve load flow analysis problems. In Chapter 5 the NR, method is used due to its characteristics of high degree of accuracy.

The new 132 kV Langeberg substation will be located near the major Port loads as well as future expansion developments. The design of this electrical substation system will take into consideration the modernization of the substation system that will improve flexibility and improved efficiency. Modern power systems substation are equipped with Intelligent Electronic Devices (IEDs) which provide features of interoperability, advanced and efficient communication abilities for substation monitoring, protection, control and testing. The integration between legacy and IEC 61850 communications protocols will be considered in the SAS development for effectively monitoring and controlling the operation of substation equipment either in remote or local mode. The developed communications architecture via Ethernet will enable proper integration between IEDs and communications protocols for coordinated monitoring, protection and control of a substation. In modern SAS the data retrieved from IEDs is used to control and operate the electrical network devices. The developed Supervisory Control And Data Acquisition (SCADA) system will offer users/operators with Human Machine Interface (HMI) or graphical representation of the electrical substation that will be used for controlling, monitoring and protection of devices in real time. This function will provide maximum availability, efficiency, reliability, safety and data integration [14, 15].

1.3 Research Questions

Based on the load profile at the two intake substations in the Port, the load growth in the PoD has been increasing however the supply capacity limit was never been increased. As a result the electrical network has been under strain. This research was conducted in order to evaluate and improve the status of PoD's electrical network to ensure reliability and availability of supply. The following research questions are required to be addressed:

(a) What is the impact of the load growth in a power system's electrical network?

(b) What are the most important aspects to consider for an electrical load flow study analysis for an electrical power systems network?

(c) What are the benefits of using SCADA systems and SAS to monitor and control an electrical power system?

(d) For effective operation of SCADA and SAS, what are the communication protocols that need to be considered?

(e) What is the proposed design for the PoD electrical network to cater for the new loads?

1.4 Dissertation Aims and Objectives

The main aim of the project is to increase the electricity supply capacity to the PoD to ensure continuous reliable supply to meet the future load demand. The main objective is also to ensure alignment with EE in phasing out 33 kV infrastructure in the Durban area. This research addressed the following objectives:

(a) Conduct electrical load flow study to analyse the voltage stability, system reliability and also perform the short circuit analysis of the new 132/33kV PoD substation in line with the statutory and regulatory requirements of SANS 10142-2, NRS 034-1:2014 and NRS 048.

(b) Evaluate and investigate various projected load forecast scenarios for effective power system network analysis.

(c) To validate if all the new selected reticulation cables and transformers as part the design have been correctly sized and will be able to operate reliably and without compromising security of supply with the implementation of all planned future loads.

(d) To configure, develop and implement a SCADA and SAS for monitoring and control of an electrical power system.

(e) Design, establish and commission 132/ 33 kV Legacy and IEC 61850-based integrated electrical network on CitectSCADA platform and test for effective operation in conjunction with the associated hardware IEDs.

(f) Configure IEDs i.e. VAMP, MiCom P122 and GE relays individually utilising vendor proprietary tools.

(g) Investigate and analyse application of communication protocols such as Modbus RTU, Distributed Network Protocol (DNP3), IEC 60870-5-103 and compare their functionality with the IEC 61850 standard for effective integration of legacy and modern design.
(h) Examine the application of the integrated legacy and IEC 61850 technology by implementing and testing different protections scenarios such as Circuit Breaker Failure, Circuit Breaker Trip Coil Status, Cable Earth, Overcurrent and Earth Fault.
(i) Test the developed SCADA model for operation and isolation under local and remote mode conditions.
(j) Testing and validating the communication and data flow between IEDs to ensure IEC 61850 compatibility is possible and effective data transfer from the IEDs using the communications architecture implemented on the network model.
(k) Test functionality and effective operation of the substation equipment, which include circuit breakers, isolators, supervisory features, and interactive features.

1.5 Structure of the Dissertation

Chapter One entails the background, motivation, research questions, the aims and objectives of and an outline of the dissertation.

Chapter Two provides information on the reviewed literature and theory surrounding the research topic. This was required to understand the fundamental elements used in this research. The literature review focused mainly on aspects of electrical load flow study analysis and power systems protection. It further indicates how different authors have conducted studies related to this topic.

Chapter Three presents the review of the existing power supply and upgrade requirements in the PoD. It investigates the PoD's SCADA and Automation Systems and presents integration of the new 132 kV substation network into the currently existing electrical network.

Chapter Four discusses the study methodology, process, software and the study model.

Chapter Five presents an electrical load flow study developed taking into account the future PoD's load requirements. The electrical network model is developed and simulated on PowaMaster software. The objective of this study is to analyse the voltage stability, system reliability and perform the short circuit analysis of the new 132/33kV PoD substation and verification of the correct sizing of the selected equipment. Various simulation scenarios and results are presented in detail.

Chapter Six presents the development of SCADA and Automation system for the PoD's power supply upgrade. An interactive and automatic electrical substation network model is developed on Schneider's CitectSCADA software. The designed SCADA system enables the user/operator to visualise and collect data from IEDs located at remote sites and allows for fault management and operations functions. The implemented SCADA systems provides graphical user interface of the electrical network, alarm features, trends and substation geographical location for the user/operator to remotely perform functions of control and interact with the substation equipment.

Chapter Seven consolidates main research points into a final summary and conclusion, and presents suggestions for further work.

CHAPTER 2: BACKGROUND THEORY AND LITERATURE REVIEW

2.1 Introduction to Load Flow Studies

This chapter entails a review of literatures related to power systems load flow analysis studies. Extensive amount of studies have been conducted on load flow analysis. There are several methods of modern power flow analysis used and these entails of GS, NR method and Fast-Decoupled method [16, 17, 18, 19, 20].

In an electrical power system network, the load is not constant and changes every moment, leading to voltage variation above tolerance levels and affects power factor and load performance [17]. The main purpose of load flow studies is to determine the steady state operation of the electrical network. The following parameters are obtained from this study [16, 17]:

(a) Busbar voltage and current ratings and phase angle;

(b) Real and reactive Power, and;

(c) Load at each level of the busbars.

The information obtained is analysed to identify whether the current network can accommodate any future additional load requirements and is for continuous system monitoring [16, 18].

2.2 Load Flow Analysis

In electrical power systems, power flows from generating stations to load centres, therefore requires load flow analysis to check performance of existing system and determine the network steady state operating conditions [17, 18, 19]. Under steady state conditions the study provides information of the power delivered, power loses occurred in the system, current through each branch, voltages at each bus, active and reactive power [16, 17]. The study is use to determine if the conductors, transformers and transformers are overloaded and whether the voltages are kept at the required limits in the event of any fault occurring in the network [17, 18]. In order to solve a power flow problem, it is of great importance that the bus type is identified first and at each bus, two of the four quantities $|V_i|$, δ_i, P_i and Q_i are specified and the remaining two are to be calculated. In a PQ bus, P_i and Q_i are known and $|V_i|$ and δ_i are to be determined. In a PV bus, P_i and $|V_i|$ are known therefore Q_i and δ_i are to be determined [20].

2.3 Load flow methods

From the literature reviewed there three methods of load flow analysis used i.e. GS method, NR method and Fast-Decoupled method [16, 17, 18, 19]. In any of these power flow techniques, initial voltage being specified to all buses, for the first iteration, PQ bus voltage values are set to *(1+j0)* whereas for PV bus voltages are set to *(V+j0)* [20].

2.3.1 Gauss-Siedel method

The GS method is an iterative algorithm for solving a set of non-linear algebraic equations [16]. In order to obtain a load flow solution using GS method, the assumption is that all buses except for the slack bus are PQ buses. The slack bus voltage is specified, there are *(n-1)* bus voltages starting values of whose magnitudes and angles are assumed. These values are therefore updated through an iterative process. In GS algorithm, equation (1) is utilised to find the final bus voltages using successive steps of iterations [20].

$$V_i = \frac{1}{Y_{ii}}\left(\frac{P_i - jQ_i}{V_i^*} - \sum_{k=1;k\neq 1}^{N} Y_{ik}\, V_k^p\right); i = 2, 3, \ldots, n \qquad (1)$$

2.3.2 Newton-Raphson method

The NR method is an iterative process used for solving a set of simultaneous non-linear algebraic equations with equal number of unknowns. It is a practical method of load flow solution of large power networks [16, 20]. The Jacobian matrix in equation (2) provides the linearized relationship between small changes in voltage angle Δδ and voltage magnitude ΔV with the small changes in active and reactive
power ΔP and ΔQ [19].

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J1 & J2\\ J3 & J4\end{bmatrix}\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \qquad (2)$$

2.3.3 Fast-Decoupled method

Fast-decoupled load flow method approximate decoupling of active and reactive flows in well-behaved power networks and additionally fixes the value of the Jacobian during the iteration in order to avoid costs matrix decompositions [18]. In this method, for accuracy up to five iterations are required and the speed for iterations is nearly five times that of the NR method [20].
The authours of [18] performed an analyses, design and comparison between GS method and NR method using MATLAB. From the results obtained in this literature it was observed that in the GS method the rate of convergence is slow and the number of iterations directly increases with the number of buses in the system. Whereas in the NR method the rate of convergence is very fast and the number of iterations is independent of the size of the system therefore it is higly accurate compared to GS method [18]. According to literature [19] GS method is simple and easy to execute however it has more iterations as the number of buses increase; NR method is more accurate than all other methods and it provides better results in less number of iterations. Fast-decoupled load flow method is the fastest of all methods but it is less accurate since assupmtions are taken for fast calculation. Fast-decoupled load flow method has the least number of iterations

[19]. NR method is more functional and effective because it produces accurate calculation of the load line losses without depending on the number of buses [20].

2.4 Introduction to Power Systems Protection

This chapter also entails a review of literatures related power systems protection. The purpose of an electrical power system is to generate and supply electrical energy to consumers.

The Port's power system design ensures that electrical power is delivered at the load centres in a reliable and economic manner [22]. The electric power systems are made up of facilities and equipment that generate, transmit and distribute electrical energy [23]. It is very crucial that a power system is properly designed; the system must be able to clear faults as reliably as possible when there is a fault or disturbance on the protected equipment. It must be able to remain inactive if the protected equipment is in a healthy state or if the fault is not within the zone of protection. Regardless of how well designed the power system, faults and failures normally occur and these poses a risk to life and property. Due to great amounts of energy involved, faults represent a threat to the operation and security of power systems if the faults are not promptly corrected. Power systems require an auxiliary system that must take corrective actions on the occurrence of a fault. This auxiliary system is known as protection system [23, 24]. Protection systems are sets of equipment, schemes and policies dedicated to detect faults in the protected elements of the power systems, to disconnect the faulted element and to re-establish the service. Power Systems operate in different operating states, therefore different fault scenarios may occur. Protection systems must provide different schemes and equipment to detect and react to each one of these fault scenarios, from the simplest to the most complex and compelling [24]. The protection system should embody characteristics of reliability, selectivity, stability, speed and sensitivity. A reliable protection system should be able isolate the fault condition as fast as possible without affecting the whole protection system [24].

2.5 Zones of Protection

Power systems protection schemes are designed to eliminate electrical equipment damage and prevent network failure by detecting fault conditions and isolating the failed component without affecting the entire system [24]. To achieve these functions, the protection is arranged according to zones and it is important that the zones of protection overlap, to ensure that the entire power system is protected [22, 24].

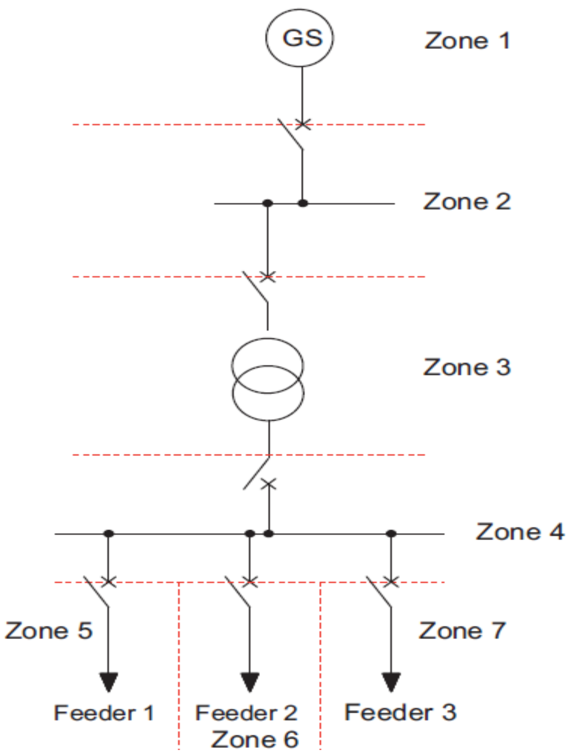


Figure 2-1: Division of Power Systems into protection zones [22]

Figure 2-1 shows typical zones of protection for a power system. From this diagram it is evident that a zone of protection begins at a circuit-interrupting device and all the equipment are included in the zones for maximum protection under fault conditions. The power systems configuration, relay characteristics, equipment location determine the zones of protection [24].

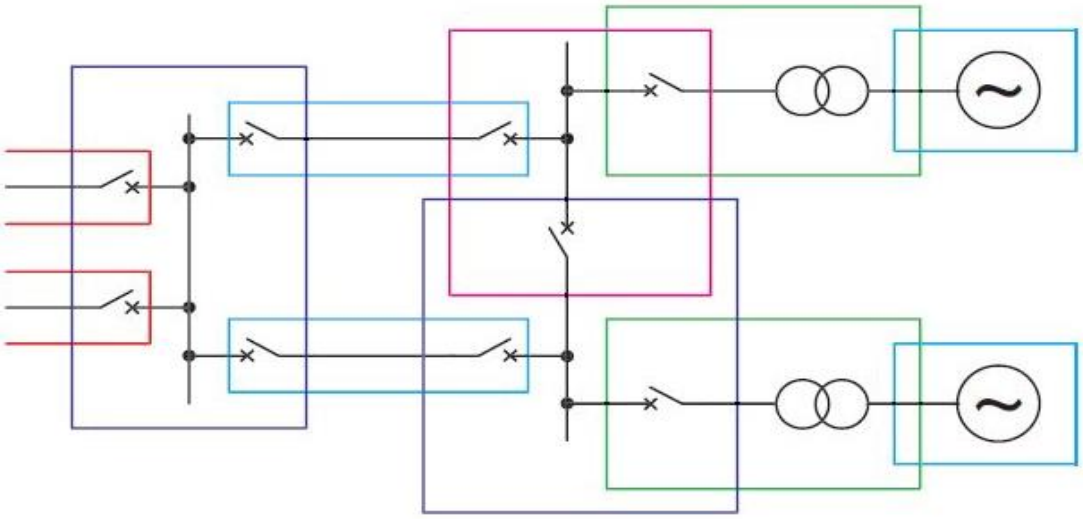


Figure 2-2: Overlapping zones of protection systems [22]

Figure 2-2 above shows a typical arrangement of overlapping zones. Circuit breakers and circuit re-closers need to be included in two overlapping zones of protection for instance a transmission line circuit breaker would be included in the zone of protection for the bus and the zone for transmission line. Some components may be included in special overlapping zones of protection for instance a large generator that is directly connected to a step up transformer may be provided with a generator differential protective that have a zone of protection that includes the main generator, the step up transformer and inter-closing bus work [22].

2.6 Requirements of a Protection Scheme

The main important objective of a protection system is to provide isolation of fault/problem area in the power system quickly as quickly as possible without affecting the rest of the power system. The purpose of using protection equipment is to minimize the duration of the fault and limiting the damage and outage time [25]. Protection systems/devices requirements are as follows [22, 25]:

- Reliability.
- Selectivity.
- Stability.
- Speed.
- Sensitivity.

2.6.1 Reliability

Reliability is the assurance that the protection will perform correctly. The protection system is required to provide its functions to avoid damage to equipment, people and property [24]. It has two important aspects i.e. dependability and security. Dependability indicates the ability of the protection system to perform correctly when required whereas security is the ability to avoid unnecessary operation during normal day-to-day operation and faults and problems outside the designated zone of operation [25]. Reliability problems stem from incorrect design, incorrect installation/ testing and deterioration [24].

2.6.2 Selectivity

Selectivity is the relay coordination. It is the process of applying and setting the protective relays that overreach other relays such that they operate as fast as possible within their primary zone but have delayed operation in their backup zone. This is necessary to allow the primary relays assigned to this backup or overreached area time to operate [25]. In the event of a fault, the protection scheme is required to trip only those circuit breakers whose operation is required to isolate the fault. This property of selective tripping is also referred to as discrimination and is achieved by time grading and unit systems [22]. Protection systems in successive zones are arranged to operate in times that are graded through the sequence of protection devices so that only those relevant to the faulty zone complete the tripping function. The speed response is dependent on the severity of the fault. For clearly defined zone, unit protection systems are applicable under fault conditions [24].

2.6.3 Stability

Under stability conditions the external conditions outside the zone of protection are not affected in the event of a fault [24].

2.6.4 Speed

It is very crucial that protection schemes are able to clear a fault as quickly as possible to avoid equipment damage and loss of power. This ensures continuity of supply as it isolates the faulted area to avoid affecting the whole power system [24, 25].

2.6.5 Sensitivity

Considering the case of overcurrent protection, the protective system must have the ability to detect the smallest possible fault current. The smaller the current the protection system can detect, the more sensitive it is [24]. Highly sensitive relay equipment are extremely reliable for clearing fault at the right time [24].

2.7 Protective Relaying

The primary objective of all power systems is to maintain a very high level of continuity of service and when intolerable conditions occur to minimize the outage times. The main function of a relay is to isolate any elements of a power system from service in the event of a fault or under abnormal conditions in a power system. [22, 25]. In the event of a fault condition in a power system, the protection relays sends a trip signal to the circuit breakers to isolate the faulty section as quickly as possible before it affects the entire system [22, 26].

2.7.1 Relay Operating Principle

According to the authors of [22, 27] power system protection used to be constituted of electromechanical relays. Due to technological advancement nowadays, these electromechanical relays are being replaced by digital and microprocessor-based relays or numerical relays. Numerical relays have better operating speed, better accuracy, fewer maintenance requirements and better communication facilities for linking to SCADA system. These relays have the ability to verify, supervise themselves and the entire system connected to it. Mechanical switches for protection, metering and monitoring can be wired through them for event recording and backup [27]. Numerical relays are configured using the relay software and by inputting all parameters set by client and it will be installed, tested and commissioned [27, 28]. Numerical relays accepts analog inputs and process them electronically to develop a logic output representing a system quantity and makes a decision resulting in an output signal. Sampling of analog signals and using an appropriate computer algorithm to create suitable digital representations of the output signals i.e. power system voltages and currents [29].

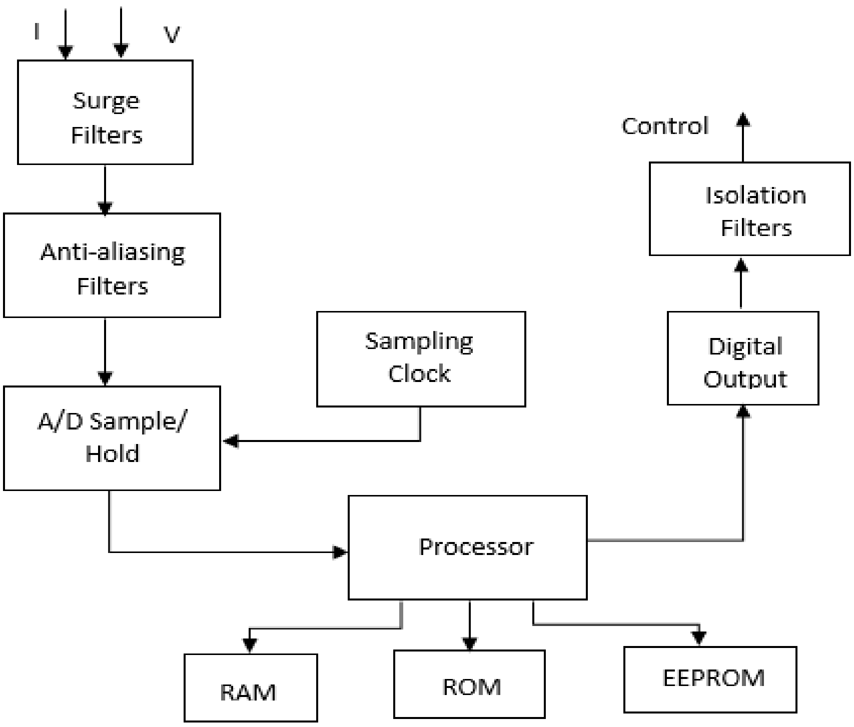


Figure 2-3: Functional Block Representing Numerical Relay Configuration [29]

Figure 2-3 shows the functional block representing numerical relay configuration. The current and voltage signals from the power system are processed by signal conditioners, which consists of analog circuits such as transducers, and surge suppression circuits. The sampling clock provides pulses at sampling frequency. A sample-and-hold circuit generally freezes the analog input signals, in order to achieve simultaneous sampling of all signals regardless of the data conversion speed of the analog-to-digital converter. The relaying algorithm processes the sampled data to produce a digital output [29].

2.7.2 The Protection Scheme

Electrical power systems generate power and redistribute the electrical energy to various load centres. Power systems protection schemes are designed to eliminate and clear faults in the network as quickly as possible. Their function is also to isolate the faulted area without affecting the whole power systems [22].

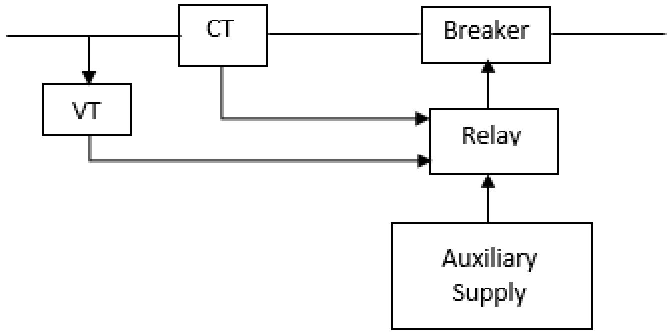


Figure 2-4: Basic Protection Scheme [24]

Figure 2-4 shows the basic protection scheme arrangement, which consists of a voltage transformer (VT), current transformer (CT), circuit breaker, and a relay. The CT measures the current on the primary coil and steps it down to lower voltages in the secondary coil making it more acceptable as input to the relay. The VT is used for voltage measurements and steps it down making it acceptable as input to the relay. The relay is a decision-making element in the protection scheme. It is triggered by current and voltage measurements obtained from CT's and VT's. The relay detects an abnormal condition that could potentially endanger the entire power system and then takes a preventative action [22]. The circuit breaker receives a trip signal from the relay to take the necessary action required to isolate a fault condition from the system and restore supply after the fault has been cleared [24].

2.7.3 Overcurrent Relays

An overcurrent is any current, which exceeds the ampere rating of conductors, equipment or devices under conditions of use. Unless removed in time moderate overcurrent's quickly overheat the system components, damaging insulation, conductors and equipment. Types of overcurrent protection schemes includes directional scheme, non-directional scheme, time grading scheme, current grading scheme or a combination of time and current grading scheme [31, 32]. Overcurrent relays are used for overcurrent protection. Directional relays are mostly used because they significantly lower fault-clearing times. Directional relays can be obtained by installing relays that can differentiate between short circuits in the forward and reverse direction [22]. Overcurrent relays are divided into three types, which are the definite-time overcurrent relay; instantaneous overcurrent relay and inverse-time relay [26].

2.7.3.1 Definite Time Overcurrent Relay

A definite time overcurrent relay operates after a predetermined time when the current exceeds its pick-up value. The operating time is constant irrespective of the magnitude of the current above the pick-up value. The desired definite operating time can be set with the help of an intentional time delay mechanism provided in the relaying unit [26]. This type of relay is normally used in situations where the power system fault current varies very widely due to changes in the source impedance, because there is no relationship between the change in time and the variation of the fault current [22].

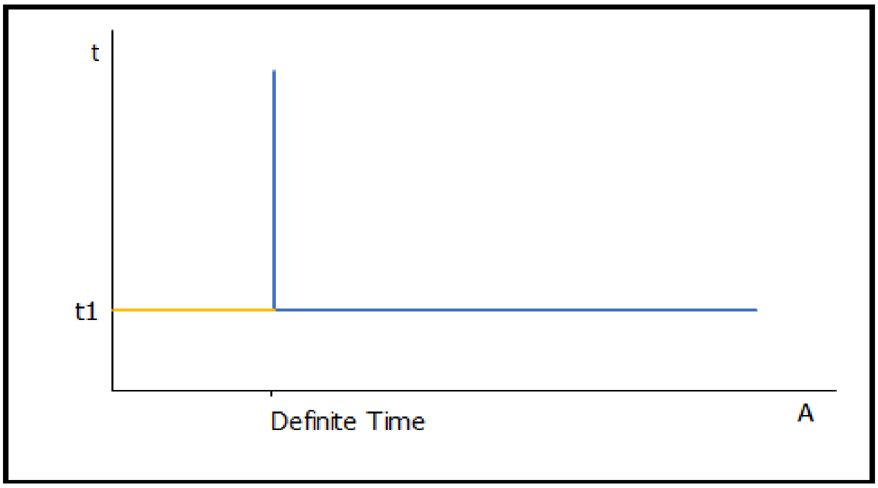


Figure 2-5: Definite time of overcurrent relay [32]

Figure 2-5 shows a definite time of overcurrent relay curve. Two conditions of operation must be satisfied in this relay i.e. the current must exceed the setting value and the fault must be continuous at least a time equal to time setting of the relay [32]. The definite time relay has lower operating times at the lower current values. The current settings in this relay are chosen such that relay does not operate for the maximum load current in the circuit being protected but does not operate for a current equal or greater to the minimum expected fault current [22].

2.7.3.2 Instantaneous Overcurrent Relay

An instantaneous overcurrent relay is a relay with no intentional time delay that operates when input current exceeds a pick-up value. In order to set these relays, pick-up current needs to be specified and CT ratio needs to be documented. Instantaneous overcurrent relay should complete their function every time input current exceeds the set point. When setting overcurrent relays it is necessary to specify pick-up setting and the CT ratio [22].

2.7.3.3 Inverse Overcurrent Relay

An inverse time overcurrent relay operates when the current exceeds its pick-up value. The operating time depends on the magnitude of the operating current and the operating time decreases as the current increases [26]. This type of relays are normally used in situations where the operation of the network includes high-level short-time overloads, magnetising inrush currents at switch-on may be considerable for several tenths of a second and where relay operation must be co-ordinated with a large number of fuses. Inverse time overcurrent relays are divided into four types:

(a) Very inverse overcurrent relay

$$t = TMS \times \frac{13.5}{I_r - 1} \tag{3}$$

(b) Extremely inverse overcurrent relay

$$t = TMS \times \frac{80}{I_r^2 - 1} \tag{4}$$

(c) Standard Inverse Overcurrent Relay

$$t = TMS \times \frac{0.14}{I_r^{0.02} - 1} \tag{5}$$

(d) Inverse definite minimum time (IDMT) overcurrent relay

Equations (3),(4) and (5) represents the mathematical definition of the curves in Figure 6-2 based on a common setting current and time multiplier setting of one second [22].

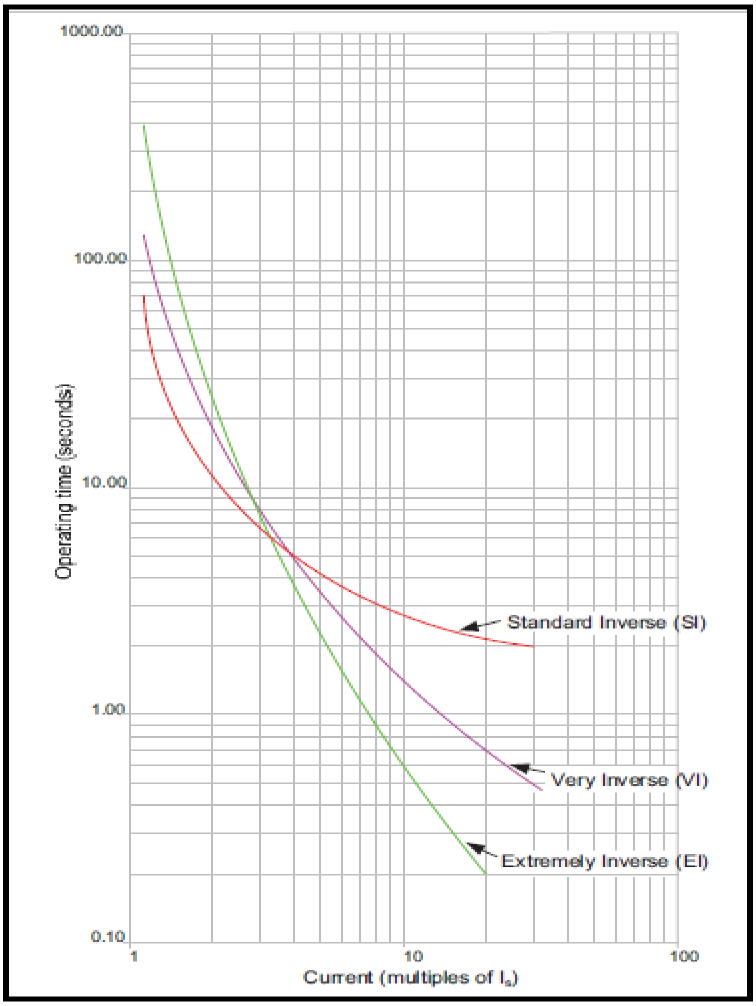


Figure 2-6: IEC 60255 IDMT Relay Characteristics, TMS = 1.0 [22]

The standard inverse (SI) curve indicated in Figure 2-6 is usually appropriate for most applications. If grading with other protection devices is not adequately achieved, either the very inverse (VI) or extremely inverse (EI) curves can be applied [22].

2.7.3.4 Very Inverse Time Overcurrent Relay

VI time overcurrent relay is generally employed in cases where the source impedance is much smaller than the line impedance [33]. According to the authors of [22] the VI operating characteristic are such that the operating time is approximately doubled for reduction in current from seven to four times the relay current setting. This allows for the use of the same time multiplier setting for several relays in series.

2.7.3.5 Extremely Inverse Overcurrent Relay

This relay application is mainly in electrical machines to protect them from overheating and restoring load after a fault condition occurred. Alternators, power transformers, earthing transformers, electrical cables and railway trolley wires are protected by the EI overcurrent relays. Alternators are protected against overloads and internal faults. This relay is also used for reclosing distribution circuits after a long outage [26].

CHAPTER 3: REVIEW OF THE EXISTING POWER SUPPLY AND UPGRADE REQUIREMENTS IN THE PORT OF DURBAN

3.1 Introduction

The electrical power supply to Durban Harbour is from EE's 33 kV Congella and Old Ford Road substations with 17 MVA capacity limit in each incomer due to infrastructure exceeding its design lifespan. The 33 kV voltage supply at the intake substations that is Durban Harbour Intake (DHI) Substation and Stanger Street Substation (STS) is stepped down and redistributed to 11/6.6 kV to supply Port operations and consumers in the Ports electrical network [7, 34]. The supply 300 mm^2 oil cable to STS and DHI were installed and commissioned in the early 1970's and 2003 respectively. The Port's historical load profile data revealed that the 17 MVA firm supply limit was exceeded during the Port's peak loading intervals in winter months. This compromises the reliability and firmness of the existing network and increases the likelihood of failure. According to the Port Master Plan, the Port has expansion plans and future developments that require additional load demand which is not available in the currently existing network. Electrical network system improvement that ensures a firm and robust network is required to cater for the additional load requirements. EE is also phasing out 33 kV as a distribution voltage to large power users [34, 35].

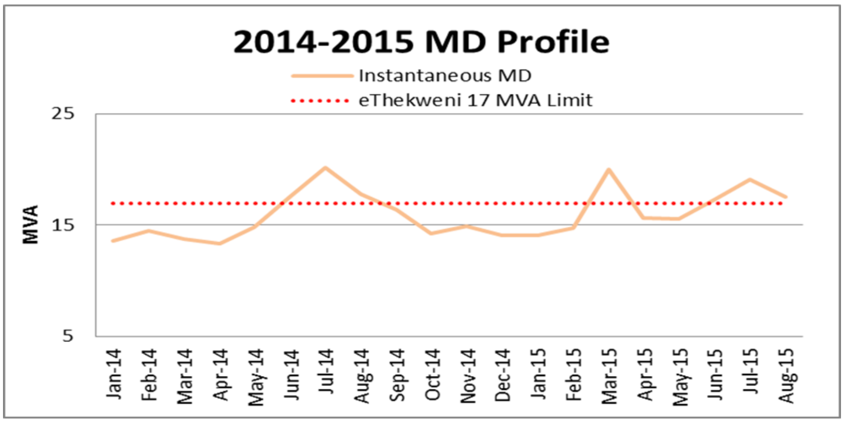


Figure 3-1: Historical Maximum Demand Load Profile for the Port [35]

Figure 3-1 is a graphical representation of the Port's historical instantaneous maximum demand load profile in comparison to the 17 MVA firm supply capacity from EE, which was exceeded during peak periods. The port network is under strain during the winter months due to high base loads caused by the refrigerated containers, which are imported/exported through the container terminals. These high demand peaks have resulted in the PoD reaching the 17 MVA capacity on the electrical network for extremely short durations of times [35]. An electrical power supply upgrade in the Port is required to strengthen and improve the electrical network and the proposed supply capacity from EE is 132 kV at a capacity of 80 MVA from their 132 kV Edwin Swales substation closest to the Port's proposed 132 kV outdoor substation site. The electrical upgrade includes the implementation of SCADA system and SAS for the new substation. This will enable the monitoring and control of the electrical network. This chapter evaluates the PoD's existing SCADA system, SAS and evaluates what considerations need to be taken into account for undertaking this upgrade [35].

Modern SCADA master stations are equipped with communications architectures that integrates hardware and software in distributed systems. The real-time data transfer between various viewing computers and servers is via the control centre's Local Area Network (LAN) platform. The SCADA system design in divided into three main components i.e. Master station or Control centre, Remote Terminal Units (RTUs) and communications. A Master station is for visually seeing the whole plant and is equipped with features and capabilities to view real-time data, plant state and perform functions of control and monitoring remote stations [36, 37]. All the acquired data from the whole system is collected and sent into the control centre for processing to be done. On completion of data processing, the control centre completes the task of issuing control signals to the required part of the system [38]. The Master station retrieves data required by substation equipment from remote station [37]. RTUs are connected physically with equipment such as switches, circuit breakers, etc. and they monitor and control these devices. The system HMI enables the user/operator to view the entire plant status through raised alarms and status indications. Alarms are automatically detected under equipment abnormal conditions that require operator's attention to acknowledge and resolve the conditions raising an alarm [38]. Modern communication protocols provides data integration between master station and remote station. The designs for SCADA systems should take into account capacity to allow the future automation of the operation of equipment to allow future substations growth and expansion of the electrical power system [39].

SASs are required to increase reliability and performance of electrical protection of circuits in substations, which will improve the efficiency of power distribution [39]. These mainly rely on automation software integrated via communications architecture to IEDs which receives and processes signals coming from high voltage equipment [40]. IEDs play a major role in the power systems protection because of the ability to identify the faulted area or abnormal condition in the network and isolate it as quickly as possible before any damage to the equipment is incurred [41, 42].

3.2 Supervisory Control and Data Acquisition Systems

SCADA systems functions are to monitor and control remote or geographically dispersed systems or plants. SCADA systems retrieves and stores data of the status of the entire plant or substation, indicates and displays areas with abnormalities for the user/operator to take action to normalize the network [36]. Due to that, electrical systems are growing at a rapid rate with power plants interconnected with the power system substation. The real-time data obtained from the SCADA system is essential for the plant operation as the user/operator can easily execute supervisory commands [37]. It also enables the operator to execute supervisory commands. In order to allow for future substation growth, expansion and the inclusion of new application functions, SCADA systems should be designed to have sufficient capacity. This will ensure that there is sufficient capacity for adding more equipment via the primary feeders in the substation [39]. Modern communication protocols integrate with IEDs for efficient equipment status monitoring and control during abnormal fault conditions SCADA systems enables the user/operator to easily identify the fault location in a complex electrical network, which improves plant productivity and reduces maintenance costs [36]. SCADA systems consists of the following main components [43]:

(a) Multiple RTUs, which are numerical relays.
(b) Communication channel infrastructure.
(c) Master station and HMI Computers.

Medium voltage electrical networks, building air-conditioning, standby generators and SMART energy metering systems are monitored on the SCADA system.

Figure 3-2: Geographically dispersed electrical substations monitored on the PoD's SCADA system [44]

The PoD has several 33 kV substations and air conditioning plants that are monitored and controlled on the SCADA system. Figure 3-2 is a map displaying various substations that are monitored and controlled on the Port's SCADA system. The numbers on the map are explained as follows [44]:

(a) 1 denotes the 6.6 kV Sand Bypass Substation.
(b) 2 denotes Ocean Terminal Building air-conditioning plant.
(c) 3 denotes the 33 kV incomer STS supplied from EE's Old Fort Road substation.
(d) 4 denotes the 33 kV incomer DHI supplied from EE's Congella substation
(e) 5 denotes the Port's 132 kV proposed substation located at Langeberg road.
(f) 6 denotes the 33 kV Pier 2 Substation which supplies the Durban Container terminal which is the load centre in the Port.
(g) 7 denotes Allan Dalton substation (AD) 33 kV Substation.
(h) 8 denotes Pier 1 33 kV Substation.
(i) 9 denotes the Fynnlands 33 kV Substation.
(j) 10 denotes the Millennium Tower that is utilised to navigate the ships entering the Port.

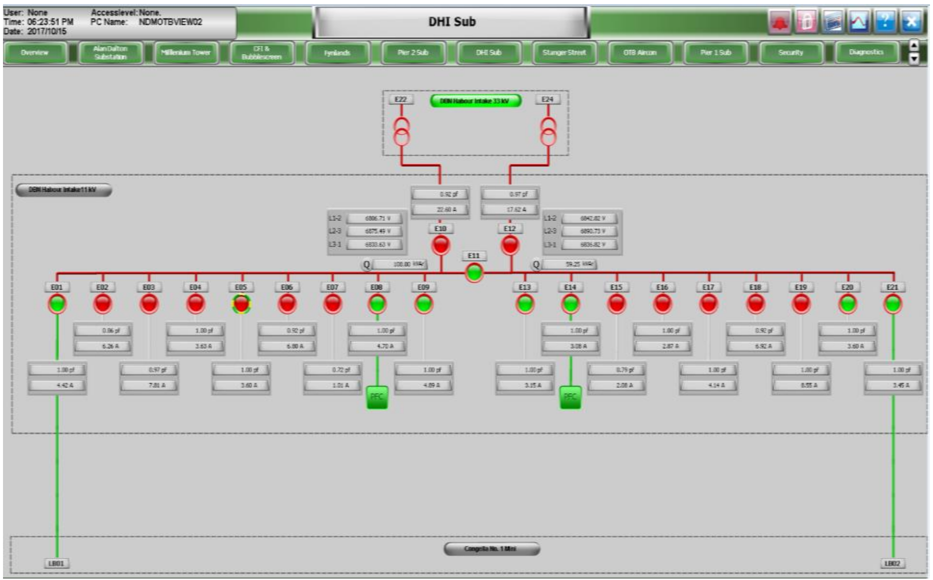


Figure 3-3: Substation Electrical Network Reticulation [44]

Figure 3-3 represents SCADA view showing 33 kV DHI intake substation electrical network model with the 17 MVA firm capacity that is stepped down to 6.6 kV and redistributed to various Port consumers. The real time power factor values, bus bar voltages and currents on each feeder are displayed. From this, it is easy to identify the status of the network and easily retrieve network parameters or data. The Operator is able to perform operation functions in this view such as opening or closing of circuit breakers, applying earths etc. The PoD's SCADA platform is ArchestrA systems platform that is mainly used for industrial applications and provides features for configuration, data deployment, cyber security, communications protocols, data management and storage. The system platform is equipped with high performance historian process that archives and keeps records of production history [45].

3.2.1 SCADA Architecture

It is very crucial that the system's physical architecture is clearly defined. In order to support the specified functionality it is important that the servers and IEDs are physically connected via Ethernet platform. The integration of the IEDs into a system architecture is achieved by the interconnection of IEDs, servers, workstations and communication interfaces [36]. Modern SCADA systems designs are equipped with communications architectures that enable interoperability of different system. SCADA systems designs can either Centralized or a Distributed architecture. The master station is the focal point for SCADA, which performs the supervisory control and data acquisition as well as display, logging, data processing and archiving functions used mainly for operations. Master station serves as an information gateway to the utility enterprise [36]. The SCADA architectures systems are used based on application requirements and availability objectives [39].

(a) Centralized Architecture: this configuration is for less complex applications, which entail distribution network monitoring and control functions. In this design configuration, the operator functions and displays are on redundant hardware platform [36, 39]. Hardware maintenance is cheaper since there are few computers [36].

(b) Distributed Architecture: this configuration is used in complex applications demanding more extensive data processing and availability requirements. This configuration utilizes multiple network servers to allow for redundancy and increase capacity availability for additional servers. This configuration has the functionality to allow different operating systems to be used for different applications [36, 39]. The server platform is responsible for all substation communications functions and all processing functions. In advanced distributed systems the applications software run on multiple computing platforms [36].

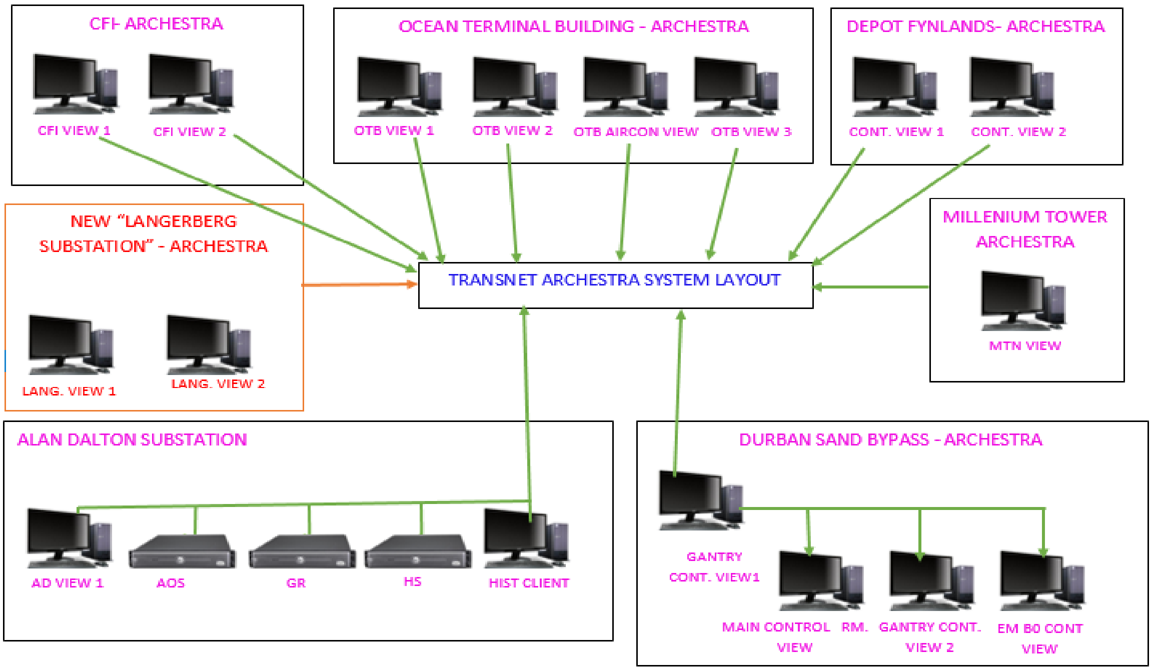


Figure 3-4: PoD's SCADA Architecture [46]

Figure 3-4 shows the ports existing distributed SCADA architecture. Currently there are six monitoring and control stations i.e. Sand Bypass system, Millennium tower, Alan Dalton substation, Depot Fynnlands, Ocean terminal building and fire fighting system (CFI). Alan Dalton is the main viewing and control station that is equipped a galaxy repository (GR) server, applications object server (AOS - standby) and the historian server. GR is a windows service that manages the development and deployment of the application. Historian server provides process data historisation, alarm, and event logging for application server. It exposes the data through SQL server/ open data interface [39, 46, 47]. The historian client view is a collection of tools to access the historical data in a historian server. It includes a feature-rich Trend application, a Query application that allows the construction of SQL queries through a point, click interface, and report generation through add-ons for Microsoft Excel and Word [39].

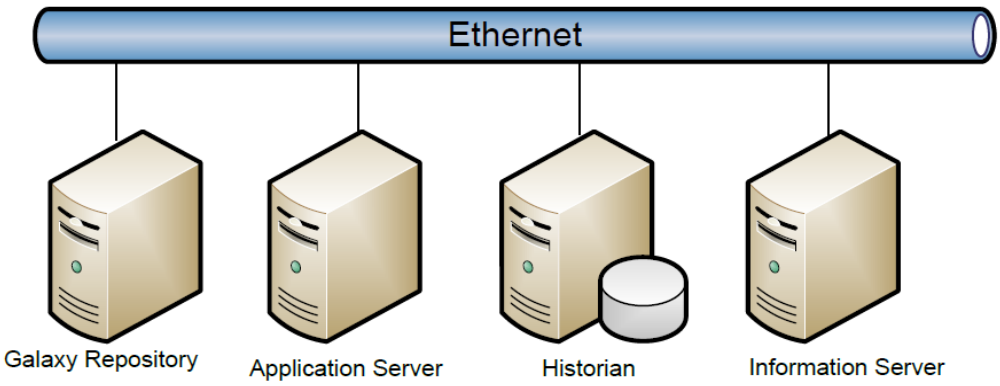


Figure 3-5: Overview of the Port's system architecture [46, 47]

Figure 3-5 represents an integrated Wonderware systems platform architecture, which is via Ethernet platform. This design configuration allows for electrical network expansion and is developed and implemented on the ArchestrA software [48].

3.2.2 Communications

Master stations utilize communication protocols to retrieve data from IED, RTUs and Gateways for data acquisition functions in substations. SCADA systems design primary requirement is the ability to acquire quality data at a high speed [39]. The PoD's SCADA system utilises fibre optics for network communications applications. The main advantage of using fibre optic is its ability to provide high bandwidth with excellent signal-to-noise ratio (SNR). It is mainly for long distance applications due to high performance data networking ability and is less susceptible to electromagnetic fields [49, 50]. The entire LAN in the Port is monitored by the SCADA system. In the event where there is loss of communication in the network or remote stations, the SCADA system will not be able to retrieve data from the IEDs in the affected remote stations [44].

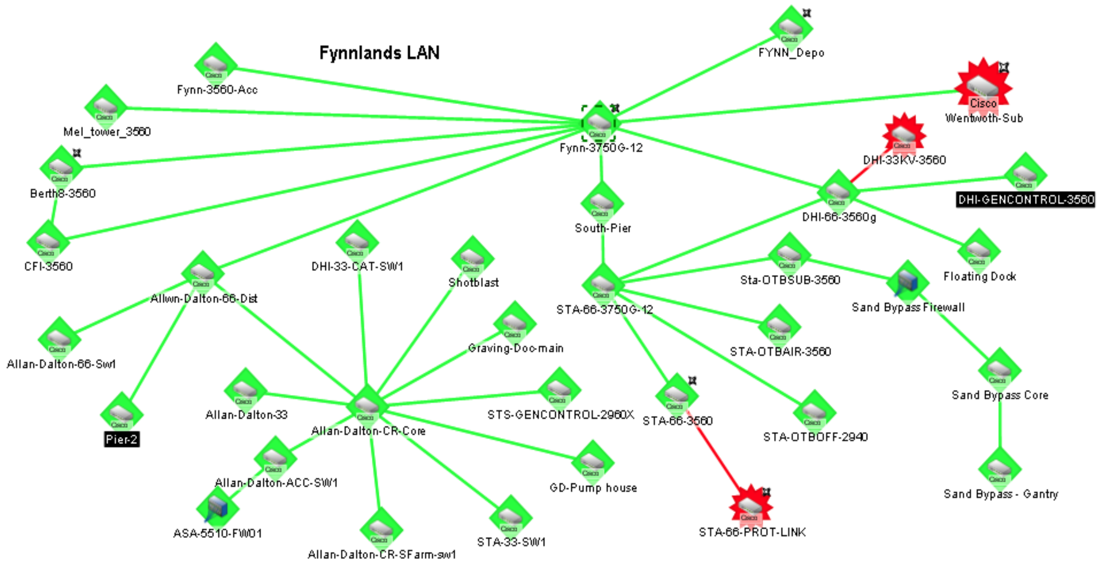


Figure 3-6: PoD's Communication Network for substations [44]

Figure 3-6 represents the PoD's communication network status for all the substations in the network. The substations are interconnected via fibre optic cable and network switches. Under normal operating conditions fibre optic cables and network switches are indicated in green colour and indicated in red under abnormal conditions when communication is lost. This SCADA view enables the operator the quickly identify the faulted area in the network and reduces fault finding duration [44, 45].

3.2.3 Performance

Availability, maintainability, performance, security and expandability are the most important aspects of SCADA system design.

(a) System Availability: this is measured according to the availability of system functions. This is purely dependent on the reliability of both the software and hardware. To ensure high availability and continuity of the system, redundancy is provided. In modern SCADA systems, most computers are connected to a redundant LAN and in a case where one computer fails, all communications will switch over to the remaining computer. The most critical computers are doubled so that in case of hardware or software failure, the other one will take over the processing [36]. The SCADA software should be able to operate in different hardware or software platforms to avoid dependency to a specific manufacturer [39].

(b) System Maintainability: maintainability is a very crucial factor of system availability as this minimizes repair times for hardware or software failures if the system provides good diagnostic tools. It is of great importance that preventative maintenance, system debugging, corrections, updates, tests and enhancements are conducted without affecting the performance of the system [36].

(c) System Performance: in a SCADA system, the desired response time for each function should be determined. Response time is the amount of time it takes from the instant a function is requested until the instant the outputs from this function are available. Power system operation and control procedures should comply with response times. In a control centre, response time is categorized into critical and non-critical functions. The operating conditions for a power system can be in either normal state or emergency state. In a normal state the power system's load and operating constraints are satisfied. In this state, the system's basic control and performance are met. In an emergency state of a power system the response time is very slow, operating constraints are not satisfied, status changes and measurement variations are very high [36].

(d) Expandability: is the ability to add new functions or equipment to the power system and the amount of down time required without difficulty [39]. The following are expandability limitations considered [36]:

    (a) Available physical space.
    (b) Power supply capacity.
    (c) Heat dissipation.
    (d) Processor throughput and number of processors.
    (e) Memory capacity of all types.
    (f) Point limits of hardware, software or protocol.
    (g) Bus length, loading and traffic.
    (h) Limitations on routines, addresses, labels or buffers.
    (i) Unacceptable extension of scan times by increased data.

3.2.4 Primary and Backup Systems

It is important that the designed system is equipped with both primary and backup system to ensure that data is secured in the event of a software or hardware failure to maintain continuity in the system functions and prevents data loss. The use of multiple servers allows for system redundancy as one server is in active mode performing all the system functions while others are running offline as backup. The backup system is equipped with a processor whose function is to monitor the status of the primary system and quickly assumes this role in the event of a system failure [39].

3.3 Substation Automation Systems

The IEDs are designed to have multiprocessor functions to send and receive data from other devices or Master station. The IEDs accepts inputs and processes them using logic systems to develop outputs addressed to make decisions resulting in a trip command or alarm signal. SAS is the ability to perform control functions to devices in various areas of a power system in remote mode [36, 51]. The PoD's SAS utilises GE Multilin F35 feeder protection relays as a standard IED which retrieves and displays data of equipment status, active power, bus bar voltages and currents. These also have internal failure self-monitoring functions.

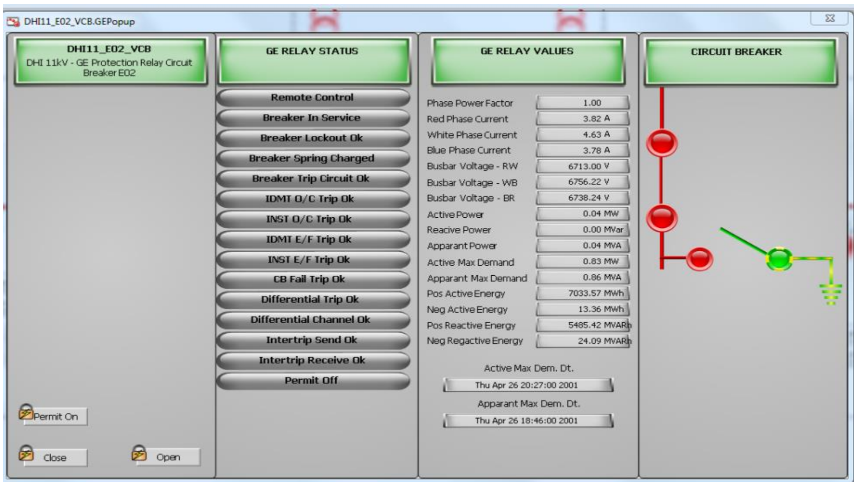


Figure 3-7: Substation incomer feeder protection relay status [44]

Figure 3-7 is the substation incomer feeder protection relay status SCADA view at DHI 33 kV substation. The busbar is live with circuit breaker is in its closed state and the earth switch is opened. The relay values such as the active power, reactive power, bus voltages and currents are also displayed. [44]. Substation Integration System (SIS) is essential to perform simple or complex automatic functions in SAS. The integration of SCADA systems and IEDs communications protocols allows for data acquisition and control [41]. The SAS obtain plant data that enhances the plant operations, maintenance planning and execution, and system status monitoring in order to optimise the effective utilisation of the equipment [52].

Substation automation consists of the following main elements [36]:

(a) HMI - this is a hardware interface, which runs software that creates graphics on video display. SCADA HMI allows operators to view the state of any part of the power systems plant equipment by means of alarm indicators. Alarm detection occurs under abnormal conditions in the plant equipment and requires operator's attention or intervention for the power system to keep running smoothly [38].

(b) RTU – is equipped with hard-wired inputs or outputs that connects substation equipment such as IEDs, Ethernet switches etc. for functions of control and monitoring [38]

(c) Data Concentrator – main objective is to retrieve information from all substation IEDs so that it can be visually displayed on the SCADA system.

(d) Remote Access Controller – this device has a functionality to access the IEDs remotely for configuration and data retrieval.

(e) SIS – this systems ensures integration between the IEDs, SCADA and local HMI for data sharing and display for effective running of the plant [48].

3.3.1 Substation Automation Design Requirements

Figure 3-8 shows the four levels to be considered for substation automation design. Level 0 represents the IEDs that need to selected to ensure compliance and compatibility with IEC 61850 standard. Level 1 is consideration for substation LAN platform for data flow. Level 2 is the substation RTUs interfaced with the SCADA system and physically connects substation devices for information sharing and storage. Level 3 entails development of the communications architecture for that to be displayed on the SCADA system [39].

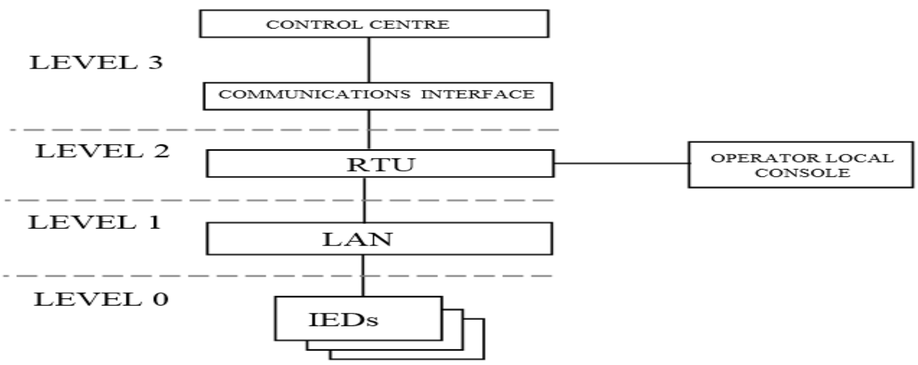


Figure 3-8: Substation Automation Hierarchic Levels [39]

3.3.2 Selection of IEDs

It is of great importance that functional requirements are determined prior the selection of IEDs. The selected IEDs should be compliant to IEC 61850 standard and possess features of interoperability with various devices implemented in the communications architecture [36]. The use of IEDs improves the operation and service of automation systems as they reduce the cost of automation and integration [36]. For functional requirements, the following have to be considered:

(a) Effects of equipment maintenance on critical data.
(b) Provision to view I/O value and state.
(c) Provision to view point mapping.
(d) Processing time for the parameters present at IED inputs to be available as parameter at the communication part. For each equipment item and all applicable data types data processing capabilities shall be defined.
(e) Ease of automated data retrieval and centralized storage of trends, events, disturbances and faults for IEDs.
(f) Input power requirements when IED will be placed on the DC system.

The RTUs obtain notifications and real time analog and digital data from the IEDs and stores the information on the RTU database. This information is therefore processed and sent to the control centre to be displayed on the SCADA system. RTUs are capable of the following information related to IEDs [39].

(a) Know each IED address.
(b) Know the alternating communications routes with each IED.
(c) Know which IED can be used to carry out a specific function.
(d) Know the state of all the IEDs connected
(e) To synchronize the time of all the IEDs connected.
(f) To have access to the IEDs sequence of events storage.

3.3.3 Human Machine Interface

A HMI is an interaction between human and a technical process for control purposes. HMI is a computer based interface that enables the operator to view the entire plant status to perform operation functions [39, 64]. The HMI provide features that include report generation from any historical or real-time measurement or status point, log files, links to documentation, help files that are context sensitive, multiple users, multiple security levels, symbol template, symbol libraries, multiple protocol support, printing etc. [7].

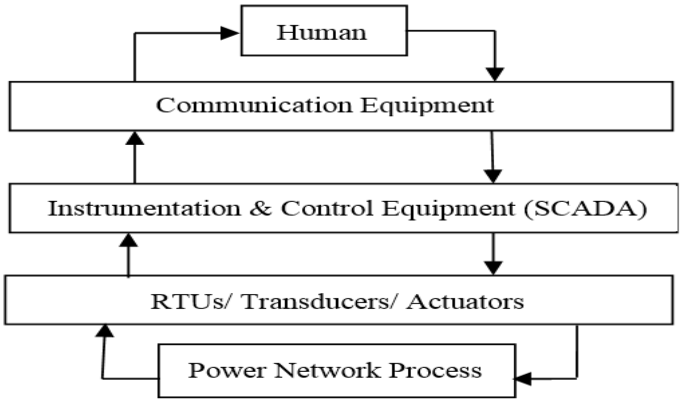


Figure 3-9: HMI flow diagram [39]

Figure 3-9 shows the flow diagram for human machine power interface. The computer system at the control centre integrates with RTU over the communication link with its transmission protocol, acquires the remote substation a data and transfers the same to the computer system [38]. The PoD's HMI graphic system is designed to be self-explanatory with clearly written English language messages indicating the available options within the specific graphic screen to the operator. All graphic objects are represented in a simple 2–dimensional fashion. Graphic screens are configured using the following configurations [45]:

(a) Plant overview to assist the operator with an overall understanding of the areas of the plant that are to be controlled.

(b) Simplified block diagram to illustrate sequences, interactions and selected options.

(c) Diagrammatic representation of the process equipment using predetermined symbols to represent the various equipment.

(d) Process and instrumentation Diagram (P&ID) using recognized instrumentation and electrical symbols.

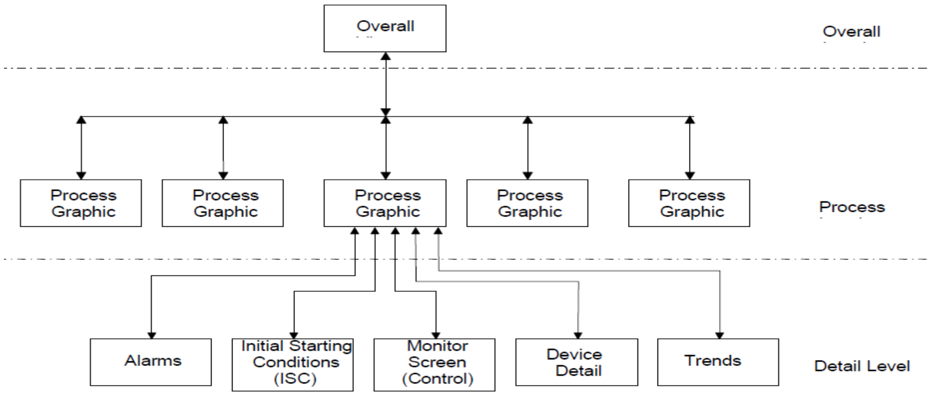


Figure 3-10: Graphic Screen Tree Hierarchy [45]

The plant hierarchical structure is limited to three screen levels as shown in Figure 3-10. Overall level is the banner, navigation area and process overview screen. Process level is the main process mimics.

Detail level is the pop-up screens, which consists of the following [44, 45]:

(a) Detailed equipment mimics (zoom).

(b) Initial Starting conditions (if applicable).

(c) Monitor control screens (if applicable).

(d) Alarm display.

(e) Alarm histories – list of previous and active alarms.

(f) Trend displays.

(g) Device detail pop-up screens.

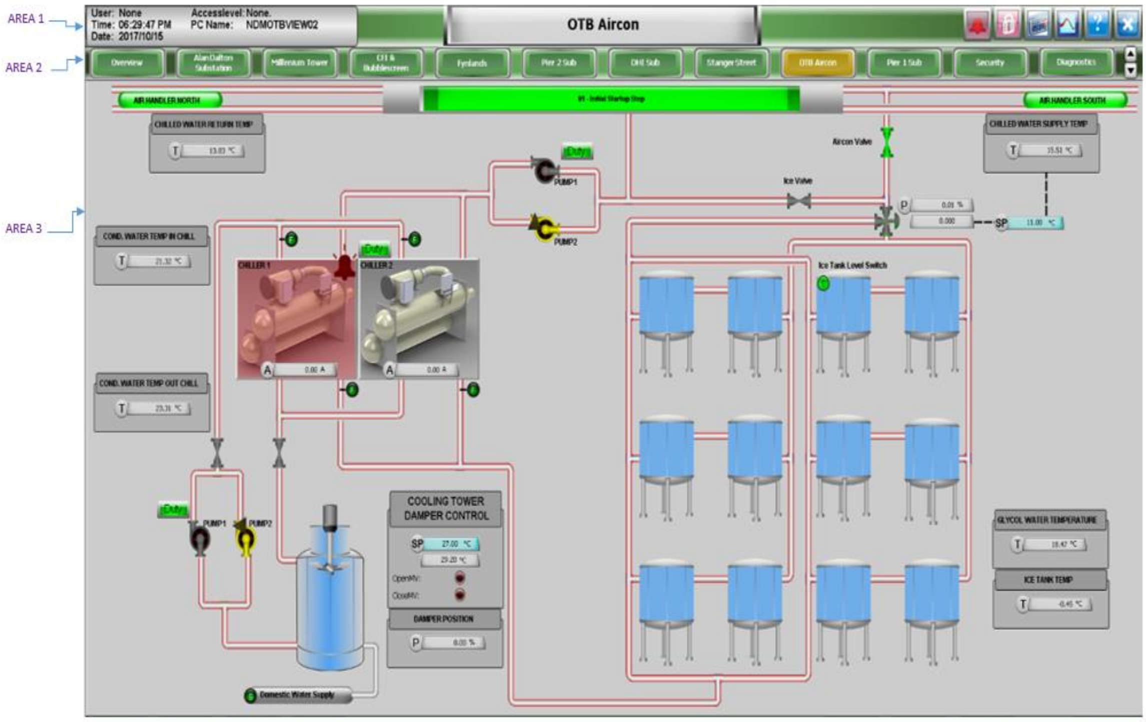


Figure 3-11: Application Graphic Screen Layout [44, 45]

Figure 3-11 shows the application graphic screen layout for the air-conditioning plant in the Port. This screen is categorised into three sections i.e. Area 1, 2 and 3. Area 1 is for display and general command buttons, area 2 direct screens request navigation buttons for various control and viewing stations. Area 3 is the graphical view of the plant model which is a representation of the real life system [45].

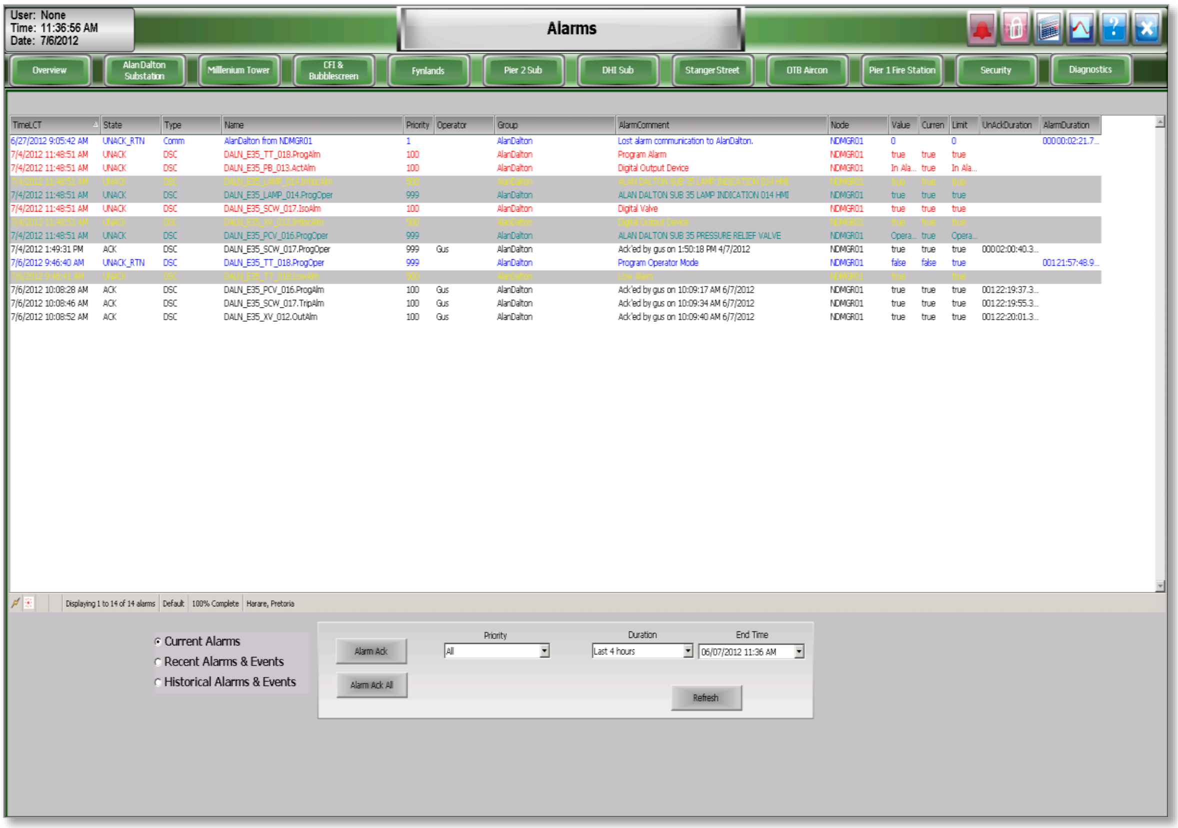


Figure 3-12: Alarm Screen Display [45]

Figure 3-12 shows the alarm pop-up screen display on the PoD's SCADA view. The alarm screen displays current active alarms or short-term history alarms. Different filters can be selected for alarm priorities, acknowledged, unacknowledged or all alarms [45].

3.4 Security requirements

It is essential to have an effective SCADA security system to prevent unauthorised access users from making any changes to the plant. The design of the Port's SCADA system i.e. ArchestrA galaxy security records and audit all the alarms and events that occurred while the user was logged on to the system. The security requirements that should be considered are the following [43]:

(a) Access Control: for protection from unauthorised users, access to selected devices and information should be restricted [36, 45]

(b) Use control: control use of selected devices, information or both protect against unauthorised operation of the device or use of information [36, 45].

(c) Data Integrity: ensure integrity of data on selected communication channels to protect against unauthorised changes [36, 45].

(d) Data Confidentiality: Ensure the confidentiality of data on selected communication channels to protect against eavesdropping [36, 45].

(e) Restrict data flow: restrict the flow of data on communication channels to protect against the publication of information to unauthorised sources [45]
(f) Timely response: respond to security violations by notifying the proper authority, reporting needed forensic evidence of the violation and automatically taking timely corrective action in mission critical or safety critical situations [43, 45].
(g) Network availability: ensure the availability of all network resources to protect against denial of service attacks [36, 45].

Port's SCADA system security is categorised into six privilege levels [45]:

(a) None: is a default start-up mode that does not have control privileges and is mainly for only viewing or read only capability [45].
(b) Operator: access, monitors and controls all the areas of the entire plant for daily system operating functions [45].
(c) Supervisor: is similar to the operator level with additional operating functions that have restricted access [45].
(d) Maintenance: is similar to functions of operator and supervisor level options, with an added function to conduct maintenance related options [45].
(e) Specialist: is a privilege level similar to functions of operator supervisor and maintenance level options, with an added functionality to perform PID settings, set points and related options [45].
(f) Administrator: is a privilege level that enables the user to access to all levels of the system, can make changes in the system perform administrator functions [45].

3.5 Electrical Power Supply Identification

In order to prevent uninterrupted loss of power to SCADA equipment in a substation, all equipment associated with substation automation should be powered from isolated and dedicated electrical supply circuits. These circuits can either be DC/AC and it is of great importance that they are isolated from all other facility loads and clearly labelled as critical equipment that should never be disconnected. DC batteries are used to back-up AC power. Alarming to indicate loss of either source should be provided by this equipment [36].

3.5.1 Electrical Power

The electrical power interfaces to control and data acquisition equipment shall meet the following requirements [36]:

(a) The AC source may originate directly from the station source from a regulating/ uninterruptible power supply. AC power sources require being able to operate successfully over a minimum range of 80% to 110%of rated voltage and frequency.
(b) The nominal AC voltage rating shall be 220 V – 240 V at 50 Hz.

(c) Equipment on DC source shall not sustain damage if the input voltage declines below the lower limit specified or is reversed in polarity. DC power sources shall be able to continuously withstand the maximum design voltage.

3.5.2 Redundant Power Sources

Some substation devices are fitted with power supplies that operate nominally from station AC service but provide internal DC backup supply from the substation DC battery or a dedicated storage battery. For specifying dedicated batteries, the following considerations should be specified [36]:

(a) Duration of backup power operation without battery charging i.e. not less than four hours but not exceed twenty-four hours.

(b) Longevity of the battery sources as estimated by its shelf life on charge.

(c) Temperature range over which the battery will maintain required voltage and current capabilities.

(d) Replacement interval for backup batteries.

(e) Precautions of possible corrosive material spill/seepage and explosive gas accumulation.

(f) Recovery time of the backup battery after a full discharge.

(g) Alarming for failure of either power supply.

3.6 The integration of 132 kV Substation (Langeberg) into the PoD's Electrical Network and SCADA System

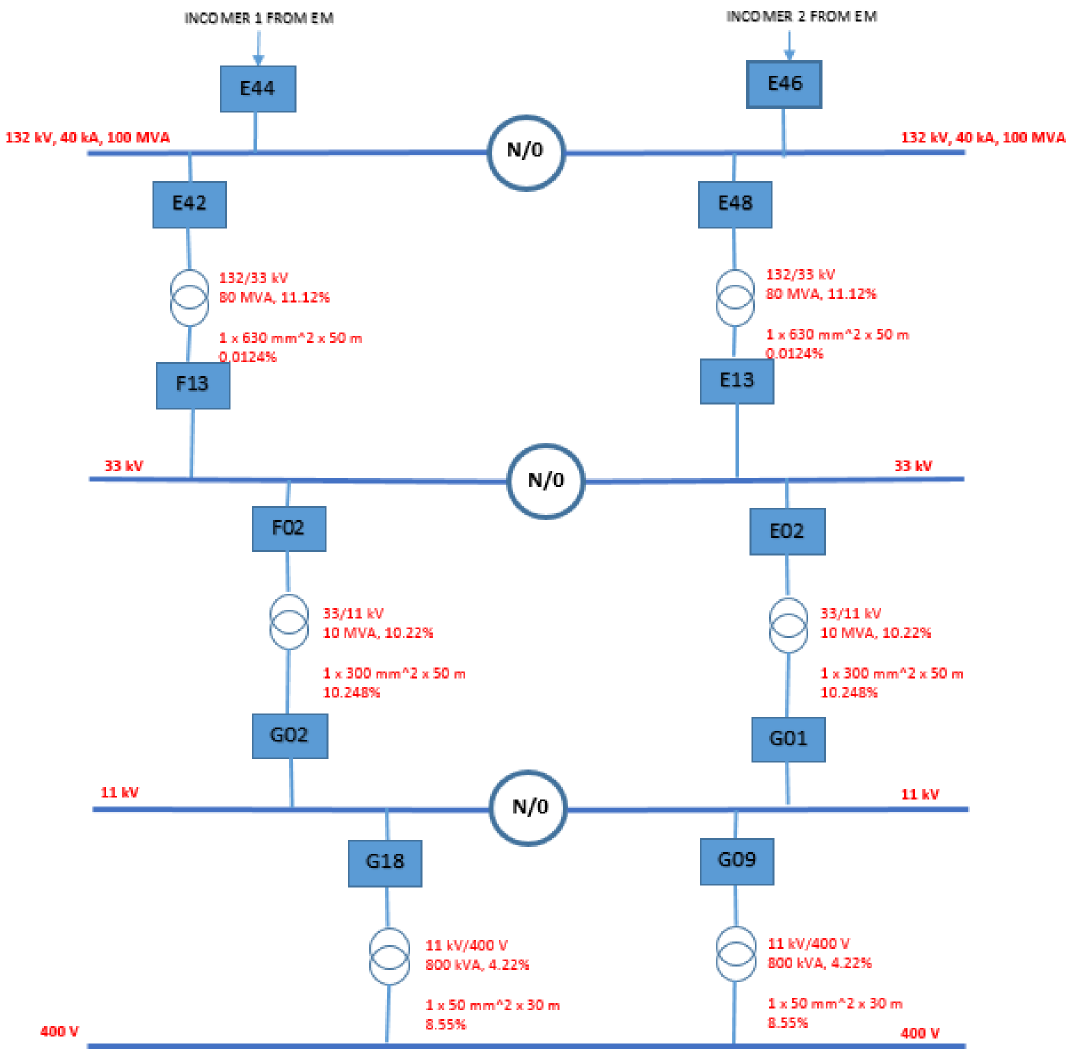


Figure 3-13: PoD's new 132 kV Langeberg Substation Reticulation [7]

Figure 3-13 represents the proposed electrical reticulation network for the new 132 kV Langeberg Substation supplied from EE's 132 kV Edwin Swales substation that will be integrated to the currently existing 33 kV Port electrical network. The electrical reticulation consists of the following equipment [35, 53]:

(a) 2 x 132 kV, 100 MVA 500 mm^2 XLPE aluminium incomer cables rated at 40 kA.

(b) 2 x 80 MVA 132/ 33 kV transformers.

(c) The new 33 kV network will be linked to the ports existing 33 kV network via DHI, Alan Dalton (AD) and STS substations.

The IEC 61850 standard will be used as a guide to develop the modern SCADA systems and SAS design which will be equipped with IEDs that will enable effective functionality for power systems protection, monitoring and control [53, 64].

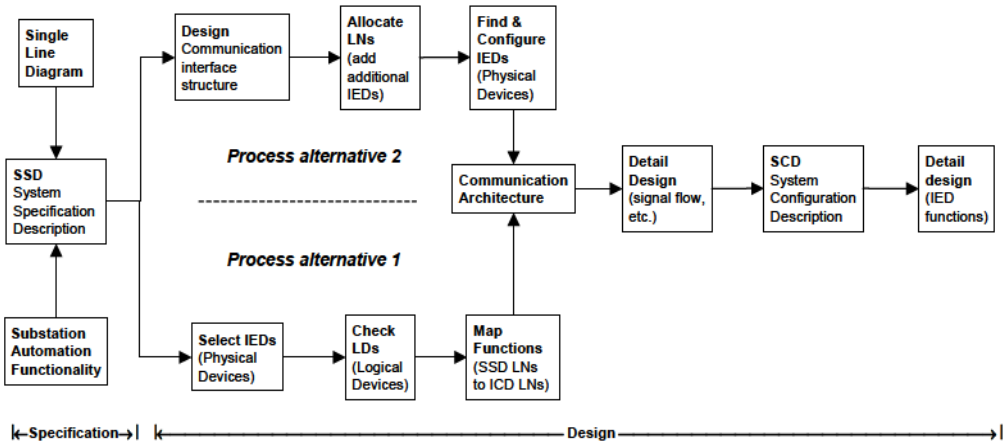


Figure 3-14: Design Process Steps [55]

Figure 3-14 represents the typical design process steps that are considered when developing the utility's specification that incorporates the IEC 61850 standard features [54]. The design process begins with a clearly explaining the system specification with respect to the IEC 61850 standard. The selection of the IEDs is done to ensure correct grouping of Logic Nodes (LNs) satisfy availability and safety criteria. Cost effective communications architecture for integration of IEDs is designed in accordance to the IEC 61850 standard. The system design functionality allows for spare capacity for future additional IEDs, features for redundancy and interfacing of IEDs [54, 55]. This design approach is useful for large number of IED types available and allows for easy configuration [54, 55].

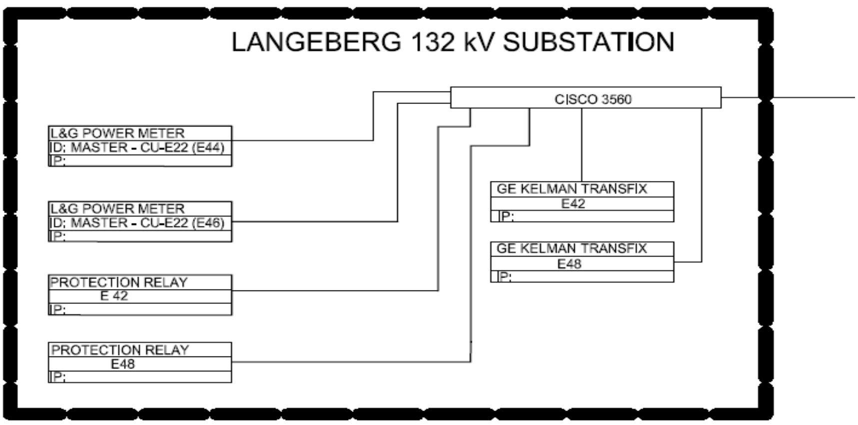


Figure 3-15: Network and protection communications layout for the new 132 kV Langeberg Substation [53]

Figure 3-15 shows the proposed protection and network layout for the 132 kV Langeberg substation that will be integrated to the currently existing network.
This layout entails Landis & Gyr (L&G) energy meters for incomers, feeder protection relays and transformer monitoring units. All these will be connected to the network switch (CISCO 3560) via Ethernet and be assigned with Internet Protocol (IP) addresses. Communications between devices in the Ports network will be achieved [53].

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Introduction

This chapter presents the description of the research process. It provides information concerning the methods used to undertake this research. This chapter describes various stages of the research, which includes literature review conducted, review of PoD's power supply and upgrade requirements, load flow studies conducted, implementation of SCADA and Automation systems. Furthermore, this chapter entails an overview of the hardware protection relays and their communication protocols used for protection system implemented. Figure 4-1 shows the block diagram of the methodological followed to undertake this dissertation.

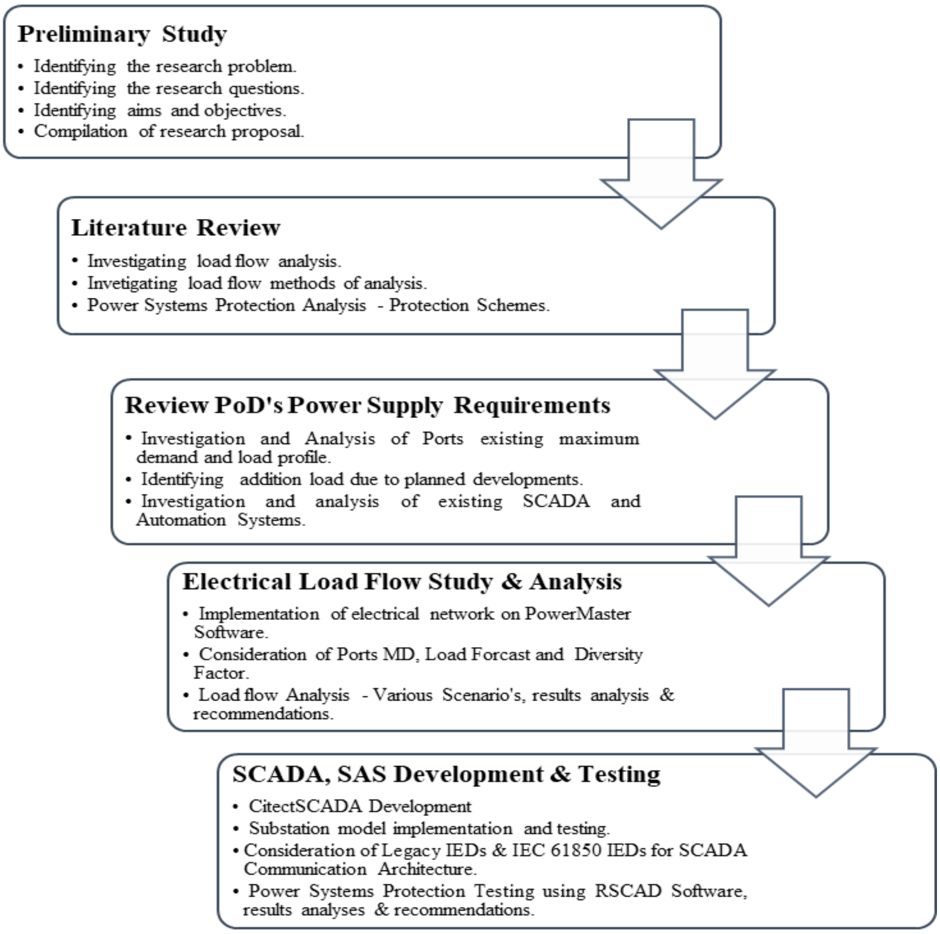


Figure 4-1: Methodology Block Diagram

Figure 4-1 represents the methodology block diagram that was used in this project. The preliminary study is the initial stage of the research development and it entails identification of a research problem, research questions, aims and objectives. Various literatures on load flow analysis and power systems were reviewed. A review of the PoD's existing power supply and upgrade requirements was done in order to identify and analyse the PoD's Maxim demand, obtain additional load required by planned development and analysis of the existing SCADA and

Automation system. An electrical load flow study was conducted using PowaMaster software in order to evaluate the impact of the additional loads on the existing electrical network. Schneider CitectSCADA software was used to develop a 132/33 kV substation model for monitoring and control of the electrical network.

4.2 Software

In order to address the research questions discussed in Chapter 1, PowaMaster software was utilized to undertake the load flow study analysis of the electrical network and Schneider CitectSCADA software was used to develop a SCADA and Automation System for monitoring and control of the 132/33 kV substation.

4.2.1 PowaMaster – Electrical Analysis Software for Transmission & Distribution Systems

PowaMaster is a simulation tool or system that is ideally suited for transmission and distribution networks, substation design and building services applications. It is a PC based program, which runs on the Microsoft Windows operating system. It provides features for the modelling of balanced, meshed electrical networks by representing the electrical network and equipment in an intuitive user-friendly manner. It also enables the user to model any electrical network easily, quickly and efficiently.

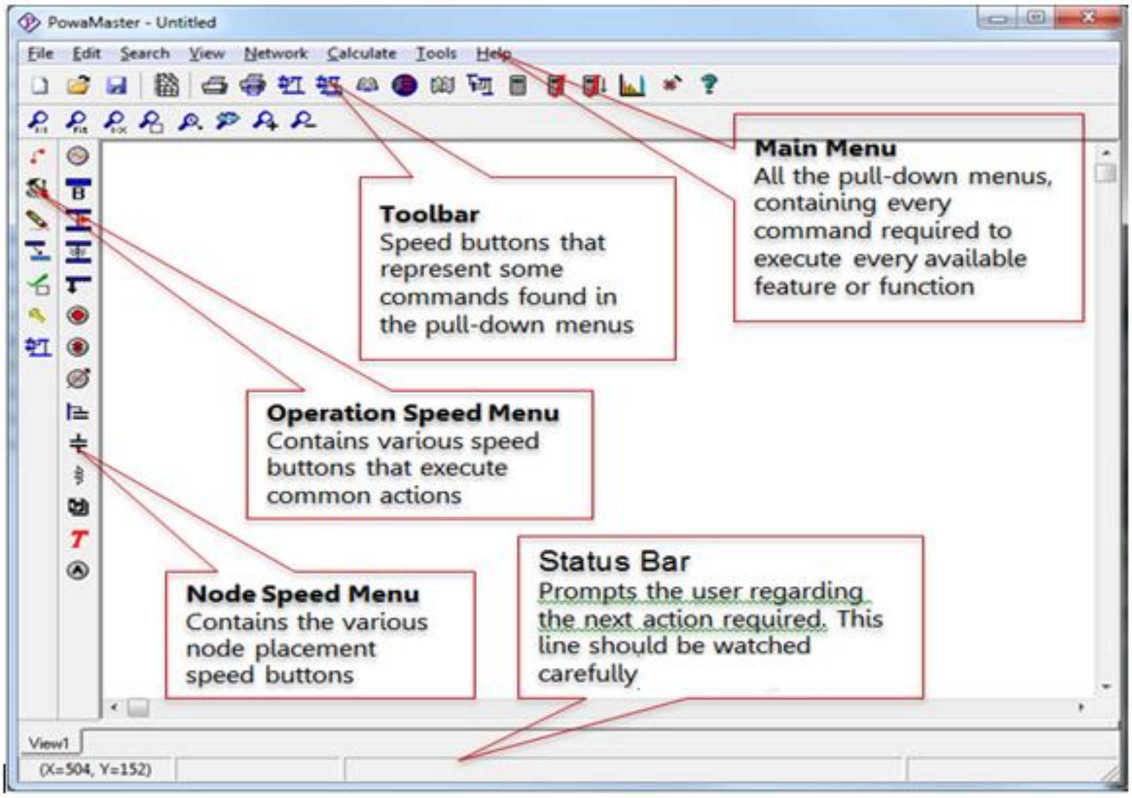


Figure 4-2: PowaMaster Graphical User Interface

Figure 4-2 represents the PowaMaster Graphical User Interface that provided a canvas on which the network was designed. The Main Menu consists of all the pull down menus containing every command required to execute every available function. The Toolbar allowed the user to perform functions such as invoking the load flow, Fault Calculations and viewing the User Reports. The network was manipulated by using the Operations Speed Menu and the layout of the network was manipulated by using the zoom functions. The network elements were placed using the Node Speed Menu. The Status Bar was constantly monitored to check the next action required.

4.2.1.1 Electrical Load flow Study Process Flow

The PoD's Planning Department was consulted in order to identify the planned developments and expansion projects as listed in the Port Electrical Master Plan that required additional loads and their years of execution. This information was vital because the additional load was going to have an impact in the Port's existing electrical network. The information gathered was used to perform load forecasting which plays a huge role in determining the required future load demand, network reconfiguration and infrastructure development. The planned developments and expansion plans require additional load demand which is not available in the currently existing electrical network. Based on the required load demand requirements equipment selection calculations were done i.e. Transformers and Cables as explained in detail in Chapter 5.

The PoD receives its Power Supply from EThekwini Municipality at 33 kV via the Port's two main intake substations each with a capacity limited to 17 MVA. The PoD's electrical network sustains revenue-creating operations; therefore, it is imperative that there is sufficient capacity and reliability of power supply to the PoD. The Ports' SCADA and Billing systems were interrogated in order to obtain information on the Ports yearly Maximum Demand and Load Profile. From the information gathered it was evident that over the years the load growth in the Port has been increasing however, the supply capacity was never upgraded resulting in the existing power supply being under threat. It was evident from the load profile curves that during winter season the 17 MVA firm capacity was exceeded which compromises the existing network reliability and firmness.

For system strengthening and enhancement, the Electrical Load Flow Study was conducted using PowaMaster Software to improve reliability and increase the electrical supply to and within the port ensuring a firm and reliable electrical network. The load flow study was also to verify if the selected equipment will be suitable for the projected load growth and that was investigated by considering six network configuration scenarios. The network configuration scenarios considered the load forecast for a period of 5 years, 7 years and 10 years as described in Chapter 5. The behaviour of the PoD's electrical network was analysed post implementation of the new substation onto the currently existing network as part of the strengthening option due to planned development projects that are planned to be commissioned between 2017 and 2027.

4.2.1.2 Electrical Supply Proposed Solution

Figure 4-3 shows the proposed solution high-level block diagram for the new power supply. The PoD will obtain its 132 kV electricity supply from EThekwini Municipality Edwin Swales outdoor yard through the 132/33 kV outdoor substation at Langeberg which will be geographically located at Bayhead along Langeberg Road. With this power, supply arrangement a firm supply with redundancy will be guaranteed and the supply point will be closer to the major port loads of Durban Container Terminal and Pier as well as other future developments.

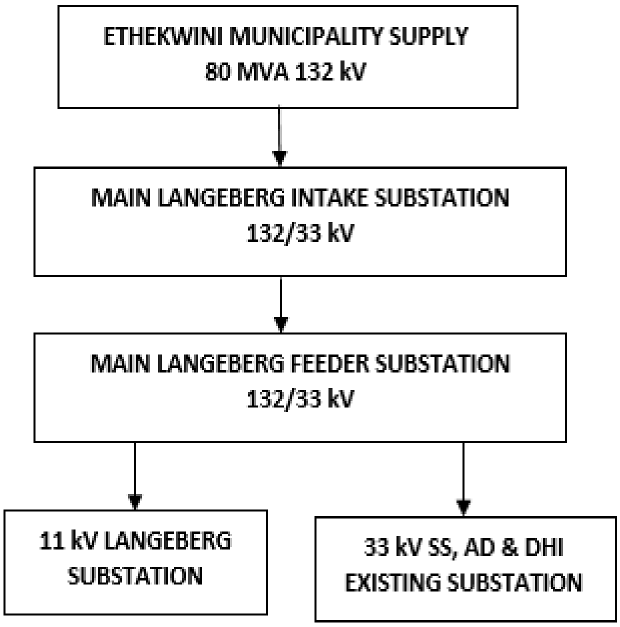


Figure 4-3: Bulk Power Supply Block Diagram- Proposed New Solutions

4.2.1.3 Electrical Network Implementation

Figure 4-4 shows the PoD's electrical network that was implemented on PowaMaster which consisted of the two 132 kV 500 mm^2 aluminium XLPE incomer feeders at supply capacity of 100 MVA. The 40 kA rated cables will supply 2 × 132 / 33 kV 40 MVA transformers at Langeberg Substation. The new 33 kV network is integrated to the ports existing 33 kV network via the main substations in the Port i.e. DHI, AD and STS 33 kV substations.

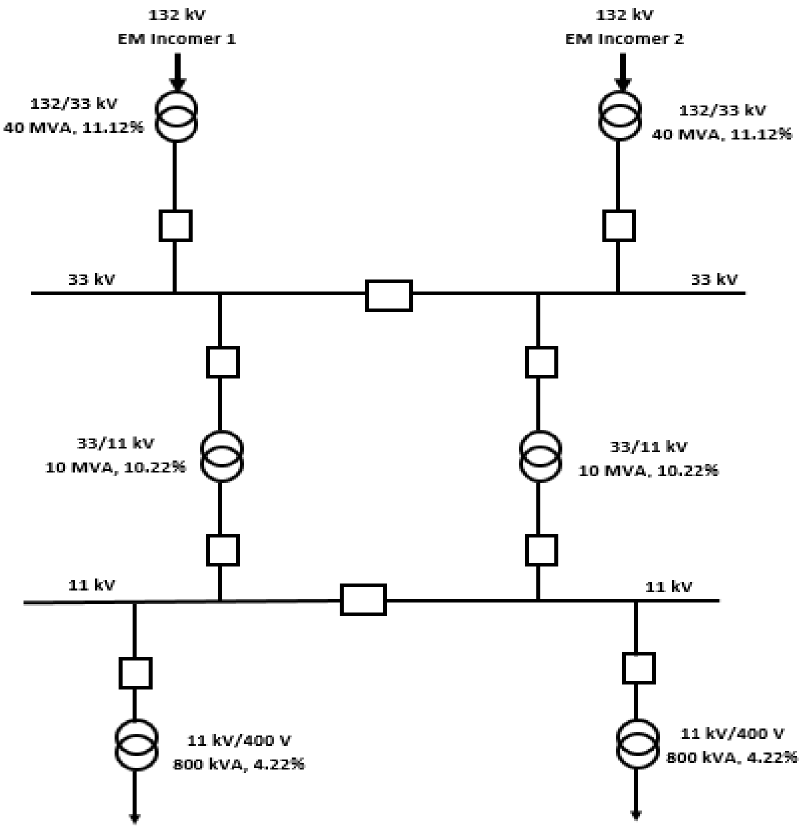
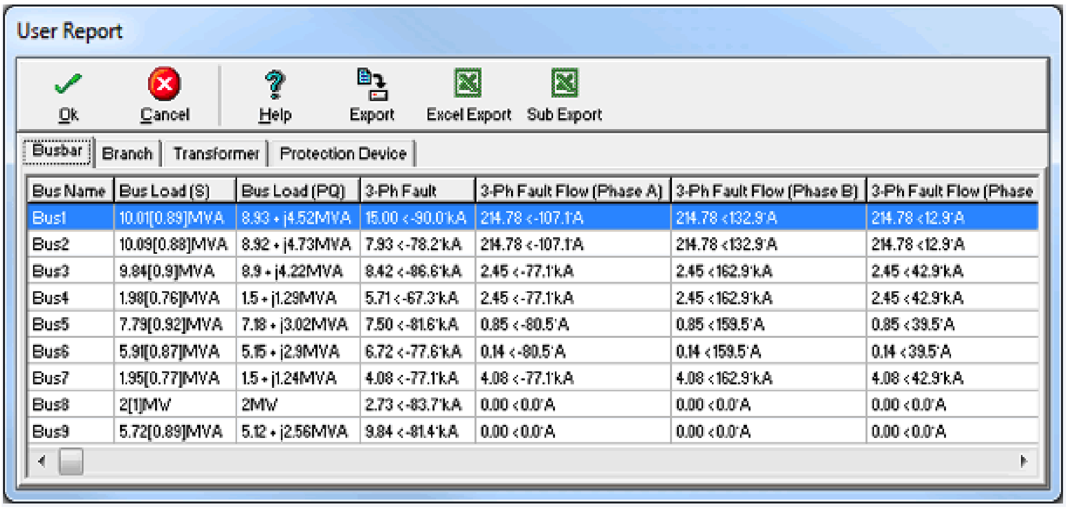


Figure 4-4: Electrical Reticulation implemented on PowaMaster of the new 132 kV Langeberg Substation

NR method was used for network analysis. For effective performance of the new Langeberg 132/33 kV substation and the existing substations the busbar, branch or conductor and transformer results were analysed. Figure 4-5 shows the screenshot of the user report generated on PowaMaster with the results for busbars, branch, transformers and protection devices that were analysed.



Bus Name	Bus Load (S)	Bus Load (PQ)	3-Ph Fault	3-Ph Fault Flow (Phase A)	3-Ph Fault Flow (Phase B)	3-Ph Fault Flow (Phase
Bus1	10.01[0.89]MVA	8.93 + j4.52MVA	15.00 <-90.0'kA	214.78 <-107.1'A	214.78 <132.9'A	214.78 <12.9'A
Bus2	10.09[0.88]MVA	8.92 + j4.73MVA	7.93 <-78.2'kA	214.78 <-107.1'A	214.78 <132.9'A	214.78 <12.9'A
Bus3	9.84[0.9]MVA	8.9 + j4.22MVA	8.42 <-86.6'kA	2.45 <-77.1'kA	2.45 <162.9'kA	2.45 <42.9'kA
Bus4	1.98[0.76]MVA	1.5 + j1.29MVA	5.71 <-67.3'kA	2.45 <-77.1'kA	2.45 <162.9'kA	2.45 <42.9'kA
Bus5	7.79[0.92]MVA	7.18 + j3.02MVA	7.50 <-81.6'kA	0.85 <-80.5'A	0.85 <159.5'A	0.85 <39.5'A
Bus6	5.91[0.87]MVA	5.15 + j2.9MVA	6.72 <-77.6'kA	0.14 <-80.5'A	0.14 <159.5'A	0.14 <39.5'A
Bus7	1.95[0.77]MVA	1.5 + j1.24MVA	4.08 <-77.1'kA	4.08 <-77.1'kA	4.08 <162.9'kA	4.08 <42.9'kA
Bus8	2[1]MW	2MW	2.73 <-83.7'kA	0.00 <0.0'A	0.00 <0.0'A	0.00 <0.0'A
Bus9	5.72[0.89]MVA	5.12 + j2.56MVA	9.84 <-81.4'kA	0.00 <0.0'A	0.00 <0.0'A	0.00 <0.0'A

Figure 4-5: PowaMaster generated User Report

4.2.2 Development of SCADA and SAS using Schneider CitectSCADA Software

In this project there were two SAS designs considered which entailed of Legacy Substation Automation System design and IEC 61850 Substation Automation design. This consideration was based on the available devices available at the time at the university. Legacy substation automation communications protocols and hardware or software architectures provide basic functionality for power systems automation. Legacy substation automation protocols designs have technical limitations when compared to IEC 61850 designs. Over the years, technology has evolved and there were major improvements in the power systems automation in substations from a networking technology perspective. The latest developments in networking entail high-speed Wide Area Network, redundant Ethernet, TCP/IP technology, high-performance embedded processors that have improved the capabilities of the legacy substation automation protocols. The Legacy substation automation system design was equipped with Modbus, Distributed Network Protocol (DNP3) and IEC 60870 communication protocols, which are vendor dependent and cannot be adopted as a complex solution [56]. These communication protocols operates at the electronic utility level. Modbus protocol supports serial communication, optical or radio networks, RS-232, RS-422, RS-484 serial communication or the TCCP/IP enhancements. Modbus is mainly suitable for serial communication and is not optimized for communication over Ethernet [64]. DNP3 is a set of communication protocols used for the interconnection of automation systems. It is mainly used within the SCADA system and IEDs. IEC 60870 is for communication between master stations and remote units.

IEC 61850 substation automation design provides the capability of interoperability between the IEDs for protection, monitoring, control and automation in substations. The IEC 61850 substation automation architecture consists of three levels i.e. Station level, Bay level and Process level. Station level consists of the HMI and gateways to communicate with remote control centre and integrate IEDs at bay level to the substation level. It also performs different process related functions such as implementation of control commands for the process equipment by analysing data from bay level IEDs. In the bay level, the process level equipment’s are connected to station bus via IEDs at the bay level that implement monitoring, protection, control and recording functions. Process level includes switchyard equipment, sensors and actuators. The current and potential transformers are located at the process level to collect system data and send them to bay level devices for automatic control and protection operations, which are achieved through circuit breakers and remotely operated switches.

IEC 61850 communication and data transfers is via serial and modern computer networks technologies using TCP/IP model and Ethernet encapsulation techniques [57, 58, 59].

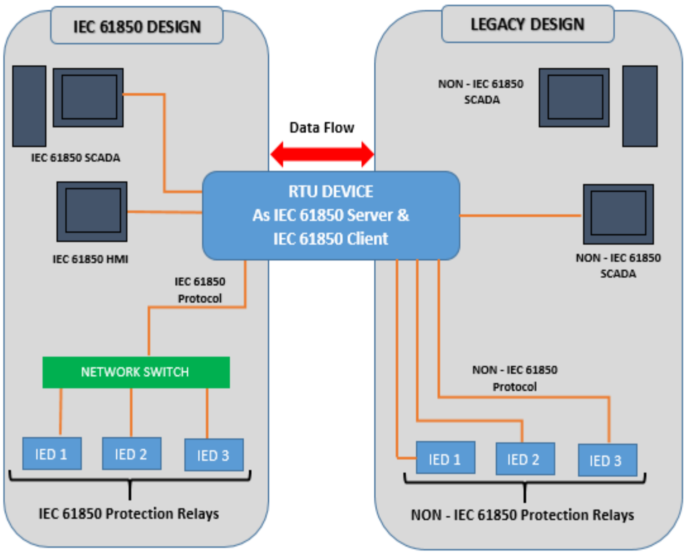


Figure 4-6: A combination of Legacy and IEC 61850 Automation System Design

Figure 4-6 above shows the automation system with a combination of legacy design and IEC 61850 design that was used in this project. The data transfer between the two system designs is achieved by the RTU device in between the two systems, which functions as both IEC 61850 server and client. The RTU is designed to integrate the latest IEC 61850 technologies with legacy technologies using configuration tools to convert protocols and create object models.

4.2.2.1 Electrical Substation Model development on CitectSCADA Platform

An automatic and interactive electrical substation model representing the physical system was developed on the Schneider CitectSCADA platform, which was installed on the host laptop. For data flow from IEDs to host laptop the RTU was connected to host laptop through Ethernet switch. The RTU stored the information, variables and commands of the developed substation. The CitectSCADA Project Editor Configuration tool was used to define and configure the substation system components, tags, alarms and communication components. The CitectSCADA Graphics Builder Configuration tool was used to design the graphical components of the substation. The substation consisted of two 132 kV incomers from EE, two 132/33 kV 40 MVA transformers, a connecting bus section on the 33 kV bus, six outgoing feeders with three on either side of the bus section. Each incomer and feeder was equipped with isolators, circuit breakers and earth switches. This model was equipped with control points for the operation of the circuit breakers and isolators, visual indications of the status of switchgear modes of operation, current readings, alarms, alerts and warnings under network fault conditions. The information communication, commands and signals between different devices was established through IEC 61850, Modbus RTU and DNP3 protocols as per developed communications architecture explained in Chapter 6. This communications architecture was implemented to control the operation, automation and provide protection to the substation model equipment and switchgear.

4.2.2.2 Testing of the implemented Electrical Substation Model

The circuit breakers and isolators basic operation i.e. Open/Close functions were tested by clicking the created symbols on the graphics page in order to prove their practical operational functionality. The supervisory features displayed the status alerts and visual indications of operation for circuit breakers or isolators. The status condition was also displayed on the IEDs HMI screen to notify the operator/user of the network status. In order to investigate the operational effectiveness of the substation model and capturing of graphical, numeral and visual results the system was tested under fault conditions. This was achieved using VAMPSET software to inject current to the protection relay or IED and the triggered fault condition displayed on the SCADA model and IED HMI display screen.

4.3 Analysis Summary

Chapter 4 outlines the methods used in order to meet the PoD's existing power supply upgrade requirements to ensure the firmness and availability of power supply in the Port. PowaMaster Software was used to undertake an electrical network study analyse the prospective behaviour of PoD's electrical network post implementation of the new 132/33 kV substation on to the currently existing network as part of strengthening due to the planned infrastructure development projects. The results from this study were obtained from PowaMaster User Report, which entailed results for transformers, conductors and all buses in the network.

The SCADA and Substation Automation system was development using Schneider CitectSCADA software for monitoring and control of the new substation, which entailed equipment operation, alarming and trend analysis. The implemented automation system design was a combination of legacy design and IEC 61850 design. The implemented network model was tested for effective operation under various fault conditions and the results were captured from alerts, alarms, process analyst i.e. trends, SCADA model visual aids and connected IEDs HMI display screens.

CHAPTER 5: ELECTRICAL LOAD FLOW ANALYSIS

5.1 Introduction

This chapter entails the results of the electrical load flow study that was conducted to analyse the voltage stability and system reliability of the PoD's electrical network in conjunction with new 132/33 kV Langeberg Substation. The load flow analysis is based on the projected load growth in the Port and it is in line with the statutory and regulatory requirements of SANS 10142-2 and NRS048. The load flow study was also used to validate if all the new selected reticulation cables and transformers as part of the design have been correctly sized and will be able to operate reliably and without compromising security of firm supply with the implementation of all planned future loads.

5.2 Port Historical Load Data

In order to correctly forecast the PoD's electrical growth, in alignment with the planned infrastructure development plans, it was of great importance to understand the historical and current electrical demand at the port. This analysis was used to provide the basis for determining the potential constraints on the electrical network because of project implementation and further provide guidance on network strengthening options.

The TNPA's energy metering database was interrogated to obtain metering values i.e. Maximum demand. Table 5-1 below shows the summary of the total Port's loading that was derived by the vectorial addition of the loading at the two main incomer substations i.e. 33 kV STS and 33 kV DHI substations. Metering data from January 2012 to October 2018 was included in this analysis. This data was used to examine Port's electrical load profile over the years. Figure 5-1 shows the graphical representation of the Port's yearly load profiles from 2012 to 2018.

Table 5-1: Summary of total port load at 33 kV STS and 33 kV DHI substation incomers

	Months	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Maximum Demands (kVA)	**January**	9 177	7 663	9 478	8 532	8 698	8 935	8 946
	February	8 251	11 061	8 302	8 753	8 724	8 405	8 730
	March	8 210	12 329	8 340	8 825	8 899	9 528	9 432
	April	8 304	11 251	8 184	9 187	8 700	8 702	10 350
	May	9 252	10 831	9 996	9 672	10 122	10 711	11 178
	June	11 061	12 329	12 084	11 688	10 876	12 770	13 527
	July	12 329	11 251	14 654	12 530	12 211	13 234	13 824
	August	11 251	14 630	12 481	13 471	13 404	12 624	15 093
	September	10 831	12 228	11 020	11 104	11 196	12534	12 978
	October	8 578	10 726	8 093	8 578	8 834	8901	11187

	November	7 980	10 771	7 867	7 870	8 958	10469	
	December	7 457	11 220	8 140	8 232	8 959	10917	
Average		9.39	11	10	10	10	11	12

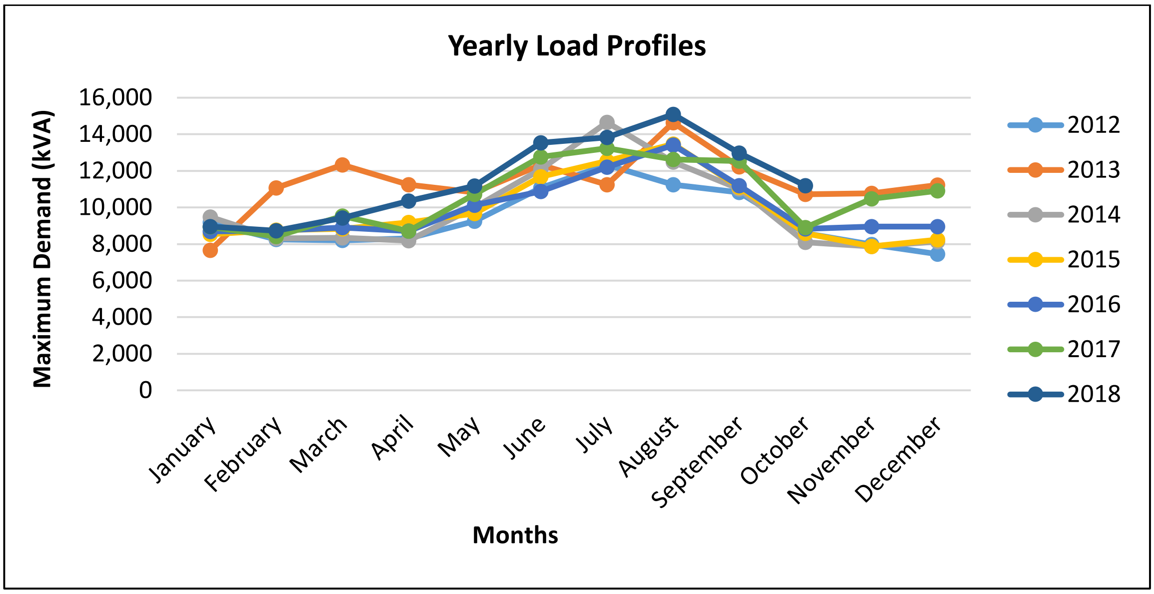


Figure 5-1: Port historical load from 2013 to 2018

5.3 Projected Infrastructure Developments

The PoD has various expansion projects listed in the corporate plan for the near future. These projects will have significant impact on the electrical demand and are tabulated in Table 5-2 below. The load forecast was achieved by estimating the load added to the electrical network for each year from 2018 to 2027. The most dominant projects, which will results in major increase in electrical power, are the Berth Deepening and Pier 1 Salisbury Island projects. The load forecasting was performed using the diversity factor considering current port operations.

Table 5-2: Planned Future projects with their estimated loads and planned commissioning year

Project Name	Load Requirements	Planned Commissioning Year
CFI Island View fire fighting Infrastructure upgrade	± 5MVA	2021
CFI Berth 9 firefighting installation	± 2 MVA	2022
Dry Dock upgrade and new equipment additional load that will be connected	± 2 - 4 MVA	2024

Figure 5-2 shows the forecasted port load from 2016 to 2028. The current firm supply limit as obtained from the supply authority is limited to 17 MVA as shown on the graph. The thermal

Berth Deepening including TPT equipment upgrade and additions (dependent on terminal operations)	± 38 – 40 MVA (Dependant on terminal operations)	2020 -2024
Pier 1 Salisbury Island Infill (Commissioned in phases)	± 5 – 20 MVA (dependent on terminal operations)	2025 -2027
Ambrose Park Developments	± 20 MVA	2023

limit of 34 MVA as shown in the graph represents the current Port's maximum demand when both incomers supply the port without redundancy. The graph also shows the projected maximum demand growth as per implementation of projects listed in Table 5-2. It is evident from the graph that the load increases gradually over the years and remains constant at 58 MVA when the execution of all the planned projects is completed.

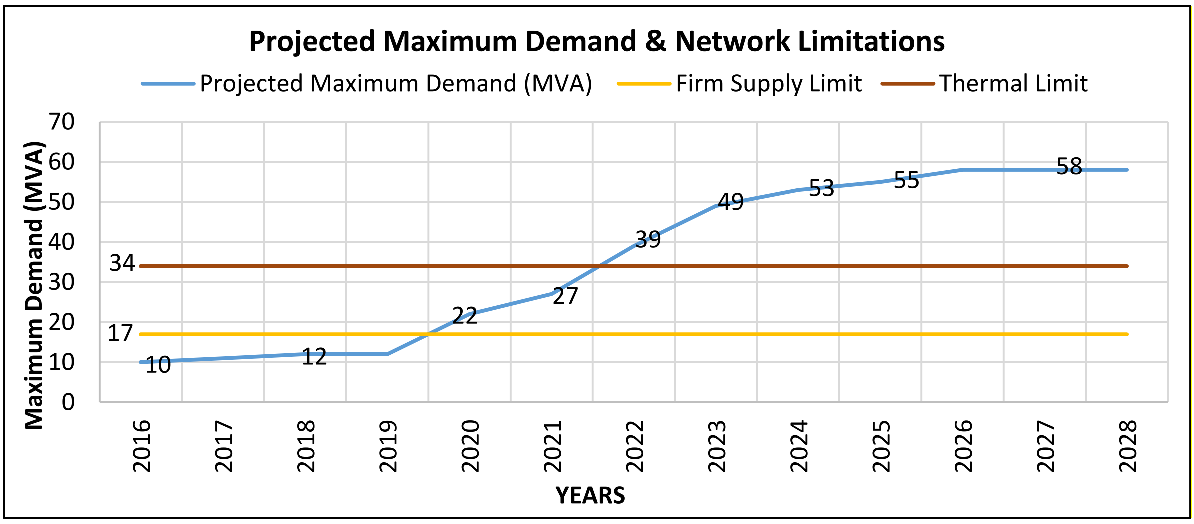


Figure 5-2: Projected electrical load demand in line with the port infrastructure development plan

5.4 Modelling and Load Flow Study

In performing the electrical load flow study, load diversification is one of the critical input parameters because it is a true representation of the network behaviour. Another option is to simulate with a diversity factor of 1 i.e. no diversity, which simulates the maximum theoretical loading of the network. Since it is almost impossible for all the port loads to peak at the same time, diversification have been applied to different port network points as per the SCADA logged data. Equation (1) below was used to calculate the diversity factor in each substation in the electrical network.

$$Diversity\ Factor = \frac{Installed\ Load}{Running\ Load} \quad (1)$$

The raw data collected from SCADA is included in Annexure A.

PowaMaster Simulation tool was used to perform the load flow study. It is a simulation tool used for electrical analysis of transmission and distribution systems. It caters for the modelling of meshed electrical networks by representing the electrical network and equipment in a user-friendly manner. It also enables the user to easily model any electrical network quickly and effectively. PowaMaster Simulation tool uses co-incidence factor instead of diversity factor and equation (2) below was used to calculate this factor.

$$Coincidence\ Factor = \frac{Running\ Load}{Installed\ Load} = \frac{1}{Diversity\ Factor} \tag{2}$$

Table 5-3: Diversity Factor and Coincidence Factor Applied at Various Substation and Minisubstations

Substation / Network Point	Diversity Factor	Coincidence Factor
DHI 33 kV LHS OF BUS	4.56	0.22
DHI 33 kV RHS OF BUS	4.60	0.218
STS 33 kV LHS OF BUS	7.97	0.13
STS 33 kV RHS OF BUS	6.35	0.157
AD 33 kV LHS OF BUS	5.62	0.178
AD 33 kV RHS OF BUS	13	0.077
1MVA School of Ports Mini Sub	5.62	0.178
1 MVA Tank Washout Mini Sub	2.49	0.40
1 MVA Bayhead Mini Sub	2.08	0.48
500 kVA Pollution Control Mini Sub	2.17	0.46
500 kVA King Rest Mini Sub 1	2.23	0.448
1 MVA King Rest Mini Sub 2	1.37	0.73
1 MVA King Rest Mini Sub 3	1.30	0.766

The following were analysed to study the network performance of the new Langeberg 132/33 kV substation and the currently existing substations:

- Bus voltages are maintained within acceptable operating limits.
- Branch power factor.
- Current flow throughout the system.
- Power flow throughout the system.
- Equipment is not overloaded.

NRS 048-2:2003 Electricity Supply – Quality of Supply: Voltage characteristics, compatibility levels, limits and assessment methods specification states that the maximum voltage deviation shall not be greater than specified in Tables 5-4 and 5-5.

Table 5-4: Maximum Deviation from standard or declared Voltages

Voltage Level (V)	Limit Percentage (%)
<500 V	±5

≥500 V	±10

Table 5-5: Maximum voltages for supplies to customers above 500 V

Nominal Voltage kV	**Maximum Voltage kV**
400	420
275	300
220	245
132	145
88	100
66	72.5
44 and below	Nominal voltage +10%

It is of great importance that the voltage is within the specified limits to avoid interruptions in the electrical network. It can be observed that in all the scenarios considered in the load flow study conducted, the voltage levels in all the bus-bars is within acceptable limits under normal load conditions.

5.4.1 Load Flow Scenario Analysis

It is evident from the planned projects listed in Table 5-2 that the projected load growth in the Port is over three periods i.e. 5 years' time for projects implemented as from 2018 to 2022. 7 years' time for projects implemented as from 2018 to 2024 and final load growth will be in 10 years when all the implementation of projects is complete in 2027. From this, it is evident that the load growth pattern is over 5 years, 7 years and 10 years from 2018, therefore the load flow study forecast chosen periods were 5 years, 7 years and 10 years. There were six (6) scenarios considered for the selected periods. The electrical network is designed in a ring feed system as a result the whole network can be supplied from either one (1) 132/33 kV 40 MVA transformer with the bus section closed at 33 kV or from two (2) 132/33 kV 40 MVA transformer with the bus section open at 33 kV. This design ensures continuity of supply in case one transformer is faulty or unable to supply the Port. Therefore, it was of great importance to investigate the stability and reliability of the network for both feeding arrangements in each selected period.

Table 5-6 and Table 5-7 below represents the details of the selected transformers and cables for the new 132/33/11kV Langeberg Substation respectively. The selection of the transformers and cables took into consideration the projected load growth over a period of 10 years. In order to select the appropriate cable, equation (3) below was used to determine full load current. With reference to equipment datasheet in Appendix B and SANS 97. The calculated full load current was then used to select the appropriate type and size cable that is capable to withstand. The VD over the length of the selected cable was also determined using equation (4) with some parameters obtained from the manufacturer's datasheet in Appendix B. According to SANS 10142-2 the maximum allowable VD on the cable should be ±5%. The obtained transformer and cable parameters were used in the electrical network implemented to perform load flow analyses on PowerSmart Software.

$$Full\ Load\ Current\ (I_{FL}) = \frac{kVA \times 1000}{\sqrt{3} \times V \times Cos\emptyset} \quad (3)$$

$$Voltage\ Drop = \ mpedance\ \left(\frac{\Omega}{km}\right) \times Cable\ Length\ (km) \times \ I_{FL}(A) \quad (4)$$

Table 5-6: Details of the Selected Transformers for the new 132/ 33/ 11 kV Langeberg Substation

Name	Description of Transformer Ratings	Transformer Impedance (Z%)	Current Rating (A)
Trfr 1	40MVA 132kV/33kV	10.1	699.82
Trfr 2	40MVA 132kV/33kV	10.1	699.82
Trfr 3	10MVA 33kV/11kV	8.1	524.86
Trfr 4	10MVA 33kV/11kV	8.1	524.86

Table 5-7: Details of the Selected C for the new 132/ 33/ 11 kV Langeberg Substation

From Bus Name	To Bus Name	Cable Description	Total Length (km)	Branch Current Rating (A)
132 kV_1	132 kV_2	132 kV 500 mm^2 Al XLPE 1Core	2.5	581
132 kV_1	132 kV_3	132 kV 500 mm^2 Al XLPE 1Core	2.5	581
33 kV_1	33 kV_3	33 kV 630 mm^2 Cu XLPE 1Core	0.5	684
33 kV_2	33 kV_4	33 kV 630 mm^2 Cu XLPE 1Core	0.5	684

Scenario 1:

A load flow study analysis was conducted with the new 132/33 kV Langeberg substation implemented into the existing electrical network. The load flow analysis was based on a 5 year (2018 -2022) load projection, which is due to Port Developments as listed in Table 5-2 whereby an additional load from the CFI Island View fire fighting infrastructure upgrade and Berth Deepening upgrade were added to the electrical network. This scenario was performed with 2 x 40 MVA 132/33 kV transformers in operation with the bus section open at 132/33 kV main Langeberg substation.

Scenario 2:

A load flow study analysis was conducted with the new 132/33 kV Langeberg substation implemented into the existing electrical network. The load flow analysis was based on a 5 year (2018 -2022) load projection, which is due to Port Developments as listed in Table 5-2 whereby an additional load from CFI Island View fire fighting infrastructure upgrade and Berth Deepening upgrade were added in the electrical network. This scenario was performed with 1 x 40 MVA

132/33 kV transformer in operation with the bus section closed at 132/33 kV main Langeberg substation.

Scenario 3:

A load flow study analysis was conducted with the new 132/33 kV Langeberg substation implemented in to the existing electrical network. The load flow analysis was based on a 7 year (2018 -2024) load projection, which is due to Port Developments as listed in Table 5-2 whereby an additional load from CFI Island View fire fighting infrastructure upgrade, Berth Deepening upgrade and Ambrose park developments were added in the electrical network. This scenario was performed with 2 x 40 MVA 132/33 kV transformers in operation with the bus section open at 132/33 kV main Langeberg substation.

Scenario 4:

A load flow study analysis was conducted with the new 132/33 kV Langeberg substation implemented in to the existing electrical network. The load flow analysis was based on a 7 year (2018 – 2024) load projection, which is due to Port Developments as listed in Table 5-2 whereby an additional load from CFI Island View fire fighting infrastructure upgrade, Berth Deepening upgrade and Ambrose park developments were added in the electrical network. This scenario was performed with 1 x 40 MVA 132/33 kV transformer in operation with the bus section closed at 132/33 kV main Langeberg substation.

Scenario 5:

A load flow study analysis was conducted with the new 132/33 kV Langeberg substation implemented in to the existing electrical network. The load flow analysis was based on a 10 year (2018 – 2027) load projection which is due to Port Developments as listed in Table 5-2 whereby an additional load from CFI Island View fire fighting infrastructure upgrade, Berth Deepening upgrade, Ambrose park upgrade developments and Pier Infill upgrade (all projected loads implemented in the electrical network) were added in the electrical network. This scenario was performed with 2 x 40 MVA 132/33 kV transformers in operation with the bus section open at 132/33 kV main Langeberg substation.

Scenario 6:

A load flow study analysis was conducted with the new 132/33 kV Langeberg substation implemented in to the existing electrical network. The load flow analysis was based on a 10 year (2018 – 2027) load projection, which is due to Port Developments as listed in Table 5-2. These included an additional load from CFI Island View fire fighting infrastructure upgrade, Berth Deepening upgrade, Ambrose park developments and Pier Infill upgrade (all projected loads implemented in the electrical network) were added in the electrical network. This scenario was performed with 1 x 40 MVA 132/33 kV transformer in operation with the bus section closed at 132/33 kV main Langeberg substation.

5.5 Load Flow Study Results

PowaMaster Software was used as a simulation tool to implement the PoD's electrical network that entails of new and existing substations and minisubstations. Annexure C shows the implemented electrical network showing the new 132/33 kV Langeberg substation, 33/11 kV Langeberg substation, the existing 33 kV STS substation, 33 kV DHI substation and 33 kV AD substation. The minisubstations implemented included 11/0.4 kV 500 kVA Kingrest 1, 11/0.4 kV 1 MVA Kingrest 2, 11/0.4 kV 1 MVA Kingrest 3, 11/0.4 kV 500 kVA Pollution control, 11/0.4 kV 1 MVA Tank Washout, 11/0.4 kV 1 MVA School of ports and 11/0.4 kV 1 MVA Bayhead.

5.5.1 Analysis and Discussion of Results for Scenario 1, 3 and 5

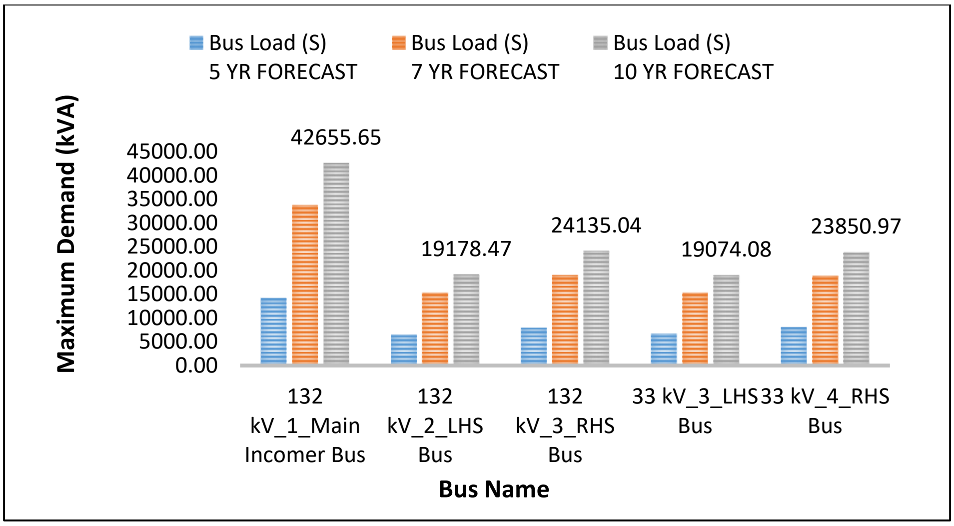


Figure 5-3: Port Load Growth for Scenarios 1, 3 and 5

Figure 5-3 illustrated the results of the port load growth on the main 132 kV incomer bus, left and right hand side 132 kV bus as well as the main 33 kV left and right buses. The graphical representation shows the port load growth in each bus represented over a period of 5 years, 7 years and 10 years. From these results, it is evident that there is exponential load growth in each bus. The main 132 KV incomer bus shows the overall total port load, which will be 42. 66 MVA in the next 10 years.

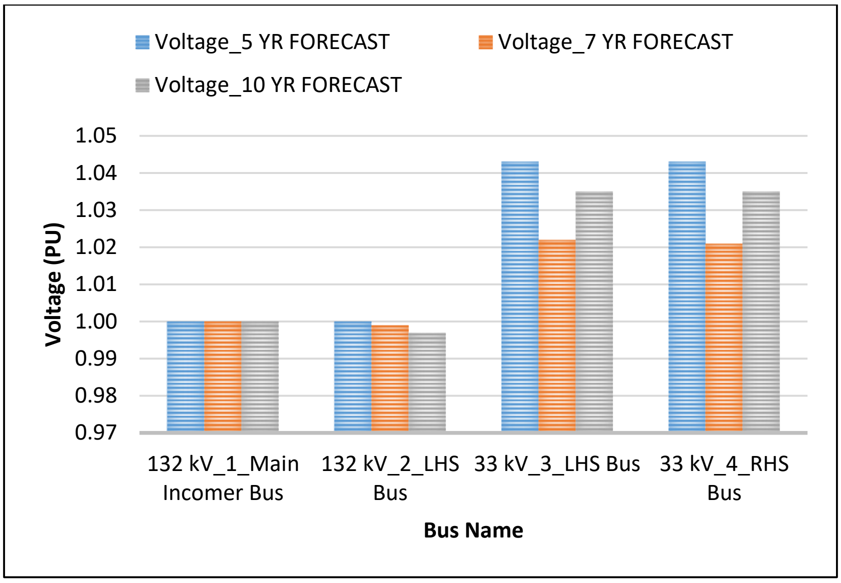


Figure 5-4: Voltage Levels at 132 kV and 33 kV for Scenarios 1, 3 and 5

Figure 5-4 is graphical representation of voltage levels at the main 132 kV incomer, left and right 33 kV buses, main left and right 33 kV buses. It can be observed that post implementation of all the loads, the network will behave as expected since all the voltages are within acceptable limits as per NRS 048 in Table 5-4 and Table 5-5 and SANS 10142.

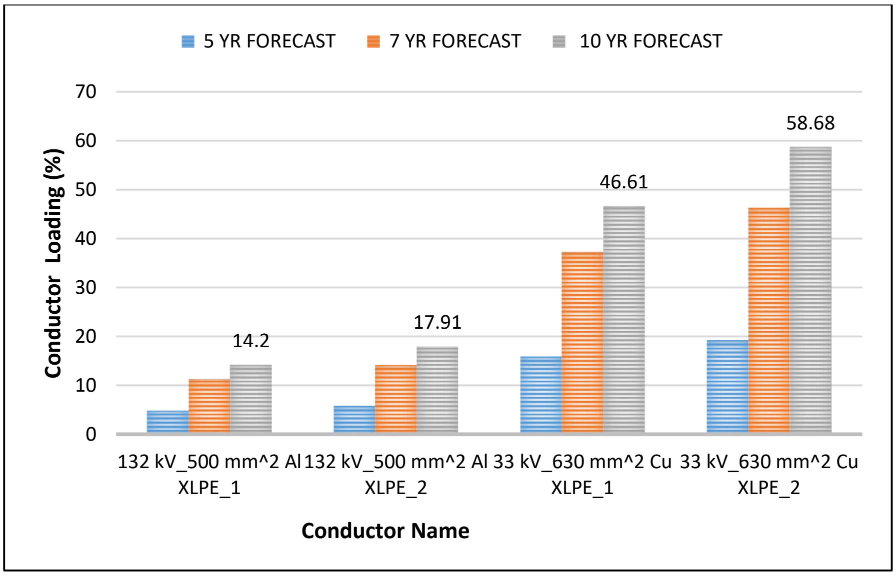


Figure 5-5: Conductor Percentage Loading - Main left and right 132 kV buses and main left and right 33 kV for Scenarios 1, 3 and 5

Figure 5-5 represents the percentage loading for the main 132 kV and 33 kV cables conductors selected. Despite the year on year load growth the selected conductors will still have sufficient capacity to carry the Port load.

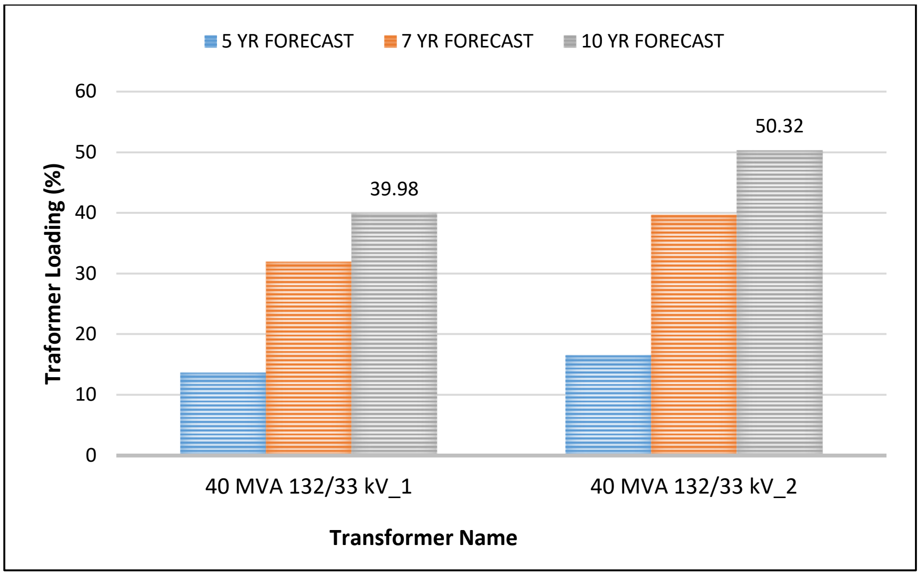


Figure 5-6: 132 kV Main Transformer Percentage Loading for Scenarios 1, 3 and 5

Figure 5-6 represents the percentage loading of the two main incomer 132 kV 40 MVA transformers. It is clear that even after 10 years load forecast implementation these transformers will still be able to carry the total Port load, as these will still have sufficient spare capacity.

5.5.2 Analysis and Discussion of Results for Scenario 2, 4 and 6

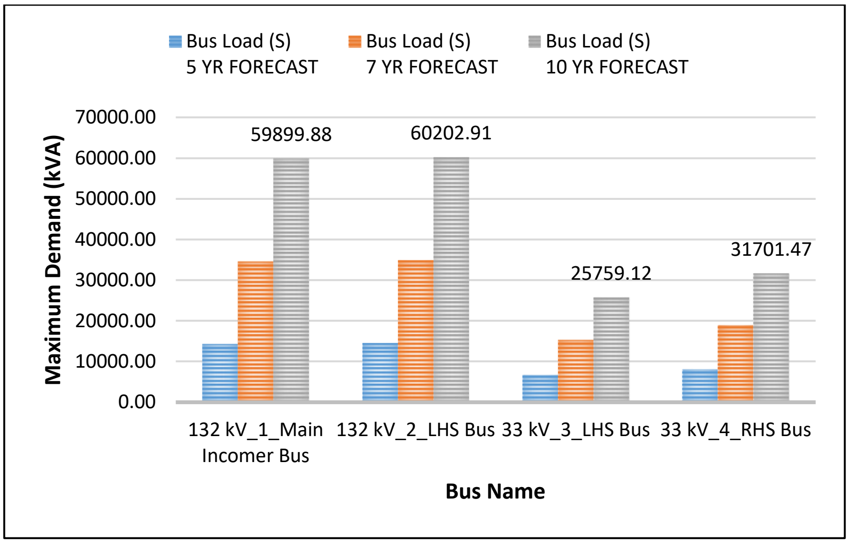


Figure 5-7: Port Load Growth for Scenarios 2, 4 and 6

Figure 5-7 shows the Port load growth for scenarios 2, 4 and 6 when one main 132 kV 40 MVA incomer transformer was in operation. The load growth shown is for 132 kV main incomer bus, left and right intake132 kV buses as well the left and right main 33 kV buses. It is evident that the total Port Load after 10 years when all the planned developments are implemented will be approximately 60 MVA.

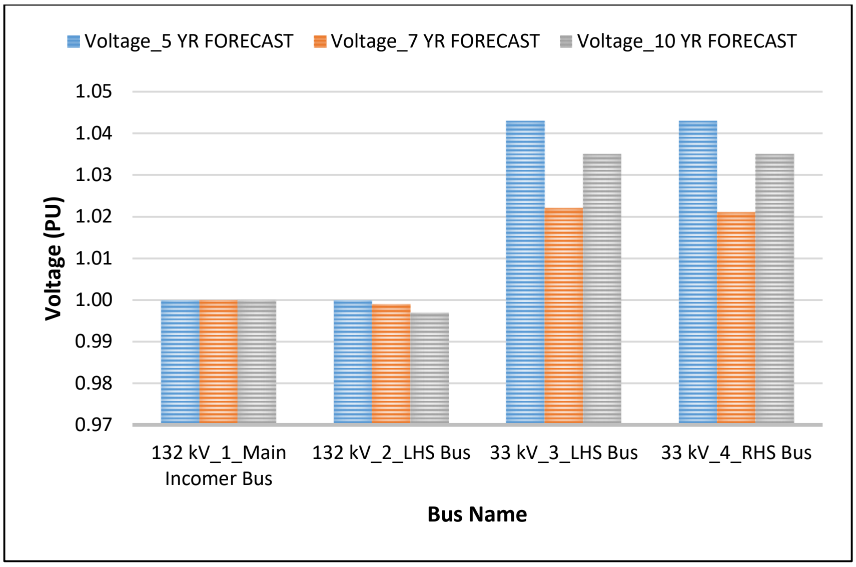


Figure 5-8: Voltage Levels at 132 kV and 33 kV for Scenarios 2, 4 and 6

Figure 5-8 is graphical representation of voltage levels at the main 132 kV incomer, left and right 33 kV buses, main left and right 33 kV buses when scenarios 2, 4 and 6 was simulated. Even in this supply configuration, the voltage acceptable limits as stipulated by NRS 048 in Table 5-4 and Table 5-5 and SANS 10142 are within acceptable range.

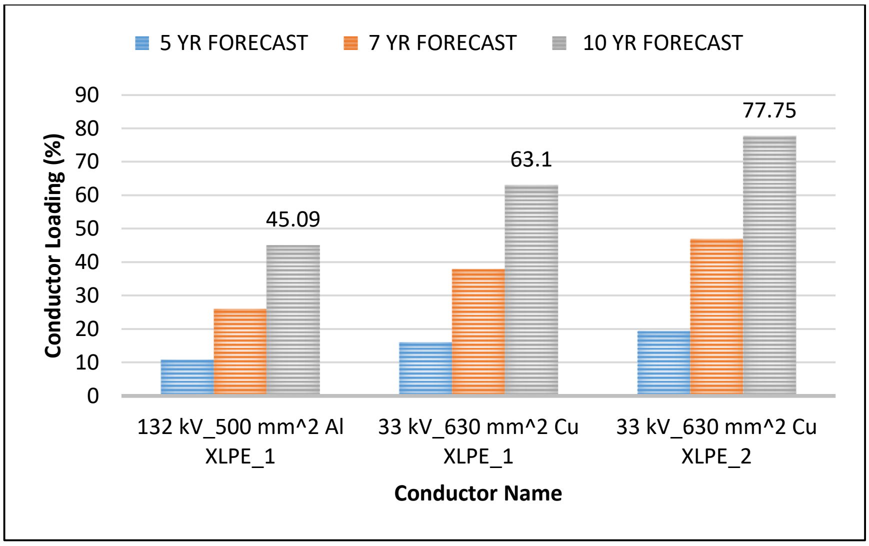


Figure 5-9: Percentage Loading for Main 132 kV and 33 kV Conductors when scenarios 2, 4 and 6 were implemented

The percentage loading for 1 x 132 kV 500 mm^2 Al XLPE conductor and 2 x 33 kV 630 mm^2 Cu XLPE conductors is shown in figure 5-9. It is evident the selected cables will still be able to withstand the total Port load as these still have spare capacity post implementation of all the projected loads.

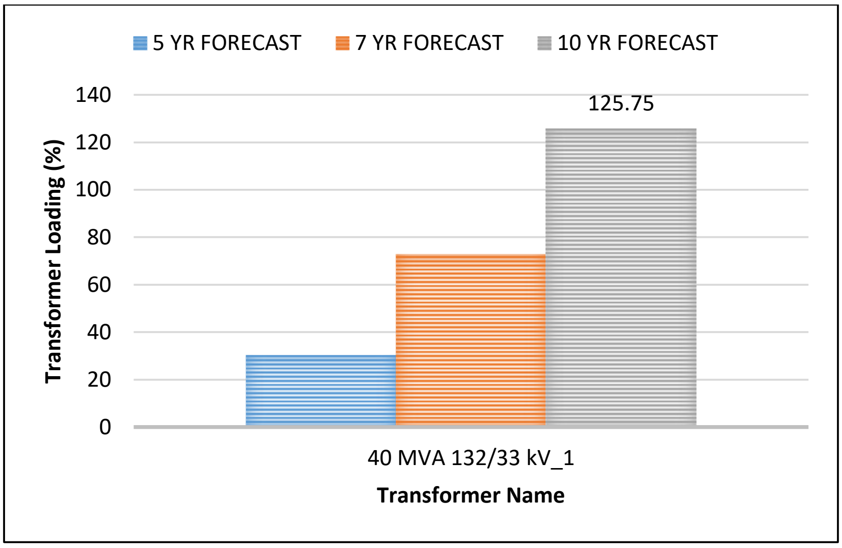


Figure 5-10: 132 kV Main Transformer Percentage Loading for Scenarios 2, 4 and 6

The implementation of scenario 2, 4 and 6 the load flow analysis was implemented with one incomer 132 kV 40 MVA transformer in operation. Figure 5-10 shows the results of the percentage loading of this transformer and it evident that with the exponential load growth over the years this transformer will be overloaded by approximately 25%. This means that this transformer on its own will not be sufficient to carry the total Port load.

5.6 Conclusion

The primary objective of Chapter 5 was to conduct a load flow study to analyse voltage profile, system reliability of the new 132/33 kV PoD Substation in accordance to the statutory requirements of NRS 048 and SAN 10142-2. The study also analysed the behaviour of PoD's electrical network post implementation of the new substation onto the currently existing network as part of the strengthening option due to planned development projects, which are planned to be commissioned between 2017 and 2027. It was also to validate if all the new selected reticulation cables and transformers as part of the design have been correctly sized and will be able to operate reliably without compromising security of firm supply with the implementation of all planned future loads. After implementation of all the planned projects by the year 2027 when the supply is sourced by one 132/33 kV 40 MVA as per scenarios 2, 4 and 6. The transformer will not be able to withstand the total Port load since loading becomes 125%, which is an overload. However when the supply is sourced via by two 132/33 kV transformers as per scenarios 1, 3 and 5, the transformer loading becomes 39.98% and 50.38% respectively and both transformers have a spare capacity. This transformer configuration allows for full redundancy and reliability of the network. The selected incoming cables for all scenarios considered, will be sufficient to carry total Port loads without compromising the reliably and stability of the PoD's electrical network. All voltages are within acceptable limits as required by NRS 048 and SANS 10142-2.

CHAPTER 6: DEVELOPMENT OF SCADA AND SAS FOR PORT OF DURBAN'S 132/ 33 kV SUBSTATION POWER SUPPLY UPGRADE

6.1 CitectSCADA System Development

SCADA system is a basic infrastructure of modern power systems. SCADA remote monitoring and control system is essential to provide a fast fault restoration with minimum cost and shorter time consuming. Substation Automation is a system that enables remote monitoring, control and coordinate the distribution components installed in the substation. Substation SCADA and automation systems provides protection, control, automation, monitoring and communication capabilities as part of a comprehensive substation control and monitoring solution [60, 61, 62]. IEDs provides interoperability and advanced communications capabilities in substation protection, coordination, control, monitoring and testing. Modern substation SCADA and automation systems utilizes data from IEDs, control and automation capabilities within the substation and control commands from remote users to control and operate power system devices. The integration of IEDs, Ethernet LAN, communications protocols, communications methods, make the whole substation a functional system with the combination of the correct physical or virtual connections, common communication protocols, shared storage and sequential or combination logic for coordinated monitoring, protection and control [62, 63].

Schneider CitectSCADA is a reliable, flexible and high performance SCADA software solution for industrial processes. CitectSCADA platform was used to develop the substation automation visualisation system for this project. An automatic and interactive SCADA model of the physical power systems electrical reticulation network was developed to allow for remote monitoring and control of key system parameters.

6.1.1 SCADA Communications Architecture

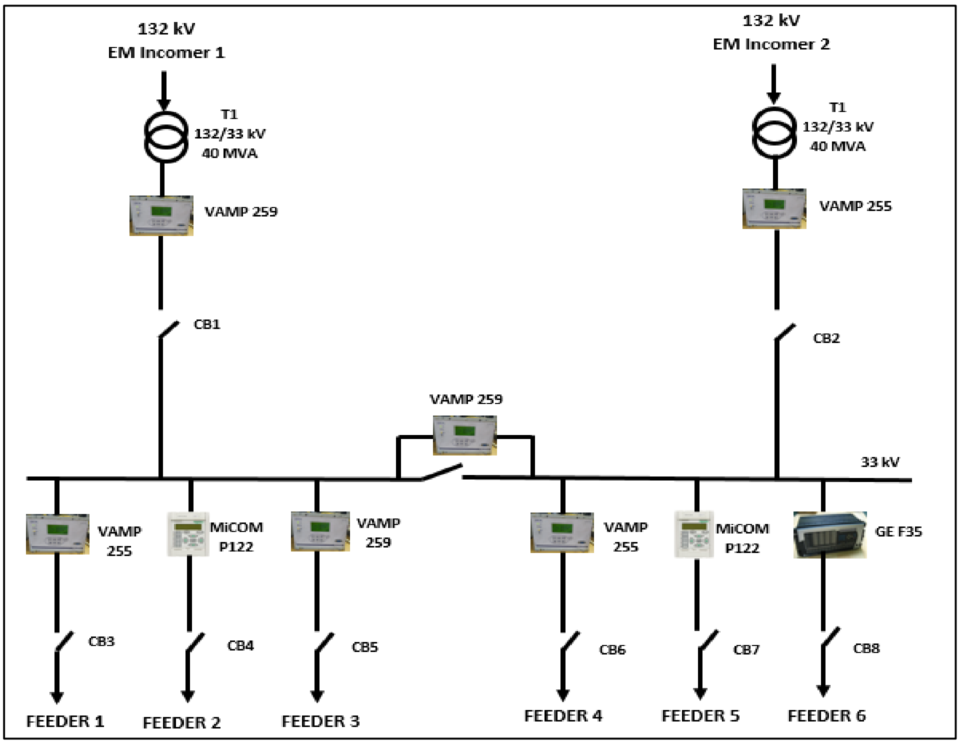


Figure 6-1: Electrical Substation SCADA Model with Protection Devices

Figure 6-1 shows the 132/33 kV electrical substation network that was implemented on the CitectSCADA software with the protection devices monitored by the SCADA system. The IEDs used in the project were donated by the manufacturer to the University. These IEDs consisted of MiCOM P122 relay, VAMP 255/259 relays and GE F35 feeder management relay. Communication between the SCADA system and these devices was achieved through a communication architecture implemented as shown in Figure 6-2. These relays provided the user/operator with the ability to view status indication as well as fault conditions of the circuit breaker, isolator and earth switch in question as displayed in the relay built-in HMI and as well as in the SCADA system runtime.

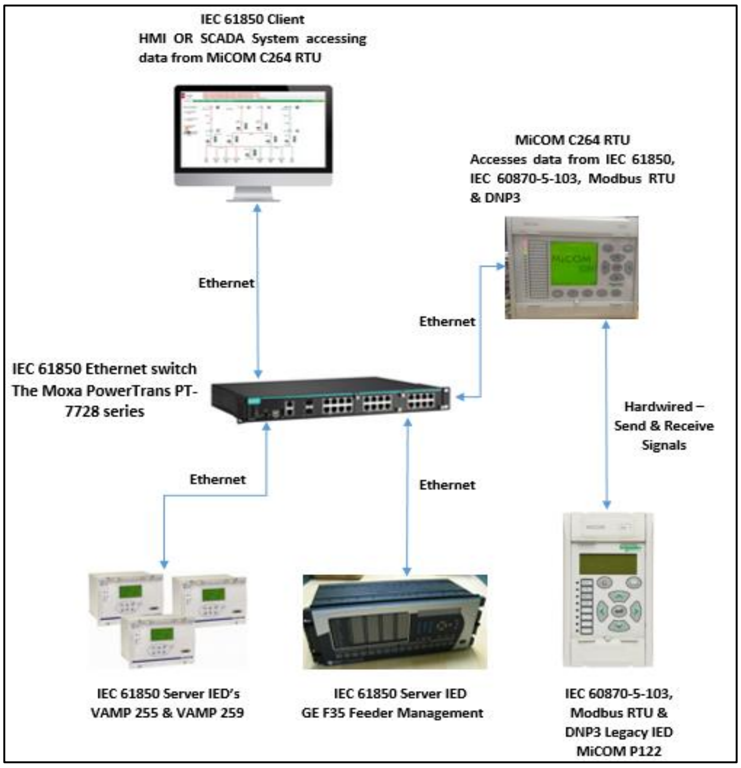


Figure 6-2: SCADA Communications Architecture

Figure 6-2 shows the simplified field SCADA system communications architecture that was implemented in this project. This architecture is a combination of both legacy and IEC 61850 technologies and these were configured and integrated for monitoring and control of the implemented substation electrical network.

The SCADA system consists of a number of different devices communicating with each other. This SCADA system consists of the following devices:

- IEC 61850 Client – This entails of the HMI or SCADA system accessing data from MiCOM C264.
- MiCOM C264 RTU – Accesses data from IEC 61850, IEC 60870-5-103, Modbus RTU and DNP3 devices.
- IEC 61850 Ethernet Switch – The Moxa PowerTrans PT-7728 series.
- IEC 61850 IEDs – VAMP 255, VAMP 259 & GE F35 Relays.
- IEC 60870-5-103, Modbus RTU & DNP3 Legacy IED – MiCOM P122

The communication channels entails the following cases of data flow:

- Data flow from IEC 61850 IEDs to IEC 61850 client - MiCOM C264 RTU accesses data from IEC 61850 IED's i.e. VAMP 255, VAMP 259 & GE F35 feeder management relays then HMI or SCADA systems accesses data from the MiCOM C264 RTU and displays it.

- IEC 60870-5-103, Modbus RTU & DNP3 Legacy IED to IEC 61850 client – MiCOM C264 RTU accesses data from legacy IEDs i.e. MiCOM P122 using DNP3, Modbus RTU, IEC 60870-5-103 communication protocols. The MiCOM C264 RTU creates IEC 61850 object models from the data accessed from IEDs. The IEC 61850 Client i.e. HMI or SCADA system accesses data from MiCOM C264 RTU.

6.1.2 Configuration Tools

CitectSCADA software is made up of several configuration tools i.e. CitectSCADA Explorer, CitectSCADA Project Editor, CitectSCADA Graphics Builder, Computer Setup Editor, Computer Setup Wizard and CitectSCADA Runtime section. Computer Setup Editor is a feature for editing configuration files and generating reports to compare and analyse files. Computer Setup Wizard allows the user to customize the computer's setup and define its role and function.

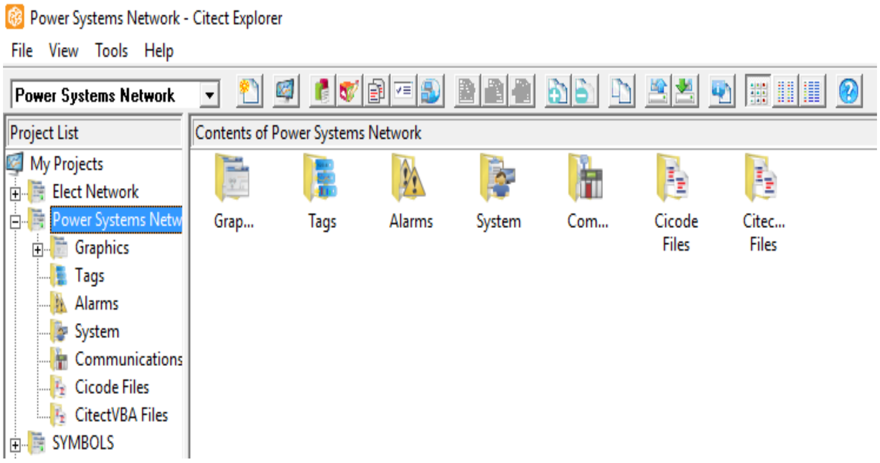


Figure 6-3: CitectSCADA Explorer Configuration Tool

Figure 6-3 above shows the CitectSCADA Explorer configuration tool that was used to create and manage the user projects; it displays a list of projects and provides direct access to the components of each. This configuration tool is also used to rename, back up, restore or delete a project.

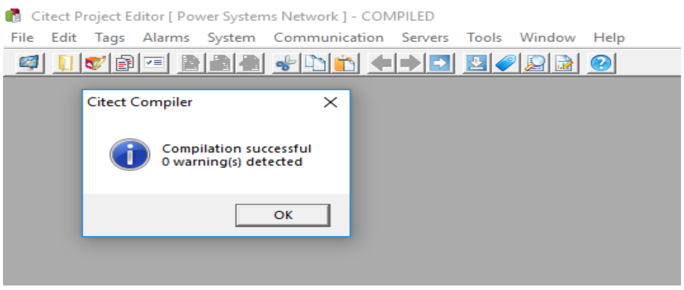


Figure 6-4: CitectSCADA Editor Configuration Tool

Figure 6-4 above shows the CitectSCADA Project Editor Configuration tool that was used o create and manage the configuration information for the project, including tags, alarms, system components, and communications components.

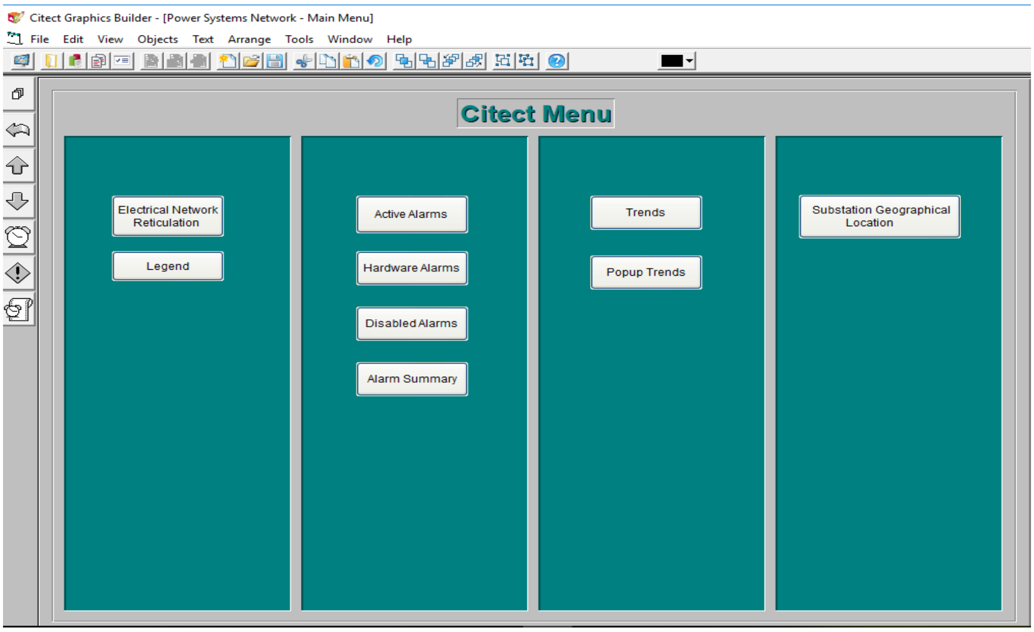


Figure 6-5: CitectSCADA Graphics Builder Configuration Tool

Figure 6-5 shows the CitectSCADA Graphics Builder configuration tool that was used to design, create, and edit the graphics components of the project, including templates, graphics objects, symbols, genies, and Super Genies. For this project, the configurations entailed the following items:

a) Electrical Network Reticulation – Graphical representation of the 132/33 kV Substation.
b) Symbols Legend – Description of each symbol used in the reticulation network.
c) Alarms – Active alarms, hardware alarms, disabled alarms and alarm summary.
d) Process Analyst – Trends and Popup trends.
e) Substation Geographical Location.

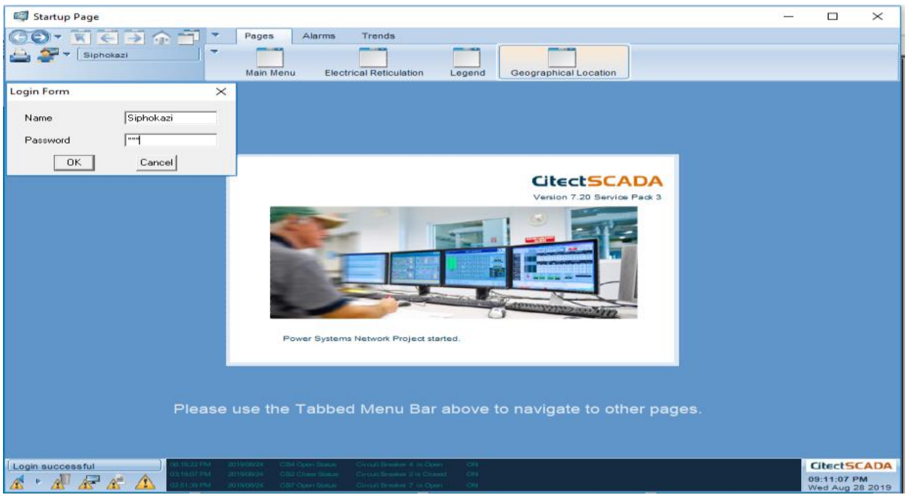


Figure 6-6: CitectSCADA Runtime

Figure 6-6 shows the CitectSCADA Runtime section i.e. Startup Page that provides the active operator interface. The runtime "Startup Page" provides the user/operator with the option to login in and the following information is obtained from this page:

a) Project Name

b) User – At the top left it shows the name of the user logged onto the system and at the bottom left corner it is indicated that the login was successful.

c) Active Alarms are displayed at the bottom of the page with date and time they were raised.

d) Time and Date – Is indicated on the bottom right corner of the page.

e) Navigation Tabs:-

- Pages which entails of the main menu tab, electrical reticulation tab, symbols legend tab and substation geographical location.
- Alarms tab which consists of active alarms, hardware alarms, disabled alarms and summary alarms.
- Trends tab which consists of the Process Analyst and Process Analyst Pop ups.

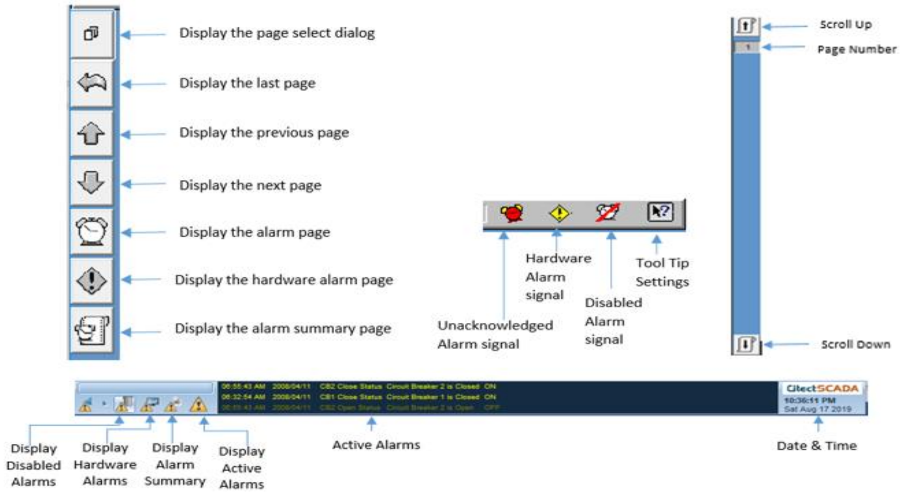


Figure 6-7: Explanation for navigation panels

Figure 6-7 explains the various navigation controls that are in the runtime page when various pages are opened. These controls provide the user with ease to navigate directly to the required page. The page templates entail of vertical and horizontal scroll bars to allow users to view columns and rows off-screen.

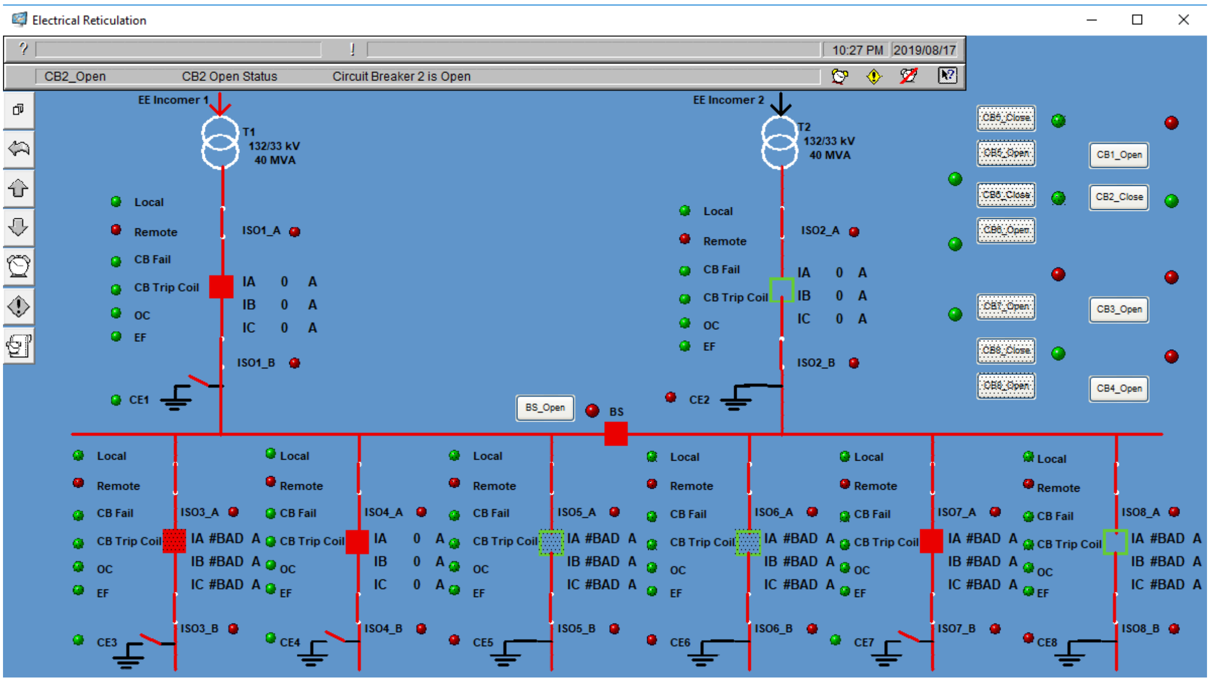


Figure 6-8: Electrical Network Reticulation Implemented

Figure 6-8 shows the interactive electrical network SCADA model of the physical system that was implemented on Schneider's CitectSCADA software. This model was configured and designed to have remote control points for the operation of circuit breakers, isolators, earth switches, visual indications of switchgear status, and modes of operation of devices, current readings, alarms and warnings under fault conditions. The implemented electrical network reticulation entails of 2 x 132 kV 40 MVA transformers, 33 kV Bus Section, 6 x 33 kV feeders and circuit breakers 2, 3, 4 & 7 are communicating and can be operated i.e. Open/Closed.

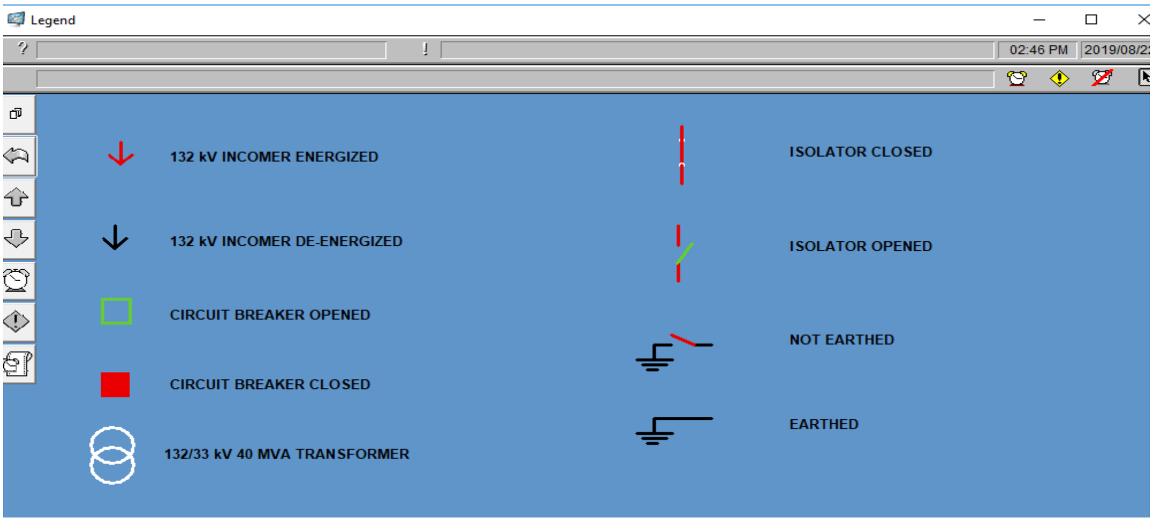


Figure 6-9: Electrical Network Reticulation Symbols Description

Figure 6-9 shows the Legend tab found in the runtime with the description of symbols used in the electrical network SCADA model implemented in CitectSCADA software. This page assist the user with identifying the device status and provides understanding and the meaning of each device symbol used in the graphic user interface.

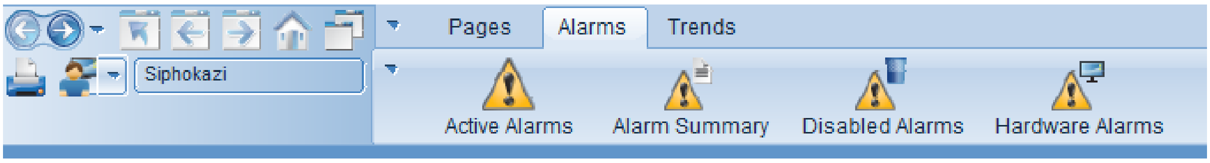


Figure 6-10: Alarms Page

Figure 6-10 shows the alarms page tab in the runtime interface, which consists of Active alarms, alarm summary, disabled alarms and hardware alarms. The alarms raised are displayed in their respective dedicated pages, however, the most recent alarms are always visible on every page. The CitectSCADA alarm server manages and processes all alarms as configured in the Project Editor. The alarm system is equipped with capabilities of being fast, reliable and provides detailed alarm information to the user/operator. To minimize downtime the user/operator has the ability to easily identify the faulted area of the network and isolate as quickly as possible. The CitectSCADA system is efficient and enables the user/operator to monitor configurable alarms i.e. variables, expressions or calculation results and reports fault conditions in the plant. The alarm are time stamped and this is essential when differentiating between alarms that occur in rapid succession. Alarms are structured according to colour, priority, category and time of occurrence.

Table 6-1: Active Alarms

Time	Variable Tag	Alarm	Description of alarm
09:22:14 AM	CBTC2 1_Active	CBTC2 Active Status	Circuit Breaker 2 Trip Coil Active
09:12:56 PM	CB2_Open	CB2 Open Status	Circuit Breaker 2 is Opened
09:05:45 PM	CBF2_Active	CBF2 Active Status	Circuit Breaker 2 Fail Active
04:40:48 PM	CB7_Close	CB7 Close Status	Circuit Breaker 7 is closed
04:40:48 PM	CB4_Close	CB4 Close Status	Circuit Breaker 4 is closed

Table 6-1 shows some of the alarms raised as shown in Figure 6-11. The active alarm page provides the user/operator with vital information regarding the status of the network since this page displays the time the alarm was activated, variable tag triggered and alarm description.

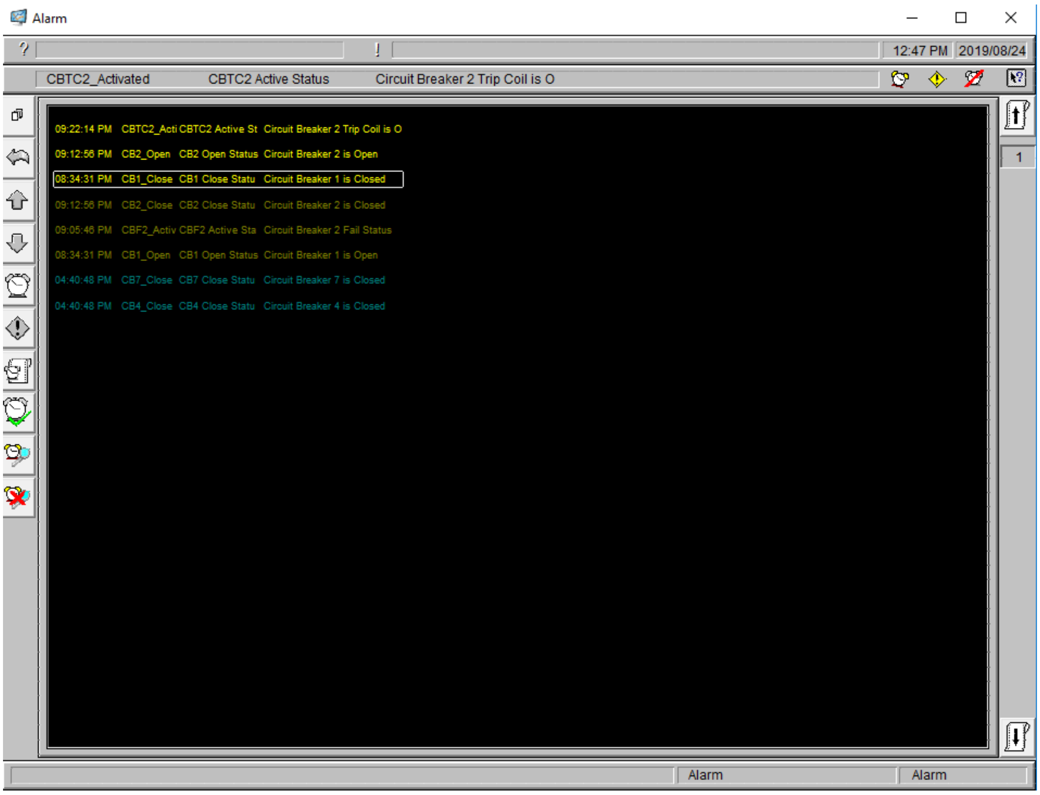


Figure 6-11: Active Alarms Page

Figure 6-11 shows active alarms page in the runtime. This page displays active alarms that are unacknowledged or acknowledged and still in active alarm state. From this view the user/ operator is able to see the entire active alarms, the alarm on time, and the date.

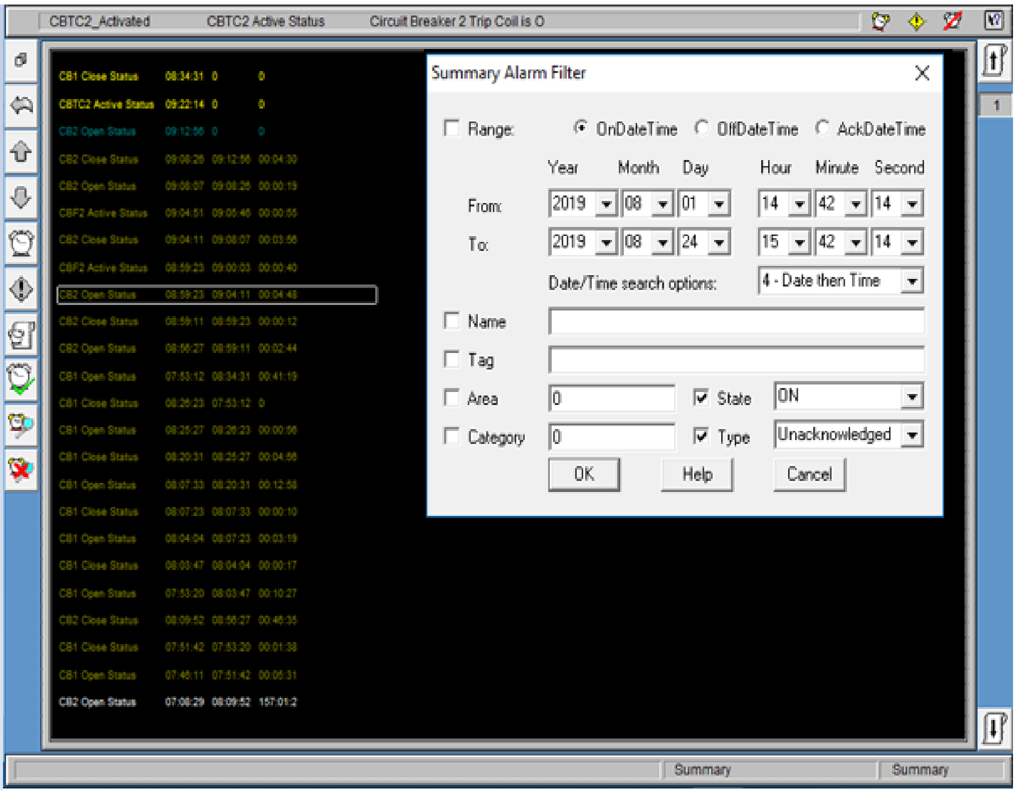


Figure 6-12: Summary Alarms Page

Figure 6-12 shows alarm summary page, which displays a historical log of alarms that have occurred and their duration. This page is mainly for troubleshooting purposes and displaying all the alarms raised in the electrical network system. This page has the equipment tree-view panel displayed on the left hand side of the page for filtering of the display list. The summary alarms filter pop up allows the user to select the alarms range, select dates, times, state and types of alarms to display.

Table 6-2: Alarm Summary

Alarm	Time Alarm Raised	Time Alarm Cleared	Duration	Alarm Status
CB1 Close Status	08:34:31	0	0	unacknowledged
CB2 Open Status	08:59:23	09:04:11	00:04:43	acknowledged
CBF2 Active Status	08:55:23	09:00:03	00:00:43	acknowledged

Table 6-2 shows some of the alarm summary as shown in Figure 6-12. The alarm summary page displays the alarm raised, the time the alarm was cleared, the duration of the alarm and whether the alarm was acknowledged or unacknowledged.

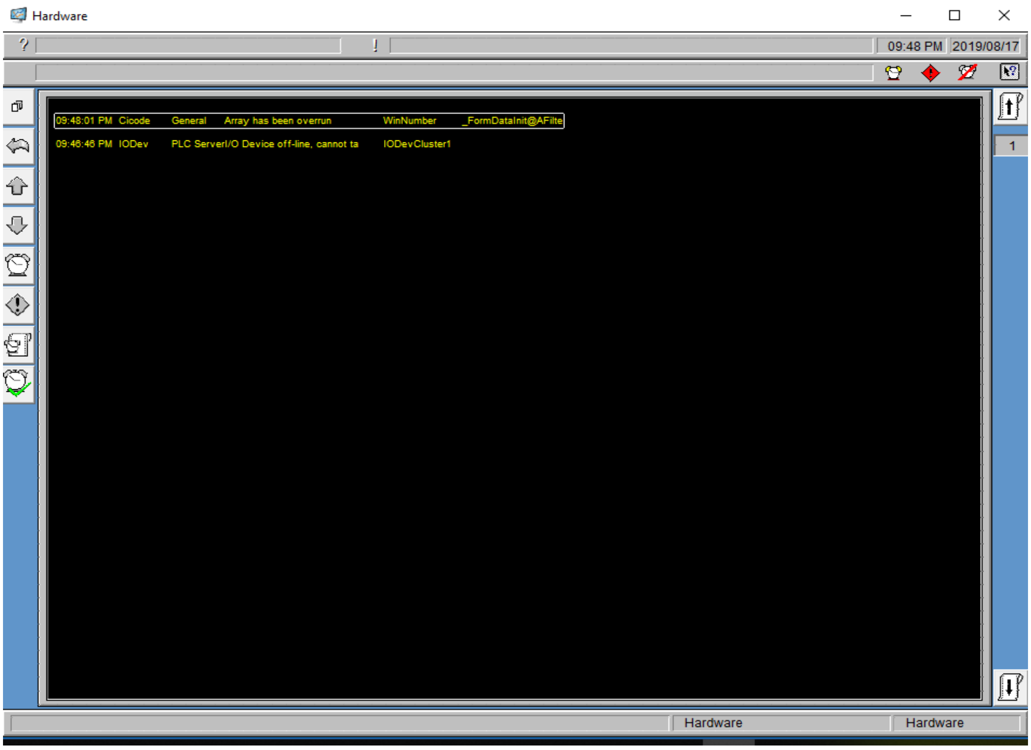


Figure 6-13: Hardware Alarms Page

Figure 6-13 shows hardware alarms page in the runtime. When an error occurs in CitectSCADA operation, a hardware alarm is generated and displayed on a dedicated page within the project. This alerts the operator to monitor the status of a system's infrastructure or current problems. Hardware alarms indicate if break in communications has occurred, if the Cicode cannot execute or if a server becomes inoperative. If the user/operator experiences problems communicating with a device, initially check the hardware alarms page for evidence of an error.

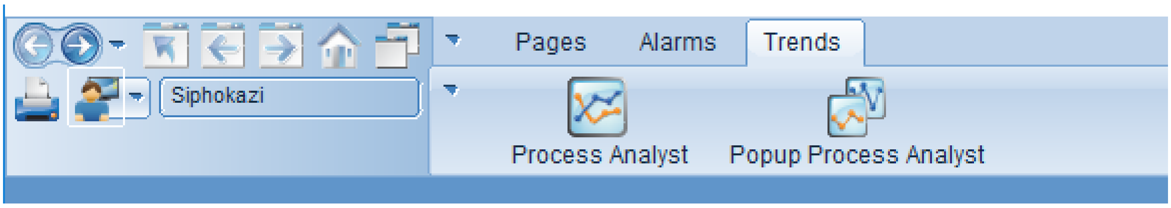


Figure 6-14: Trends Page

Figure 6-14 shows the trends page, which entails of Process Analyst and Popup Process Analyst tabs. CitectSCADA trends provides records of real-time and historical data of the electrical equipment in the substation. The user/operator is able to monitor the current activity or scroll back to view the trend history. CitectSCADA handles enormous amount of variables whilst maintaining data integrity.

Figure 6-15: Substation Geographical Location

Figure 6-15 shows the aerial view with the geographical location of the plant/substation. This aerial view indicates the geographical location of various 11 kV substations, 33 kV substations and new 132 kV Substation implemented for this project indicated in green. To navigate from to the electrical reticulation network of the substation in question, the user/operator can click on the green indication button. This makes it easy for the user/operator to operate the network as quickly as possible.

6.2 CitectSCADA Substation Model Testing

The 132/33 kV substation model implemented on the CitectSCADA system was equipped with supervisory features and interactive visual alerts that enabled the user/operator to observe the network status. The supervisory features display functions entailed of status indicators for circuit breakers, isolators, local or remote mode, circuit breaker trip coil supervision, cable earth, circuit breaker fail, overcurrent trip, earth fault and three phase currents. For switchgear operation, the SCADA model had interactive control panels for the circuit breaker and isolator. When the user/operator clicked on the circuit breaker or isolator symbols, a pop-up window appeared, allowing the user/operator to remotely open or close the circuit breaker or isolator taking into consideration applicable interlocking.

6.2.1 Circuit Breaker Basic Operation

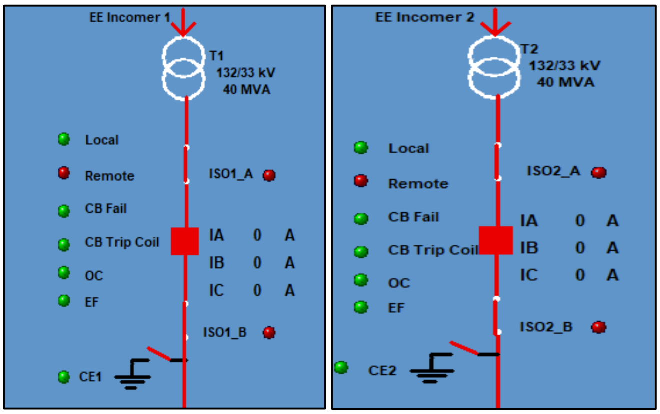


Figure 6-16: Energized Circuit Breaker Basic Operation

Figure 6-16 shows the SCADA graphical representation of the energized state of both incomer one and two when remotely operated. From this graphical representation, it is evident that both circuit breakers and isolator were closed while the cable earth switches were opened. The interactive alerts for circuit breakers, isolators, earth switches and three phase currents are shown. It can be noted that the three phase current numerical values displayed is zero due to that the associated feeders and bus section were de-energized during this test as a result the load current was zero amps.

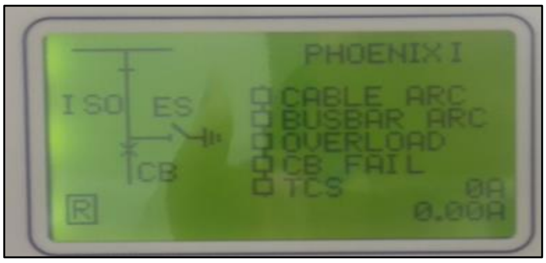


Figure 6-17: Hardware Relay Circuit Breaker Energized Status

Figure 6-17 shows the hardware relay circuit breaker energized status of incomer one when operated remotely which corresponds to the SCADA graphical representation in Figure 6-14. It is evident that the both the circuit breaker and isolator are closed whilst the earth switch is open. The remote mode operation status is also indicated as well as the three-phase currents numerical value of zero amps.

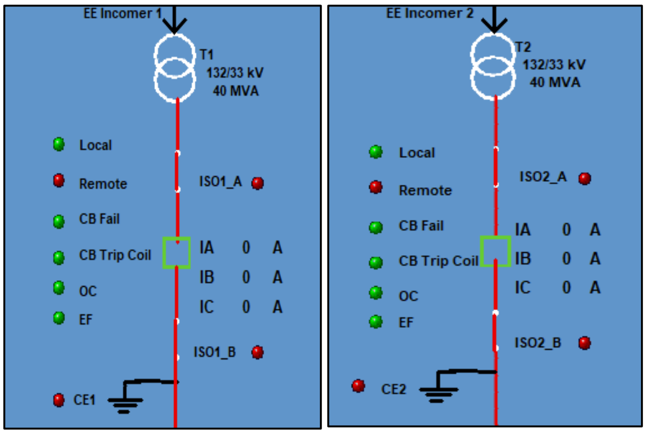


Figure 6-18: De-energized Circuit Breaker Basic Operation

Figure 6-18 shows the SCADA graphical representation of the de-energized state of both incomer one and two when remotely operated. From this graphical representation, it is evident that the circuit breakers were opened whilst the isolator and earth switch were closed. The interactive alerts for circuit breakers, isolators, earth switches and three phase currents are shown. It can be noted that the three phase current numerical values displayed is zero due to the de-energized state.

Figure 6-19: Hardware Relay Circuit Breaker De-Energized Status

Figure 6-19 shows the hardware relay circuit breaker de-energized status of incomer one when operated remotely which corresponds to the SCADA graphical representation in Figure 6-16. It is evident that the circuit breaker is opened. The remote mode operation status is also indicated as well as the three-phase currents numerical value of zero amps.

6.2.2 Bus Section Basic Operation

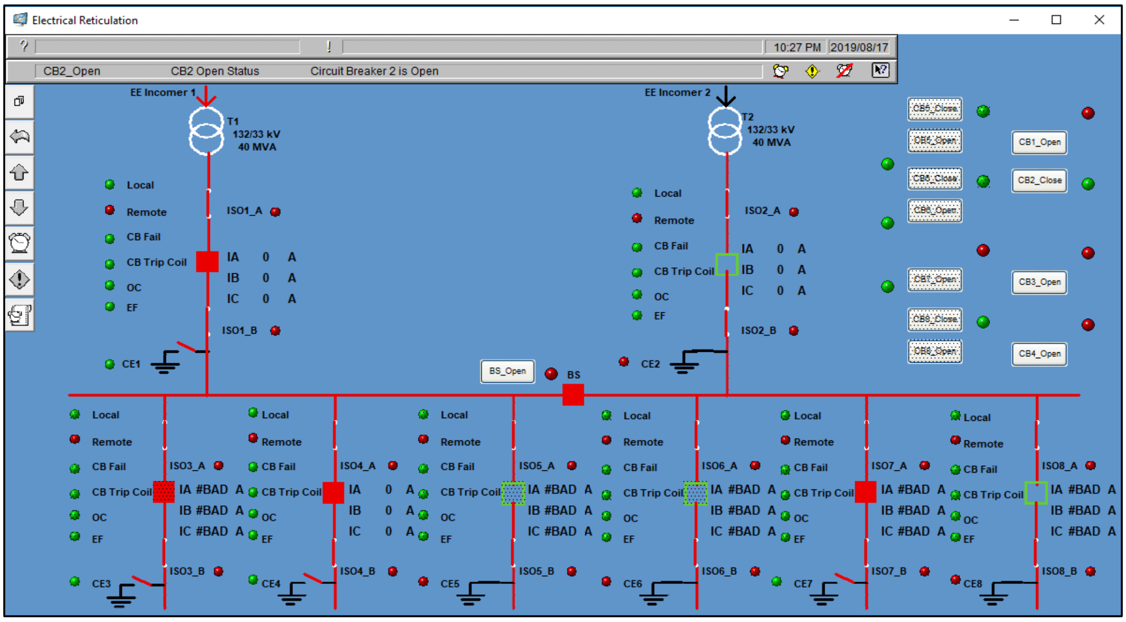


Figure 6-20: Energized Bus Section Basic Operation

Figure 6-20 shows the electrical substation SCADA model, which entails of two 132 kV incomers, six feeders and one bus section. The graphical representation indicates the status of the bus section when remotely operated through the interactive control buttons that were configured using logic operations. It is evident that the bus section is in its closed state.

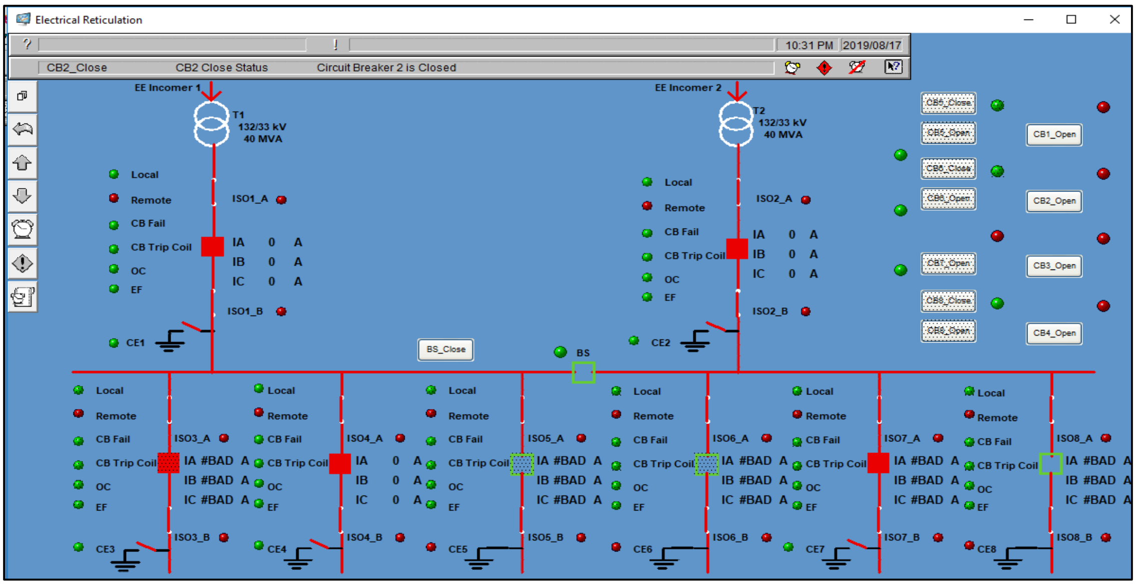


Figure 6-21: De-Energized Bus Section Basic Operation

Figure 6-21 shows the SCADA model graphical representation of the bus section when remotely operated through the interactive control buttons that were configured using logic operations. It is evident that the bus section is in its open state.

6.2.3 Testing Fault Conditions using VAMPSET software

The earth fault and overcurrent fault conditions were verified using virtual software testing i.e. VAMPSET software for VAMP 255 and VAMP 259 protection relays. The software was used to inject the current to the protection relay and the triggered fault condition would be displayed on the SCADA model and the relay HMI display screen.

Table 6-3: Overcurrent Settings and VAMPSET Tests

Overcurrent Test Settings					
Pick-up Current (I_P)		440 A			
Time Multiplier Setting (TMS)		0.5			
Tripping Curve		IEC STD Inverse			
Virtual Test 1		**Virtual Test 2**		**Virtual Test 3**	
Phase A	463 A	Phase A	463 A	Phase A	297 A
Phase B	463 A	Phase B	463 A	Phase B	297 A
Phase C	463 A	Phase C	216 A	Phase C	297 A
Status	OC Trip	Status	OC Trip	Status	No OC Trip

Table 6-3 represents the overcurrent VAMP 259 relay settings for incomer one which include the relay pick-up current, time multiplier setting and the tripping curve. This table further shows the three tests by injecting current using VAMPSET software in each phase to prove overcurrent tripping.

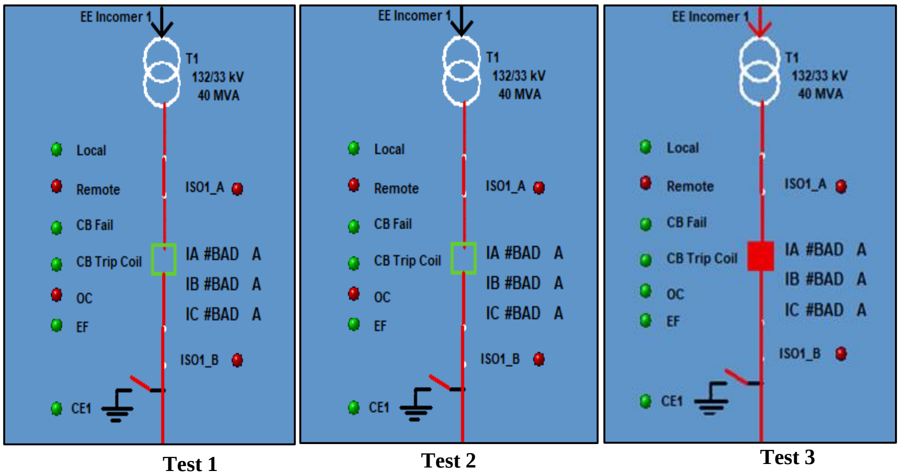


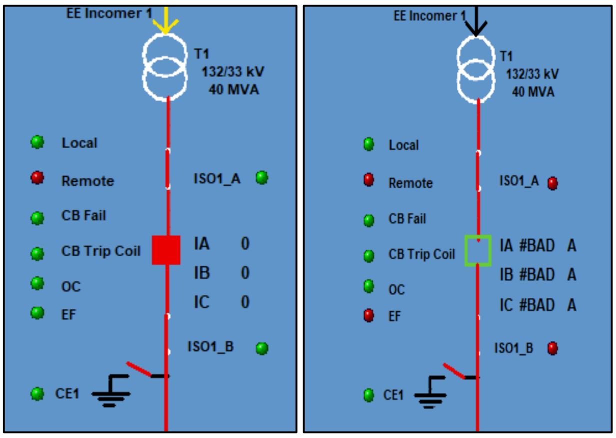
Figure 6-22: Incomer 1 Overcurrent Trip Status

Figure 6-22 shows the SCADA model graphical representation of an overcurrent trip condition for test one, two and three in remote mode. For test one and test two the current injected in all three phases and phases A and B respectively is above the pick-up current of 440A therefore the circuit breaker tripped on overcurrent. For test 3 current injected in all the three phases is below the pick-up current setting therefore, there is no overcurrent trip and the circuit breaker remains closed. Due to that the testing was done using the third party software , the system diagram on SCADA is unable to display the actual numerical current values as the relay is being tested using it's dedicated and copyrighted VAMPSET software.

Table 6-4: Earth Fault Settings and VAMPSET Tests

Earth Fault Test Settings			
Pick-up Current (I_P)		80 A	
Time Multiplier Setting (TMS)		0.05	
Tripping Curve		IEC STD Inverse	
Test 1 (Ph-G)		**Test 2 (Ph-G)**	
Phase A	75.70 A	Phase A	100 A
Status	No EF Trip	Status	EF Trip

Table 6-4 represents the earth fault VAMP 259 relay settings for incomer one which include the relay pick-up current, time multiplier setting and the tripping curve. This table further shows the two tests conducted by injecting current using VAMPSET software between phase A and ground to prove earth fault tripping.



Test 1 **Test 2**

Figure 6-23: Incomer 1 Earth Fault Trip Status

Figure 6-23 shows the SCADA model graphical representation of an earth fault trip condition for both tests the current was injected between phase A and ground. The phase to ground current for test one was below the pick-up current setting therefore there was no earth fault and the circuit breaker remained closed. For test two, the phase to ground current was above the pick-up current setting therefore, there was an earth fault and the circuit breaker tripped as shown in Figure 6-23.

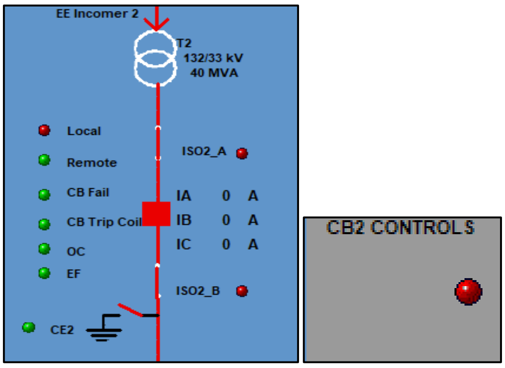


Figure 6-24: Incomer 2 Local Mode and Disabled Controls

Figure 6-24 shows the SCADA model graphical representation in local mode and circuit breaker controls. When the circuit breaker mode is in local, the user/operator will not be operate it remotely from SCADA model as the circuit breaker controls are disabled therefore the circuit breaker can't be closed or opened. This is a safety feature that prevents the operator from switching the circuit breaker while the maintenance personnel is working onsite, therefore the circuit breaker can only be physically opened or closed from the panel by the maintenance personnel.

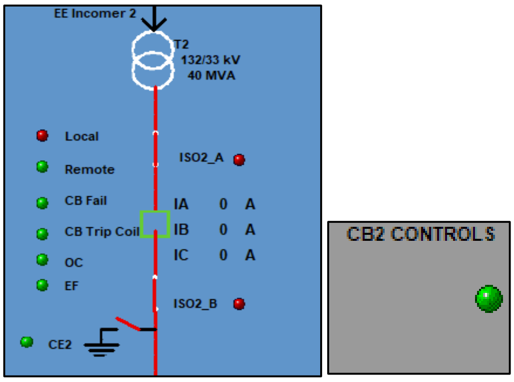


Figure 6-25: Incomer 2 Local Mode when operated by Maintenance Personnel

Figure 6-25 shows the SCADA model graphical representation in local mode and circuit breaker controls. In this case the circuit breaker is operated physically by the maintenance personnel and the user/operator can only see the status of the circuit breaker and still unable to operate remotely.

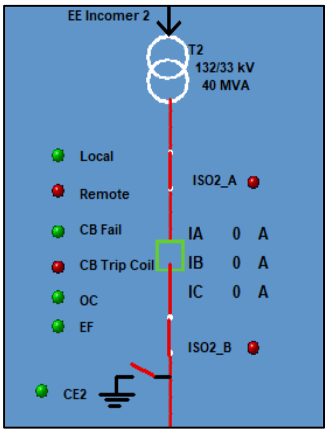


Figure 6-26: Incomer 2 Circuit Breaker Trip Coil Status

Figure 6-26 shows the SCADA model graphical representation of circuit trip coil/ trip coil supervision condition in remote mode. This trip condition was triggered when the power supply was switched off. In addition to the alerts, alarms and status indicators of the SCADA model, the relay HMI also displayed informative data to the operator/user. Figure 6-27 displays the hardware relay results of remote mode, trip coil supervision trip, circuit breaker, isolator status and earth switch status and the three phase currents observed when this test was undertaken. The numerical reading captured on the incomer 2 was zero amps due to the de-energized status of the associated feeder and bus section when this test was undertaken. The relay HMI also confirmed the functionality of the circuit breaker trip coil supervision indicator on the SCADA model.

Figure 6-27: Hardware Relay Incomer 2 Circuit Breaker Trip Coil Supervision Status

Figure 6-28 shows the SCADA model graphical representation of circuit breaker fail and earth fault status in remote mode. The earth fault was applied to the system, the circuit breaker of Incomer 2 in figure 6-29 failed to trip within the appropriate time to clear the fault, therefore the circuit breaker fail status was activated.

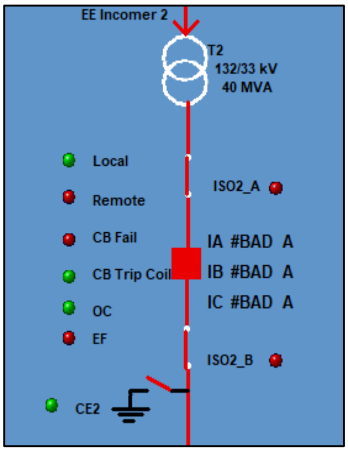


Figure 6-28: Incomer 2 Circuit Breaker Fail Status

Figure 6-29 shows the SCADA model graphical representation of feeder 2 overcurrent status indication in remote mode. An overcurrent was applied to the system, the overcurrent indication on the SCADA model was activated. The circuit breaker receives a trip signal from the feeder protection relay to clear the fault as indicated in Figure 6-30.

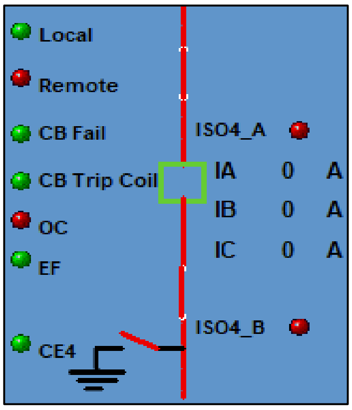


Figure 6-29: Feeder 2 3ph-G Overcurrent Trip Fault Condition

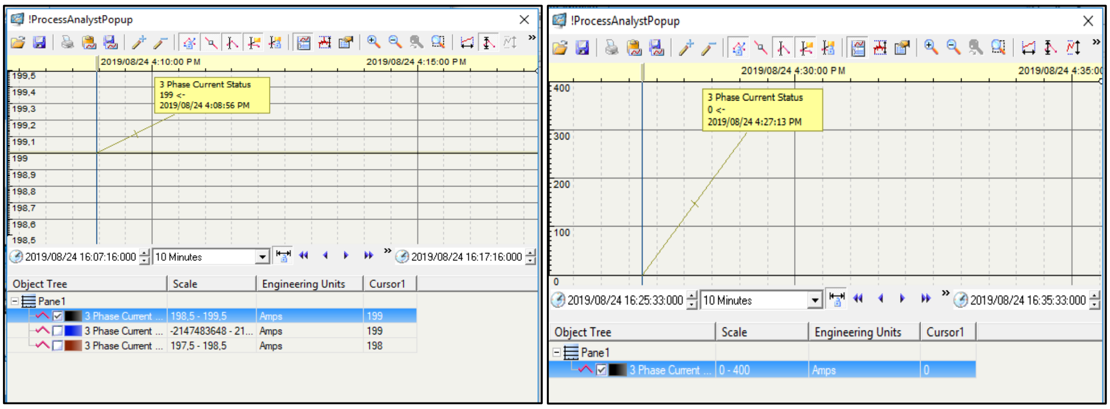


Figure 6-30: Three Phase Current under normal and overcurrent fault conditions

Figure 6-30 shows the SCADA model process analyst pop up real time trends representing the three phase currents under normal conditions and when an overcurrent was applied to the system. Under normal operating condition the three phase current was 199 A and when an overcurrent was applied the circuit breaker tripped and the three phase current was now 0 A due to the circuit breaker de-energized status.

6.3 Conclusion

The main purpose of Chapter 6 was to develop and design a SCADA and Automation system for the 132/ 33 kV substation. Schneider CitectSCADA software was used to develop and implement the SCADA model for the new substation. The designed SCADA system model is a representation of real substation equipment and provides the user/operators with fault management capabilities. The implemented SCADA systems provides graphical user interface of the electrical network, alarm features, trends and substation geographical location enabling the user/operator to visualize and interact with the substation equipment. This Chapter has demonstrated various tests conducted to confirm the operation of the implemented SCADA system. The developed system was equipped with hardware IEDs devices to perform functions of protection, control and monitoring a power system. From a network perspective, the SCADA communications network was developed. This communications architecture utilised the network switch to interconnect all devices via Ethernet communication medium. The IEC 61850 communications protocol was implemented for power monitoring and data capture between the IEDs and the implemented SCADA network. The IEC 61850 communications protocol enabled the user/operator the ability to remotely control IEDs via the use of command and control. This feature improves the operational efficiency and increases the safety of plant personnel.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

This chapter entails the conclusion summary based on the work conducted in each chapter as well recommendations and future work. The methodologies and techniques presented by different authors were reviewed and summarized in accordance to relevancy. The literatures were based on load flow analysis, protection systems, SCADA and SAS, which is elaborated on the relevant chapters of this dissertation.

7.1 Conclusion

The PoD is planning an expansion to cater for increased container throughput, therefore, requiring additional load of approximately 58 MVA. The additional demand required determined the voltage at which the power is to be supplied to the Port, which triggered the power supply upgrade to 132 kV. For the upgrade the power supply from EE is at 132 kV stepped to down to 33 kV and 11 kV [7, 8]. Power is transmitted from low demand areas to high demand in the grid. The electrical infrastructure required to support the power supply upgrade due to development and expansion plans was investigated in this dissertation. Load flow analysis was conducted to investigate the behaviour of the existing electrical network and design for the additional load demand requirements. The study was used as a means to determine voltages, active and reactive power of all buses in the network, for the specified load. The selected equipment percentage loading relative to equipment ratings was obtained to ensure these equipment will cater for the forecasted load demand. The purpose of the study was also to ensure that the voltages are maintained at acceptable limits. The NR method was used to obtain the power flow solution that is within acceptable tolerances [10, 11].

PowaMaster software tool was used to conduct the electrical network load flow study to analyse the prospective behaviour of the PoD's electrical network post implementation the new 132/33 kV Langeberg substation onto the currently existing network as part of network strengthening due to planned infrastructure developments. The load flow analysis was based on power supply options that included load forecasting for a period of five, seven and ten years. Post implementation of all the planned expansion projects by the year 2027, it was evident that it will not be feasible to source power with one 132/33 kV 40 MVA transformer as it was overloaded by 120%. The results confirmed the feasibility to source the power supply with two 132/33 kV 40 MVA transformers due to the transformer loading of 39.98% and 50.3% respectively which means both transformer have sufficient spare capacity. The power supply configuration allows for full redundancy and reliability of the network. All voltages were found to be within the acceptable ±5% limits as per SANS 10142-2 and NRS 048 requirements. The selected cables incoming cables for all scenarios considered will be sufficient to carry total Port loads without compromising the reliably and stability of the PoD's electrical network.

The SCADA and SAS was designed and developed using Schneider CitectSCADA software platform for the 132/33 kV substation. In order to achieve the SCADA & SAS requirements, the IEC 61850 and legacy compliant hardware i.e. relays/IEDs, RTU's, Ethernet switches and SCADA host software were required and utilised. A multi-protocol electrical substation network was developed to access the effectiveness of the communications protocols i.e. Modbus RTU, DNP3 and the IEC 61850 standard. This entailed the design and implementation of an interactive substation SCADA model architecture, which integrated the modern and legacy IEDs. The IEC 61850 communications network and system enabled the developed substation model the interoperability function between the IEDs of different manufacturers to perform functions of protection, control, monitoring and automation substations. The developed system was equipped with interactive features that enabled the user/operator to view the network status, alarming and trending.

7.2 Recommendations for Future Work

The work performed and presented in this dissertation confirms the theories from the literatures; however, it is not limited to the scope presented. It is therefore recommended that the following studies but not limited to these be conducted using the same electrical power systems network, namely:

(a) Protection grading study must be performed to safeguard correct selection of CT's, VT's and relay settings at the new 132/33/ kV Langeberg substations and the coordination of all other relays downstream.

(b) Harmonic filter or power factor correction study must be performed to ensure that the correct capacitor sizes are selected at the 132/33/ kV Langeberg substations.

(c) Conduct fault analysis study for the whole power system network to evaluate the network behaviour under contingency conditions.

(d) Development and implementation of security features. Assignment of privileges to user roles that control the SCADA and SAS elements of the electrical network. This will prevent unknown users from tampering with the electrical network and prevents unauthorised users from accessing the system. The different privilege access levels secures the electrical network configuration from unauthorised changes.

(e) Development and classification of alarm categories and priorities for SCADA & SAS to enable the user/operator to attend to the most critical alarms in a power system network.

(f) Introduction of flexible renewable energy based embedded generation to reduce the carbon footprint.

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APPENDICES

ANNEXURE A – MAXIMUM DEMAND RAW DATA RETRIEVED FROM SCADA SYSTEM

A. Total Average Demand at DHI & STS 33 kV Incomers

DADGEN_GENERAL.PLANT_KW_LOAD_TOT_DHI_STS33_AVG			DADGEN_GENERAL.PLANT_KW_LOAD_TOT_DHI_STS33_BUS	
DateTime	DADGEN_GENERAL.PLANT_KW_LOAD_TOT_DHI_STS33_AVG		DateTime	DADGEN_GENERAL.PLANT_KW_LOAD_TOT_DHI_STS33_BUS
2018/07/09 00:00	8706,551758		2018/07/09 00:00	9234,400391
2018/07/08 23:50	8486,75		2018/07/08 23:50	10851,81055
2018/07/08 23:40	8964,141602		2018/07/08 23:40	8759,779297
2018/07/08 23:30	8184,699707		2018/07/08 23:30	8773,599609
2018/07/08 23:20	9044,553711		2018/07/08 23:20	10755,05078
2018/07/08 23:10	9005,386719		2018/07/08 23:10	8262,120117
2018/07/08 23:00	9635,529297		2018/07/08 23:00	8699,870117
2018/07/08 22:50	8964,138672		2018/07/08 22:50	9354,199219
2018/07/08 22:40	9168,046875		2018/07/08 22:40	8870,360352
2018/07/08 22:30	9127,49707		2018/07/08 22:30	8769
2018/07/08 22:20	10367,27832		2018/07/08 22:20	9437,160156
2018/07/08 22:10	10150,23828		2018/07/08 22:10	9815,009766
2018/07/08 22:00	9095,927734		2018/07/08 22:00	8234,469727
2018/07/08 21:50	9826,760742		2018/07/08 21:50	10003,92969
2018/07/08 21:40	9353,291016		2018/07/08 21:40	8418,790039
2018/07/08 21:30	9591,063477		2018/07/08 21:30	9773,529297
2018/07/08 21:20	9406,280273		2018/07/08 21:20	10934,75977
2018/07/08 21:10	9417,339844		2018/07/08 21:10	9312,740234
2018/07/08 21:00	9544,061523		2018/07/08 21:00	9280,480469
2018/07/08 20:50	9811,089844		2018/07/08 20:50	9603,040039
2018/07/08 20:40	9524,476563		2018/07/08 20:40	9109,980469
2018/07/08 20:30	9405,129883		2018/07/08 20:30	8990,179688
2018/07/08 20:20	9421,485352		2018/07/08 20:20	8529,379883
2018/07/08 20:10	9236,013672		2018/07/08 20:10	9054,679688
2018/07/08 20:00	8955,387695		2018/07/08 20:00	9321,950195
2018/07/08 19:50	9295,689453		2018/07/08 19:50	7515,620117
2018/07/08 19:40	9817,543945		2018/07/08 19:40	10579,92969
2018/07/08 19:30	9995,414063		2018/07/08 19:30	9538,530273
2018/07/08 19:20	9520,09375		2018/07/08 19:20	9538,519531
2018/07/08 19:10	10001,86719		2018/07/08 19:10	10400,2207
2018/07/08 19:00	9365,499023		2018/07/08 19:00	9105,390625
2018/07/08 18:50	9435,774414		2018/07/08 18:50	9409,509766
2018/07/08 18:40	10143,55762		2018/07/08 18:40	9391,070313
2018/07/08 18:30	9379,09082		2018/07/08 18:30	9967,060547
2018/07/08 18:20	9247,536133		2018/07/08 18:20	8755,169922
2018/07/08 18:10	8765,076172		2018/07/08 18:10	8778,209961
2018/07/08 18:00	8875,211914		2018/07/08 18:00	8764,400391
2018/07/08 17:50	9221,503906		2018/07/08 17:50	9275,879883
2018/07/08 17:40	9591,063477		2018/07/08 17:40	9957,860352
2018/07/08 17:30	9804,871094		2018/07/08 17:30	9460,200195
2018/07/08 17:20	9886,894531		2018/07/08 17:20	9400,290039
2018/07/08 17:10	9511,111328		2018/07/08 17:10	9842,650391
2018/07/08 17:00	10476,94727		2018/07/08 17:00	11966,93945
2018/07/08 16:50	9403,514648		2018/07/08 16:50	8902,620117
2018/07/08 16:40	8107,978027		2018/07/08 16:40	8709,089844
2018/07/08 16:30	8476,386719		2018/07/08 16:30	8833,5

B. Top 10 Maximum Demand at DHI 33 kV Transformer Feeders

399. E22 DHI main 33 transformers						
DHI Distribution						
Date	kVA	kVAh	kWh Consumed	kVarh Lagging	PF	Usage Period
15/08/2017 10:30	2216,28	1 108,138	950,000	570,500	0,857	Standard
10/08/2017 13:30	2207,03	1 103,516	944,000	571,500	0,855	Standard
15/08/2017 10:00	2206,71	1 103,356	949,500	562,000	0,861	Standard
10/08/2017 14:00	2200,67	1 100,335	943,000	567,000	0,857	Standard
15/08/2017 11:00	2192,61	1 096,306	941,000	562,500	0,858	Standard
15/08/2017 09:30	2184,02	1 092,010	946,000	545,500	0,866	Standard
11/09/2017 11:00	2180,62	1 090,312	932,500	565,000	0,855	Standard
11/09/2017 11:30	2177,69	1 088,845	933,500	560,500	0,857	Standard
15/08/2017 11:30	2176,35	1 088,173	936,000	555,000	0,860	Standard
10/08/2017 14:30	2170,66	1 085,330	930,000	559,500	0,857	Standard
AVERAGE	**2191,26**					

399. E24 DHI main 33 transformers						
DHI Distribution						
Date	kVA	kVAh	kWh Consumed	kVarh Lagging	PF	Usage Period
25/05/2017 11:00	2264,47	1 132,237	960,500	599,500	0,848	Standard
03/05/2017 13:30	2212,32	1 106,161	938,500	585,500	0,848	Standard
06/06/2017 14:00	2203,87	1 101,933	950,500	557,500	0,863	Standard
06/06/2017 14:30	2187,67	1 093,833	945,500	550,000	0,864	Standard
30/03/2017 11:00	2178,19	1 089,095	943,500	544,000	0,866	Standard
30/03/2017 10:30	2159,45	1 079,723	937,000	536,500	0,868	Standard
03/05/2017 14:00	2150,70	1 075,350	916,500	562,500	0,852	Standard
04/05/2017 10:30	2142,03	1 071,017	895,500	587,500	0,836	Standard
06/06/2017 13:30	2133,54	1 066,771	920,000	540,000	0,862	Standard
04/05/2017 10:00	2118,14	1 059,070	902,000	555,000	0,852	Standard
AVERAGE	**2175,04**					

C. Top 10 Maximum Demand at STS 33 kV Transformer Feeders

397. STS E74 transformers						
E74 Distribution tx						
Block End	**kVA**	**kVAh**	**kWh Consumed**	**kVarh Lagging**	**PF**	**Usage Period**
13/02/2017 01:00	2192,92	1 096,462	987,000	477,500	0,900	Off-Peak
22/08/2017 03:30	2185,59	1 092,797	954,000	533,000	0,915	Off-Peak
16/03/2017 03:30	1857,20	928,600	853,000	367,000	0,946	Off-Peak
08/02/2017 04:00	1686,53	843,265	769,000	346,000	0,912	Off-Peak
30/01/2017 12:00	1520,49	760,243	695,500	307,000	0,915	Standard
08/06/2017 00:00	1487,61	743,803	635,500	386,500	0,854	Off-Peak
12/05/2017 18:51	1479,51	739,757	666,000	322,000	0,900	Peak
08/06/2017 00:30	1472,24	736,120	635,500	371,500	0,863	Off-Peak
30/01/2017 11:00	1466,96	733,480	673,500	290,500	0,918	Standard
08/06/2017 03:30	1460,76	730,380	633,500	363,500	0,867	Off-Peak
AVERAGE	**1680,98**					

397. STS E74 transformers						
E74 Distribution tx						
Block End	**kVA**	**kVAh**	**kWh Consumed**	**kVarh Lagging**	**PF**	**Usage Period**
30/01/2017 12:00	1520,49	760,243	695,500	307,000	0,915	Standard
08/06/2017 00:00	1487,61	743,803	635,500	386,500	0,854	Off-Peak
08/06/2017 00:30	1472,24	736,120	635,500	371,500	0,863	Off-Peak
30/01/2017 11:00	1466,96	733,480	673,500	290,500	0,918	Standard
08/06/2017 03:30	1460,76	730,380	633,500	363,500	0,867	Off-Peak
08/06/2017 03:00	1458,90	729,449	633,000	362,500	0,868	Off-Peak
07/06/2017 23:30	1457,34	728,670	629,500	367,000	0,864	Off-Peak
16/08/2017 23:00	1456,19	728,095	639,000	349,000	0,878	Off-Peak
22/06/2017 18:00	1452,80	726,399	666,000	290,000	0,917	Peak
08/06/2017 02:30	1450,46	725,232	629,000	361,000	0,867	Off-Peak
AVERAGE	**1468,37**					

ANNEXURE B – CABLE SELECTION CALCULATIONS & DATASHEETS

A. Cable Selection & Voltage Drop Calculations – For Cable after 132/33 kV 40 MVA TFR1

<u>Full Load Currents at Transformer 1 132/33 kV 40 MVA:</u>

$\boldsymbol{I_{FL1} = \frac{S}{\sqrt{3}\times V} = \frac{40\times 10^6}{\sqrt{3}\times 33\times 10^3} = 699.81\ A}$ Before derating for non-standard conditions

Derating factor for Depth of Burial 1.3 m is 0.93 (Obtained from cable Facts and Figures booklet).

Derating Factor for Soil Thermal Resistivity at 1.2 k.m/W is 1.00

Derating Factor for Ground temperature of 25 ˚C is 1.00

Therefore the derating Factor = 0.93 x 1.00 x 1.00 = 0.93

Considering the derating factor for the full load current at standard conditions is as follows:

$\boldsymbol{I_{FL1(std)} = I_{FL1} \times Total\ Derating\ Factor = 699.81 \times 0.93 = 650.82\ A}$

With reference to CBI MV XLPE cables, Cu 1 core, 19000/33000 V, Type A datasheet and SANS 1339:

For a current rating (Trefoil) of 650.8 A, the current cable size is chosen to be 630 mm^2.

Voltage Drop for 630 mm^2 Cu XLPE cable:

Voltage Drop = Impedance (Ω/km) x Cable Length (km) x Full Load Current before derating (A)

$$Voltage\ Drop = \frac{0.117}{1000} \times 50 \times 699.82 = 4.09\ V$$

$$\%Voltage\ Drop = \frac{4.09\ V}{33 \times 10^3\ V} \times 100\% = 0.0124\%$$

The % Voltage drop is way less than 5% of 33 kV therefore 630 mm^2 Cu XLPE cable size is acceptable.

Cable Selection & Voltage Drop – For Cable after 132/33 kV 40 MVA TFR2

<u>Full Load Currents at Transformer 2 132/33 kV 40 MVA:</u>

$\boldsymbol{I_{FL2} = \frac{S}{\sqrt{3}\times V} = \frac{40\times 10^6}{\sqrt{3}\times 33\times 10^3} = 699.81\ A}$ Before derating for non-standard conditions

Derating factor for Depth of Burial 1.3 m is 0.93 (Obtained from cable Facts and Figures booklet).

Derating Factor for Soil Thermal Resistivity at 1.2 k.m/W is 1.00

Derating Factor for Ground temperature of 25 ˚C is 1.00

Therefore the derating Factor = 0.93 x 1.00 x 1.00 = 0.93

Considering the derating factor for the full load current at standard conditions is as follows:

$\boldsymbol{I_{FL2(std)}=I_{FL2} \times Total\ Derating\ Factor = 699.81\ \times 0.93 = 650.82\ A}$

With reference to CBI MV XLPE cables, Cu 1 core, 19000/33000 V, Type A datasheet and SANS 1339:

For a current rating (Trefoil) of 650.8 A, the current cable size is chosen to be 630 mm^2.

Voltage Drop for 630 mm^2 Cu XLPE cable:

Voltage Drop = Impedance (Ω/km) x Cable Length (km) x Full Load Current before derating (A)

$$Voltage\ Drop = \frac{0.117}{1000} \times 50 \times 699.82 = 4.09\ V$$

$$\%Voltage\ Drop = \frac{4.09\ V}{33 \times 10^3\ V} \times 100\% = 0.0124\%$$

The % Voltage drop is way less than 5% of 33 kV therefore 630 mm^2 Cu XLPE cable size is acceptable.

Cable Selection & Voltage Drop – For Cable after 33/11 kV 10 MVA TFR1 & CB G02

Full Load Currents at Transformer 1 33/11 kV 10 MVA:

$\boldsymbol{I_{FL11} = \frac{S}{\sqrt{3} \times V} = \frac{10 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 524.86\ A}$ Before derating for non-standard conditions

Derating factor for Depth of Burial 1.3 m is 0.93 (Obtained from cable Facts and Figures booklet).

Derating Factor for Soil Thermal Resistivity at 1.2 k.m/W is 1.00

Derating Factor for Ground temperature of 25 ˚C is 1.00

Therefore the derating Factor = 0.93 x 1.00 x 1.00 = 0.93

Considering the derating factor for the full load current at standard conditions is as follows:

$\boldsymbol{I_{FL11(std)}=I_{FL11} \times Total\ Derating\ Factor = 524.86\ \times 0.93 = 488.12\ A}$

With reference to CBI MV XLPE cables, Cu 3 core, 6350/11000 V, Type A datasheet and SANS 1339:

For a current rating (in ground) of 488.12 A, the current cable size is chosen to be 300 mm^2.

Voltage Drop for 300 mm^2 Cu XLPE cable:

Voltage Drop = Impedance (Ω/km) x Cable Length (km) x Full Load Current before derating (A)

$$Voltage\ Drop = \frac{0.119}{1000} \times 50 \times 524.86 = 3.12\ V$$

$$\%Voltage\ Drop = \frac{3.12\ V}{11 \times 10^3\ V} \times 100\% = 0.028\%$$

The % Voltage drop is way less than 5% of 11 kV therefore 300 mm^2 Cu XLPE cable size is acceptable.

Cable Selection & Voltage Drop – For Cable after 33/11 kV 10 MVA TFR2 & CB G01

Full Load Currents at Transformer 2 33/11 kV 10 MVA:

$\boldsymbol{I_{FL22} = \frac{S}{\sqrt{3}\times V} = \frac{10 \times 10^6}{\sqrt{3}\times 11\times 10^3} = 524.86\ A}$ Before derating for non-standard conditions

Derating factor for Depth of Burial 1.3 m is 0.93 (Obtained from cable Facts and Figures booklet).

Derating Factor for Soil Thermal Resistivity at 1.2 k.m/W is 1.00

Derating Factor for Ground temperature of 25 ˚C is 1.00

Therefore the derating Factor = 0.93 x 1.00 x 1.00 = 0.93

Considering the derating factor for the full load current at standard conditions is as follows:

$\boldsymbol{I_{FL22(std)} = I_{FL22} \times Total\ Derating\ Factor = 524.86 \times 0.93 = 488.12\ A}$

With reference to CBI MV XLPE cables, Cu 3 core, 6350/11000 V, Type A datasheet and SANS 1339:

For a current rating (in ground) of 488.12 A, the current cable size is chosen to be 300 mm^2.

Voltage Drop for 300 mm^2 Cu XLPE cable:

Voltage Drop = Impedance (Ω/km) x Cable Length (km) x Full Load Current before derating (A)

$$Voltage\ Drop = \frac{0.119}{1000} \times 50 \times 524.86 = 3.12\ V$$

$$\%Voltage\ Drop = \frac{3.12\ V}{11 \times 10^3\ V} \times 100\% = 0.028\%$$

The % Voltage drop is way less than 5% of 11 kV therefore 300 mm^2 Cu XLPE cable size is acceptable.

B. HVCABLES MANUFACTURERS DATASHEET

DATA SHEET

HV XLPE Cable Data Sheet

CBI electric african cables

Description: ALUMINIUM, XLPE, W/B, CSA, LLDPE, HIGH STRESS

Voltage & Specification: 76/132kV, SANS 60840 / NRS 077

Water blocking: Core is standard, conductor on request

Last updated: April 2018

PHYSICAL DIMENSIONS:							
Conductor size	mm^2	300	400	500	630	800	1000
Conductor diameter	mm	20.4	23.9	26.4	29.7	34.2	38.3
Diameter over s/c conductor screen	mm	25.1	28.3	30.4	33.8	38.2	42.3
Diameter over XLPE insulation	mm	58.3	59.8	61.8	65.7	70.8	75.4
Diameter over s/c core screen	mm	61.0	62.3	64.2	68.2	73.3	77.9
Diameter over CSA sheath	mm	80.4	81.7	83.8	87.9	93.2	98.0
Final diameter of cable (D)	mm	91.4	92.7	97.0	101.1	106.4	111.2
Cable mass (approximate)	kg/m	7.3	7.6	8.4	9.2	10.3	11.4
Gross mass (500 m) (approximate)	kg	4850	5000	5400	5800	6350	6950
Minimum installation bending radius	m	1.8	1.9	1.9	2.0	2.1	2.2

RATINGS:		Trefoil	Flat (2D)	Trefoil	Flat (2D)	Trefoil	Flat (2D)	Trefoil	Flat (2D)	Trefoil	Flat (2D)	Trefoil	Flat (2D)
Current rating in ground	Amps	421	446	480	512	544	584	615	666	688	754	759	842
Current rating in air	Amps	581	653	677	770	776	888	892	1030	1021	1191	1148	1356
AC Resistance @ 90°C	Ω/km	0.1290	0.1289	0.1008	0.1006	0.0789	0.0787	0.0619	0.0616	0.0494	0.0489	0.0403	0.0396
Reactance	Ω/km	0.1546	0.2127	0.1450	0.2031	0.1416	0.1996	0.1367	0.1947	0.1309	0.1889	0.1265	0.1846
Impedance	Ω/km	0.2013	0.2487	0.1766	0.2266	0.1621	0.2146	0.1500	0.2042	0.1399	0.1952	0.1328	0.1888
Sheath standing voltage (flat - centre phase)	V/km	24.19	45.06	27.51	51.62	31.78	59.54	35.54	67.45	39.29	75.82	42.87	84.19

ELECTRICAL PARAMETERS:							
DC Resistance @ 20°C	Ω/km	0.1	0.0778	0.0605	0.0469	0.0367	0.0291
Max Electric stress at conductor screen	kV/mm	7.2	7.2	7.1	6.8	6.5	6.2
Min Electric stress at insulation screen	kV/mm	3.1	3.4	3.5	3.5	3.5	3.5
Capacitance	µF/km	0.1645	0.1860	0.1960	0.2087	0.2253	0.2401
Zero Sequence Resistance	Ω/km	0.1794	0.1503	0.1271	0.1077	0.0923	0.0808
Zero Sequence Reactance	Ω/km	0.0971	0.0877	0.0831	0.0788	0.0737	0.0700
Symmetrical fault rating (250°C)	kA (1s)	27.8	37.0	46.3	58.3	74.0	92.5
Earth fault rating (150°C)	kA (1s)	47.8	48.5	49.8	52.2	55.3	58.2

C. MV CABLES MANUFACTURERS DATASHEET

DATA SHEET

MV XLPE Cable Data Sheet

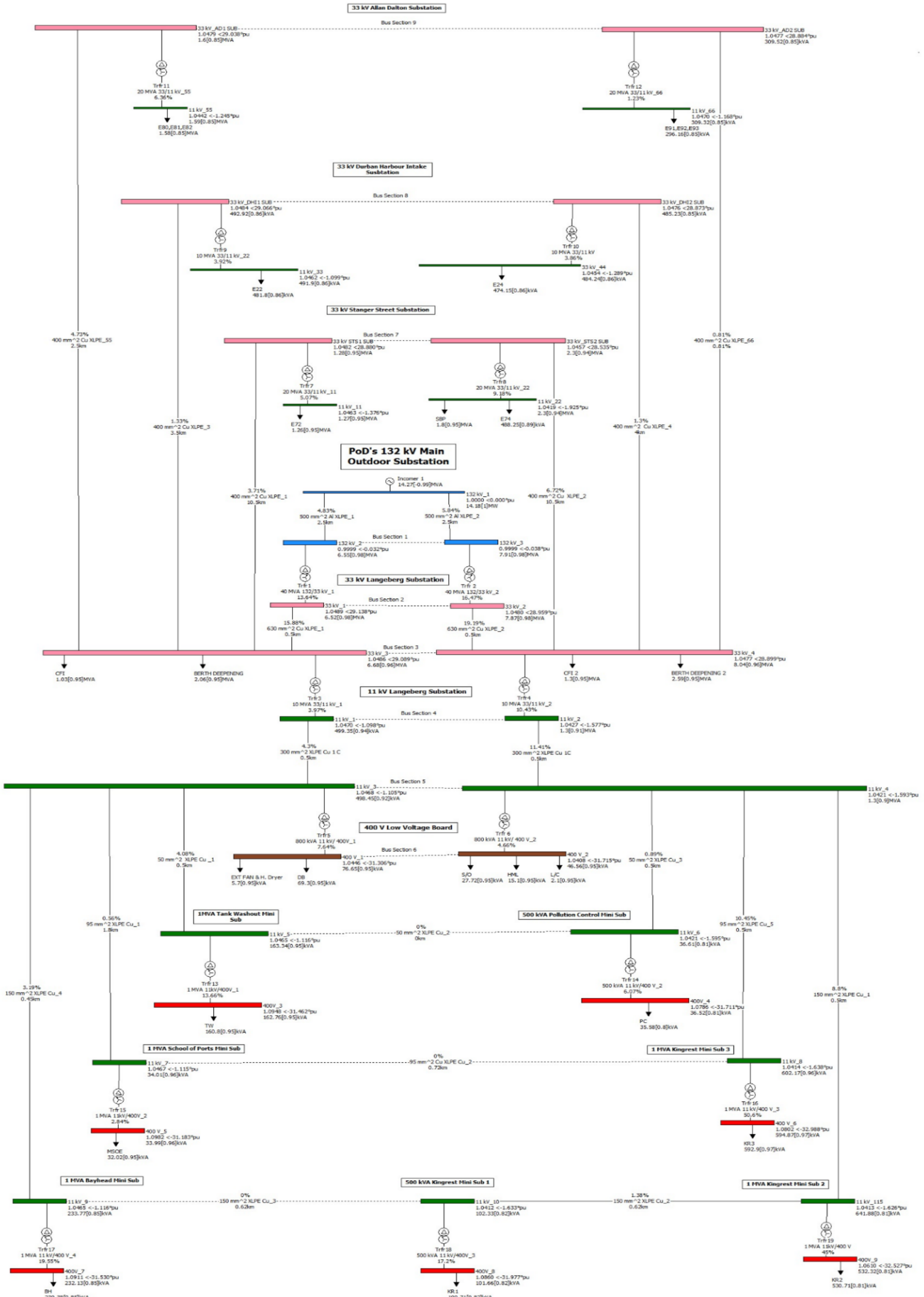
CBI electric african cables

Description:	19000/33000V, Copper, 1 Core, Type A	F2JC...
Bedding/Armouring/Sheathing:	FRPVC/AWA/FRPVC (red stripe)	...141
	LHPVC/AWA/LHPVC (blue stripe)	...242
Specification:	SANS 1339	

Last updated: October 2016

Size code	...n/a...	1050	1070	1095	1120	1150	1185	1240	1300	1400	1500	1630	1800	1999
PHYSICAL DIMENSIONS														
Conductor size	mm^2 nom	50	70	95	120	150	185	240	300	400	500	630	800	1000
Conductor diameter	mm app.	8.35	10.05	11.90	13.25	14.70	16.23	18.46	20.75	24.05	27.42	30.45	34.25	38.81
Insulation diameter	mm app.	26.45	28.15	30.00	31.35	32.80	34.33	36.56	38.85	42.95	41.98	50.13	53.93	58.49
Bedding diameter	mm app.	31.30	33.00	34.85	36.20	37.86	39.39	41.62	44.11	48.21	47.24	55.60	59.60	64.37
Armour diameter	mm app.	36.30	37.00	38.85	40.20	42.86	44.39	46.62	49.11	53.21	52.24	60.60	65.90	70.67
Cable diameter	mm app.	40.59	42.29	44.35	45.70	48.56	50.29	52.52	55.22	59.53	58.35	67.32	73.04	78.01
TECHNICAL DATA														
Normal drum length	m	500	500	500	500	500	500	500	500	500	500	500	500	500
Cable mass (approximate)	kg/m	2.15	2.45	2.81	3.11	3.65	4.11	4.82	5.59	6.59	7.94	9.44	11.71	13.98
Gross mass (500 m)	kg app.	1565	1700	1900	2050	2320	2550	3090	3475	3975	4650	5405	6550	8250
Bending radius	mm min.	812	846	887	914	971	1006	1050	1104	1191	1167	1346	1461	1560
DC Resistance @ 20°C	Ω/km	0.387	0.268	0.193	0.153	0.124	0.099	0.075	0.060	0.047	0.037	0.028	0.022	0.018
AC Resistance @ 90°C	Ω/km	0.494	0.342	0.247	0.196	0.159	0.128	0.098	0.079	0.063	0.051	0.041	0.034	0.030
Reactance	Ω/km	0.163	0.154	0.146	0.139	0.135	0.131	0.126	0.122	0.117	0.107	0.110	0.107	0.104
Impedance	Ω/km	0.520	0.375	0.287	0.240	0.209	0.183	0.159	0.145	0.133	0.119	0.117	0.113	0.108
Capacitance	µF/km	0.144	0.159	0.176	0.188	0.200	0.214	0.233	0.253	0.289	0.444	0.351	0.383	0.422
Zero Sequence Resistance	Ω/km	0.609	0.506	0.402	0.345	0.275	0.239	0.203	0.178	0.154	0.143	0.119	0.091	0.082
Zero Sequence Reactance	Ω/km	0.107	0.099	0.091	0.084	0.080	0.076	0.071	0.067	0.063	0.054	0.057	0.054	0.051
Current rating:														
In ground	Amps	205	250	296	333	368	409	463	511	565	618	670	703	742
In air in shade	Amps	246	304	367	418	470	529	610	684	774	863	955	1028	1108
In air in direct sunlight	Amps	193	239	288	328	367	413	476	533	601	672	739	794	853
Short circuit ratings:														
Symmetrical (250°C)	kA (1sec)	6.4	9.2	12.8	16.2	20.0	25.0	32.8	41.2	52.7	67.6	87.5	112.0	140.6
Earth fault (200°C)	kA (1sec)	16.8	17.7	18.7	19.4	25.1	26.0	27.4	29.0	31.6	31.0	36.2	31.6	34.1

ANNEXURE C – 132/33/11 kV Distribution Electrical Network Implemented in PowaMaster.



ANNEXURE D – LOAD FLOW STUDY PowaMaster RESULTS

A. Busbar Reports for Various Scenarios

Scenario 1 : 5 Year Load Forecast - 2 x 40 MVA Trfs						
Bus Name	**Bus Load (kVA)**	**Bus Load (PF)**	**Voltage pu**	**Voltage pu (Angle)**	**3-Ph Fault (A)**	**3-Ph Fault (Angle)**
11 kV_1	499.35	0.94	1.05	-1.10	4768.828	-85.436
11 kV_10	102.33	0.82	1.04	-1.63	3494.878	-81.302
11 kV_11	1272.97	0.95	1.05	-1.38	5029.272	-85.198
11 kV_115	641.88	0.81	1.04	-1.63	4030.288	-82.739
11 kV_2	1304.61	0.91	1.04	-1.58	4768.642	-85.436
11 kV_22	2296.58	0.94	1.04	-1.93	5028.819	-85.198
11 kV_3	498.46	0.92	1.05	-1.11	4595.501	-84.264
11 kV_33	491.90	0.86	1.05	-1.10	4333.988	-85.169
11 kV_4	1301.63	0.90	1.04	-1.59	4595.345	-84.264
11 kV_5	163.34	0.95	1.05	-1.12	3880.335	-78.631
11 kV_55	1594.33	0.85	1.04	-1.25	6648.799	-86.073
11 kV_6	36.61	0.81	1.04	-1.60	3880.226	-78.631
11 kV_66	309.32	0.85	1.05	-1.17	6391.623	-85.935
11 kV_7	34.01	0.96	1.05	-1.12	2940.284	-76.957
11 kV_8	602.17	0.96	1.04	-1.64	3981.634	-81.523
11 kV_9	233.77	0.85	1.05	-1.12	4080.789	-82.875
132 kV_1	14181.98	1.00	1.00	0.00	39966.488	-90
132 kV_2	6545.75	0.98	1.00	-0.03	22257.819	-87.445
132 kV_3	7905.99	0.98	1.00	-0.04	22257.444	-87.445
33 kV STS1 SUB	1275.28	0.95	1.05	28.88	2805.143	-84.637
33 kV_1	6522.76	0.98	1.05	29.14	6355.205	-87.222
33 kV_2	7872.29	0.98	1.05	28.96	6353.262	-87.221
33 kV_3	6683.67	0.96	1.05	29.09	6025.158	-87.109
33 kV_4	8042.07	0.96	1.05	28.90	6023.215	-87.108
33 kV_44	484.24	0.86	1.05	-1.29	4277.651	-85.134
33 kV_AD1 SUB	1599.98	0.85	1.05	29.04	4736.033	-86.122
33 kV_AD2 SUB	309.52	0.85	1.05	28.88	4361.046	-85.835
33 kV_DHI1 SUB	492.92	0.86	1.05	29.07	4362.066	-85.836
33 kV_DHI2 SUB	485.23	0.86	1.05	28.87	4195.328	-85.708
33 kV_STS2 SUB	2304.89	0.94	1.05	28.54	2804.721	-84.637
400 V_1	76.65	0.95	1.05	-31.31	20336.206	-78.424
400 V_2	46.56	0.95	1.04	-31.72	20336.097	-78.424
400 V_5	33.99	0.96	1.10	-31.18	19972.135	-77.212
400 V_6	594.87	0.97	1.08	-32.99	21513.466	-78.22

400V_3	162.76	0.95	1.10	-31.46	21383.709	-77.6
400V_4	36.52	0.81	1.08	-31.71	12310.67	-77.472
400V_7	232.13	0.85	1.09	-31.53	21634.398	-78.489
400V_8	101.66	0.82	1.09	-31.98	11859.998	-77.85
400V_9	532.32	0.81	1.06	-32.53	22099.318	-78.472

Scenario 2 : 5 Year Load Forecast - 1 x 40 MVA Trfs						
Bus Name	**Bus Load (kVA)**	**Bus Load (PF)**	**Voltage pu**	**Voltage pu (Angle)**	**3-Ph Fault (A)**	**3-Ph Fault (Angle)**
11 kV_1	499.36	0.94	1.04	-2.15	4763.997	-85.435
11 kV_10	102.32	0.82	1.04	-2.51	3492.48	-81.304
11 kV_11	1272.88	0.95	1.04	-2.43	5023.888	-85.197
11 kV_115	641.94	0.81	1.04	-2.50	4027.096	-82.741
11 kV_2	1304.77	0.91	1.04	-2.45	4764.173	-85.435
11 kV_22	2296.50	0.94	1.04	-2.80	5023.838	-85.197
11 kV_3	498.45	0.92	1.04	-2.16	4591.014	-84.264
11 kV_33	491.80	0.86	1.04	-2.15	4329.999	-85.168
11 kV_4	1301.78	0.90	1.04	-2.47	4591.194	-84.264
11 kV_5	163.32	0.95	1.04	-2.17	3877.151	-78.635
11 kV_55	1594.19	0.85	1.04	-2.30	6639.42	-86.071
11 kV_6	36.59	0.81	1.04	-2.47	3877.281	-78.636
11 kV_66	309.20	0.85	1.04	-2.04	6383.6	-85.933
11 kV_7	33.98	0.96	1.04	-2.17	2938.462	-76.962
11 kV_8	602.21	0.96	1.04	-2.52	3978.521	-81.525
11 kV_9	233.75	0.85	1.04	-2.17	4077.252	-82.876
132 kV_1	14322.15	0.99	1.00	0.00	39976.301	-90
132 kV_2	14517.49	0.98	1.00	-0.07	22255.893	-87.443
132 kV_3	-0.53	0.02	0.99	-1.92	916.301	-87.212
33 kV STS1 SUB	1275.22	0.95	1.04	27.83	2800.122	-84.637
33 kV_1	14399.22	0.98	1.04	28.09	6329.599	-87.211
33 kV_2	31.19	-0.50	1.04	28.09	6329.578	-87.211
33 kV_3	6685.41	0.96	1.04	28.04	6002.127	-87.099
33 kV_4	8043.78	0.96	1.04	28.03	6001.913	-87.099
33 kV_44	484.15	0.86	1.04	-2.16	4274.055	-85.133
33 kV_AD1 SUB	1599.89	0.85	1.04	27.99	4721.779	-86.117
33 kV_AD2 SUB	309.40	0.85	1.04	28.01	4349.856	-85.831
33 kV_DHI1 SUB	492.82	0.86	1.04	28.01	4349.968	-85.832
33 kV_DHI2 SUB	485.15	0.86	1.04	28.00	4184.97	-85.705

33 kV_STS2 SUB	2304.88	0.94	1.04	27.66	2800.075	-84.637
400 V_1	76.63	0.95	1.04	-32.36	20333.026	-78.425
400 V_2	46.54	0.95	1.04	-32.59	20333.155	-78.425
400 V_5	33.96	0.96	1.09	-32.24	19968.761	-77.213
400 V_6	594.84	0.97	1.08	-33.88	21509.837	-78.221
400V_3	162.72	0.95	1.09	-32.52	21379.839	-77.601
400V_4	36.50	0.81	1.07	-32.59	12309.512	-77.472
400V_7	232.09	0.85	1.09	-32.59	21630.43	-78.49
400V_8	101.64	0.82	1.08	-32.86	11858.895	-77.851
400V_9	532.29	0.81	1.06	-33.41	22095.578	-78.473

Scenario 3 : 7 Year Load Forecast - 2 x 40 MVA Trfs

Bus Name	Bus Load (kVA)	Bus Load (PF)	Voltage pu	Voltage pu (Angle)	3-Ph Fault (A)	3-Ph Fault (Angle)
11 kV_1	499.36	0.94	1.04	-2.28	4768.828	-85.436
11 kV_10	102.31	0.82	1.03	-3.14	3494.878	-81.302
11 kV_11	1272.79	0.95	1.04	-2.56	5029.272	-85.198
11 kV_115	642.08	0.81	1.03	-3.13	4030.288	-82.739
11 kV_2	1305.03	0.91	1.03	-3.08	4768.642	-85.436
11 kV_22	2296.34	0.94	1.03	-3.44	5028.819	-85.198
11 kV_3	498.45	0.92	1.04	-2.29	4595.501	-84.264
11 kV_33	491.72	0.86	1.04	-2.28	4333.988	-85.169
11 kV_4	1302.06	0.90	1.03	-3.10	4595.345	-84.264
11 kV_5	163.30	0.95	1.04	-2.30	3880.335	-78.631
11 kV_55	1594.09	0.85	1.04	-2.43	6648.799	-86.073
11 kV_6	36.57	0.81	1.03	-3.10	3880.226	-78.631
11 kV_66	309.01	0.85	1.04	-2.66	6391.623	-85.935
11 kV_7	33.96	0.96	1.04	-2.30	2940.284	-76.957
11 kV_8	602.29	0.96	1.03	-3.14	3981.634	-81.523
11 kV_9	233.75	0.85	1.04	-2.30	4080.789	-82.875
132 kV_1	33766.10	0.97	1.00	0.00	39966.488	-90
132 kV_2	15327.97	0.96	1.00	-0.07	22257.819	-87.445
132 kV_3	19022.24	0.95	1.00	-0.09	22257.444	-87.445
33 kV STS1 SUB	1275.14	0.95	1.04	27.70	2805.143	-84.637
33 kV_1	15155.49	0.97	1.04	28.02	6355.205	-87.222
33 kV_2	18751.84	0.97	1.04	27.55	6353.262	-87.221
33 kV_3	15337.84	0.95	1.04	27.91	6025.158	-87.109
33 kV_4	18943.13	0.95	1.04	27.41	6023.215	-87.108
33 kV_44	484.00	0.86	1.03	-2.79	4277.651	-85.134

33 kV_AD1 SUB	1599.84	0.85	1.04	27.86	4736.033	-86.122
33 kV_AD2 SUB	309.21	0.85	1.04	27.39	4361.046	-85.835
33 kV_DHI1 SUB	492.75	0.86	1.04	27.89	4362.066	-85.836
33 kV_DHI2 SUB	485.01	0.86	1.04	27.38	4195.328	-85.708
33 kV_STS2 SUB	2304.83	0.94	1.03	27.04	2804.721	-84.637
400 V_1	76.61	0.95	1.04	-32.49	20336.206	-78.424
400 V_2	46.51	0.95	1.03	-33.22	20336.097	-78.424
400 V_5	33.94	0.96	1.09	-32.37	19972.135	-77.212
400 V_6	594.81	0.97	1.07	-34.52	21513.466	-78.22
400V_3	162.71	0.95	1.09	-32.65	21383.709	-77.6
400V_4	36.48	0.81	1.07	-33.22	12310.67	-77.472
400V_7	232.07	0.85	1.08	-32.72	21634.398	-78.489
400V_8	101.62	0.82	1.07	-33.49	11859.997	-77.85
400V_9	532.25	0.81	1.05	-34.05	22099.318	-78.472

Scenario 4 : 7 Year Load Forecast - 1 x 40 MVA Trf

Bus Name	Bus Load (kVA)	Bus Load (PF)	Voltage pu	Voltage pu (Angle)	3-Ph Fault (A)	3-Ph Fault (Angle)
11 kV_1	499.02	0.94	1.04	-4.81	4712.568	-85.453
11 kV_10	102.28	0.82	1.04	-5.18	3464.888	-81.35
11 kV_11	1272.43	0.95	1.05	-5.10	4872.53	-85.18
11 kV_115	641.91	0.81	1.04	-5.18	3990.374	-82.781
11 kV_2	1304.42	0.91	1.04	-5.13	4712.743	-85.453
11 kV_22	2296.02	0.94	1.04	-5.49	4872.48	-85.18
11 kV_3	498.42	0.92	1.04	-4.82	4543.27	-84.293
11 kV_33	491.35	0.86	1.04	-4.81	4271.554	-85.177
11 kV_4	1301.79	0.90	1.04	-5.14	4543.449	-84.293
11 kV_5	163.28	0.95	1.04	-4.83	3843.369	-78.71
11 kV_55	1593.60	0.85	1.04	-4.96	6481.609	-86.072
11 kV_6	36.55	0.81	1.04	-5.15	3843.498	-78.71
11 kV_66	308.61	0.85	1.05	-4.72	6225.409	-85.93
11 kV_7	33.94	0.96	1.04	-4.83	2919.107	-77.029
11 kV_8	602.19	0.96	1.04	-5.19	3942.742	-81.575
11 kV_9	233.70	0.85	1.04	-4.83	4039.607	-82.915
132 kV_1	34571.03	0.95	1.00	0.00	39976.287	-90
132 kV_2	34890.48	0.94	1.00	-0.16	22255.879	-87.443
132 kV_3	-1.19	0.04	0.97	-4.50	916.297	-87.212
33 kV STS1 SUB	1274.74	0.95	1.02	25.16	2800.112	-84.637

33 kV_1	33928.62	0.96	1.02	25.50	6329.55	-87.211
33 kV_2	30.49	-0.49	1.02	25.50	6329.529	-87.211
33 kV_3	15343.56	0.95	1.02	25.38	6002.08	-87.099
33 kV_4	18947.99	0.95	1.02	25.35	6001.867	-87.099
33 kV_44	483.70	0.86	1.04	-4.84	4214.886	-85.141
33 kV_AD1 SUB	1599.25	0.85	1.02	25.33	4721.75	-86.117
33 kV_AD2 SUB	308.80	0.85	1.02	25.34	4349.831	-85.831
33 kV_DHI1 SUB	492.37	0.86	1.02	25.36	4349.943	-85.832
33 kV_DHI2 SUB	484.70	0.86	1.02	25.33	4184.947	-85.705
33 kV_STS2 SUB	2304.33	0.94	1.02	24.97	2800.065	-84.637
400 V_1	76.60	0.95	1.04	-35.02	20299.021	-78.44
400 V_2	46.50	0.95	1.04	-35.27	20299.152	-78.44
400 V_5	33.92	0.96	1.09	-34.90	19932.728	-77.231
400 V_6	594.81	0.97	1.07	-36.56	21467.919	-78.238
400V_3	162.69	0.95	1.09	-35.18	21338.495	-77.619
400V_4	36.47	0.81	1.07	-35.26	12296.126	-77.483
400V_7	232.03	0.85	1.09	-35.25	21588.008	-78.507
400V_8	101.61	0.82	1.08	-35.53	11846.155	-77.861
400V_9	532.23	0.81	1.06	-36.09	22052.362	-78.49

Scenario 5 : 10 Year Load Forecast - 2 x 40 MVA Trfs

Bus Name	Bus Load (kVA)	Bus Load (PF)	Voltage pu	Voltage pu (Angle)	3-Ph Fault (A)	3-Ph Fault (Angle)
11 kV_1	499.36	0.94	1.03	-2.80	4768.828	-85.436
11 kV_10	102.31	0.82	1.04	-3.79	3467.348	-81.348
11 kV_11	1272.71	0.95	1.03	-3.08	5029.272	-85.198
11 kV_115	641.77	0.81	1.04	-3.78	3993.641	-82.779
11 kV_2	1304.13	0.91	1.05	-3.73	4717.301	-85.454
11 kV_22	2296.19	0.94	1.04	-4.10	4953.394	-85.189
11 kV_3	498.45	0.92	1.03	-2.80	4595.501	-84.264
11 kV_33	2142.42	0.93	1.03	-3.55	4333.988	-85.169
11 kV_4	1301.49	0.90	1.05	-3.75	4547.686	-84.293
11 kV_5	163.29	0.95	1.03	-2.81	3880.335	-78.631
11 kV_55	1593.98	0.85	1.03	-2.95	6648.799	-86.073
11 kV_6	36.58	0.81	1.05	-3.75	3846.515	-78.705

11 kV_66	3528.20	0.91	1.03	-4.14	6313.04	-85.934
11 kV_7	33.94	0.96	1.03	-2.81	2940.284	-76.957
11 kV_8	602.11	0.96	1.04	-3.79	3945.928	-81.573
11 kV_9	233.74	0.85	1.03	-2.81	4080.789	-82.875
132 kV_1	42655.65	0.96	1.00	0.00	39966.482	-90
132 kV_2	19178.47	0.95	1.00	-0.09	22257.817	-87.445
132 kV_3	24135.04	0.94	1.00	-0.11	22257.438	-87.445
33 kV STS1 SUB	1275.08	0.95	1.04	27.18	2805.143	-84.637
33 kV_1	18893.83	0.96	1.04	27.54	6355.205	-87.222
33 kV_2	23656.54	0.96	1.03	26.92	6353.239	-87.221
33 kV_3	19074.08	0.95	1.04	27.40	6025.158	-87.109
33 kV_4	23850.97	0.95	1.03	26.74	6023.192	-87.108
33 kV_44	2134.47	0.93	1.04	-4.20	4218.532	-85.142
33 kV_AD1 SUB	1599.77	0.85	1.04	27.34	4736.033	-86.122
33 kV_AD2 SUB	3551.31	0.91	1.03	26.56	4361.034	-85.835
33 kV_DHI1 SUB	2158.08	0.93	1.03	27.28	4362.066	-85.836
33 kV_DHI2 SUB	2149.56	0.93	1.03	26.61	4195.317	-85.708
33 kV_STS2 SUB	2304.58	0.94	1.03	26.36	2804.716	-84.637
400 V_1	76.60	0.95	1.03	-33.01	20336.206	-78.424
400 V_2	46.54	0.95	1.04	-33.87	20302.209	-78.439
400 V_5	33.92	0.96	1.08	-32.88	19972.135	-77.212
400 V_6	594.86	0.97	1.08	-35.14	21471.687	-78.237
400V_3	162.69	0.95	1.08	-33.17	21383.709	-77.6
400V_4	36.50	0.81	1.08	-33.87	12297.331	-77.482
400V_7	232.05	0.85	1.08	-33.24	21634.398	-78.489
400V_8	101.64	0.82	1.09	-34.13	11847.302	-77.86
400V_9	532.28	0.81	1.06	-34.68	22056.246	-78.489

Scenario 6 : 10 Year Load Forecast - 1 x 40 MVA Trfs

Bus Name	Bus Load (kVA)	Bus Load (PF)	Voltage pu	Voltage pu (Angle)	3-Ph Fault (A)	3-Ph Fault (Angle)
11 kV_1	499.42	0.94	1.03	-7.49	4755.99	-85.438
11 kV_10	102.24	0.82	1.03	-7.88	3488.197	-81.312
11 kV_11	1272.82	0.95	1.05	-7.76	4939.618	-85.192
11 kV_115	642.00	0.81	1.03	-7.88	4021.388	-82.747
11 kV_2	1305.06	0.91	1.03	-7.83	4756.166	-85.438
11 kV_22	2296.38	0.94	1.04	-8.17	4939.568	-85.192

11 kV_3	498.39	0.92	1.03	-7.49	4583.584	-84.269
11 kV_33	3466.16	0.91	1.04	-8.74	4264.862	-85.18
11 kV_4	1302.03	0.90	1.03	-7.84	4583.764	-84.269
11 kV_5	163.22	0.95	1.03	-7.51	3871.904	-78.647
11 kV_55	1593.85	0.85	1.04	-7.63	6545.511	-86.075
11 kV_6	36.50	0.81	1.03	-7.84	3872.034	-78.647
11 kV_66	4324.86	0.92	1.04	-8.41	6290.649	-85.935
11 kV_7	33.88	0.96	1.03	-7.50	2935.462	-76.973
11 kV_8	602.24	0.96	1.03	-7.89	3972.961	-81.533
11 kV_9	233.64	0.85	1.03	-7.51	4071.4	-82.883
132 kV_1	59899.88	0.91	1.00	0.00	39975.14	-90
132 kV_2	60202.91	0.91	1.00	-0.26	22254.734	-87.443
132 kV_3	-1.77	0.06	0.95	-7.11	989.691	-87.213
33 kV STS1 SUB	1275.13	0.95	1.04	22.49	2791.821	-84.645
33 kV_1	57096.51	0.95	1.04	22.90	6287.423	-87.212
33 kV_2	31.24	-0.45	1.04	22.90	6287.402	-87.212
33 kV_3	25759.12	0.95	1.04	22.71	5964.173	-87.101
33 kV_4	31701.47	0.94	1.04	22.66	5963.961	-87.101
33 kV_44	3457.17	0.91	1.04	-8.80	4208.369	-85.145
33 kV_AD1 SUB	1599.50	0.85	1.04	22.65	4698.261	-86.123
33 kV_AD2 SUB	4358.25	0.91	1.03	22.44	4329.888	-85.839
33 kV_DHI1 SUB	3511.69	0.90	1.03	22.53	4330	-85.839
33 kV_DHI2 SUB	3502.65	0.90	1.03	22.46	4166.483	-85.712
33 kV_STS2 SUB	2304.68	0.94	1.03	22.29	2791.774	-84.645
400 V_1	76.54	0.95	1.03	-37.70	20327.775	-78.427
400 V_2	46.45	0.95	1.03	-37.97	20327.905	-78.427
400 V_5	33.86	0.96	1.08	-37.57	19963.197	-77.216
400 V_6	594.75	0.97	1.07	-39.27	21503.364	-78.224
400V_3	162.62	0.95	1.08	-37.86	21373.455	-77.604
400V_4	36.42	0.81	1.07	-37.96	12307.446	-77.474
400V_7	231.95	0.85	1.08	-37.93	21623.878	-78.493
400V_8	101.56	0.82	1.07	-38.24	11856.929	-77.853
400V_9	532.14	0.81	1.05	-38.80	22088.904	-78.475

A. Cable Loading Reports for Various Scenarios

Scenario 1 : 5 Year Load Forecast - 2 x 40 MVA Trfs						
From Bus Name	To Bus Name	Section Conductor Description	Total Length (km)	% Branch Loading A	Name	Branch Rating A (A)
11 kV_4	11 kV_115	11 kV 150mm2 Cu XLPE 1Core	0.5	8.8	150 mm^2 XLPE Cu_1	365
11 kV_10	11 kV_115	11 kV 150mm2 Cu XLPE 1Core	0.62	1.38	150 mm^2 XLPE Cu_2	365
11 kV_9	11 kV_10	11 kV 150mm2 Cu XLPE 1Core	0.62	0	150 mm^2 XLPE Cu_3	365
11 kV_3	11 kV_9	11 kV 150mm2 Cu XLPE 1Core	0.45	3.19	150 mm^2 XLPE Cu_4	365
11 kV_1	11 kV_3	300 XLPE 11kV Cu 1C Tre Gnd	0.5	4.73	300 mm^2 XLPE Cu 1 C	520
11 kV_2	11 kV_4	300 XLPE 11kV Cu 1C Tre Gnd	0.5	12.55	300 mm^2 XLPE Cu 1C	520
33 kV_4	33 kV_DHI2 SUB	33 kV 400mm2 Cu XLPE 1Core	4	1.3	400 mm^2 Cu XLPE_4	545
33 kV_4	33 kV_STS2 SUB	33 kV 400mm2 Cu XLPE 1Core	10.5	6.72	400 mm^2 Cu XLPE_2	545
33 kV_3	33 kV STS1 SUB	33 kV 400mm2 Cu XLPE 1Core	10.5	3.71	400 mm^2 Cu XLPE_1	545
33 kV_3	33 kV_DHI1 SUB	33 kV 400mm2 Cu XLPE 1Core	3.5	1.33	400 mm^2 Cu XLPE_3	545
33 kV_3	33 kV_AD1 SUB	33 kV 400mm2 Cu XLPE 1Core	2.5	4.73	400 mm^2 Cu XLPE_55	545
33 kV_4	33 kV_AD2 SUB	33 kV 400mm2 Cu XLPE 1Core	3.5	0.81	400 mm^2 Cu XLPE_66	545
11 kV_3	11 kV_5	11 kV 50mm2 Cu XLPE 1Core	0.5	4.08	50 mm^2 XLPE Cu _1	200
11 kV_5	11 kV_6	11 kV 50mm2 Cu XLPE 1Core	0	0	50 mm^2 XLPE Cu_2	200
11 kV_4	11 kV_6	11 kV 50mm2 Cu XLPE 1Core	0.5	0.89	50 mm^2 XLPE Cu_3	200
132 kV_1	132 kV_2	132 kV 500mm2 Al XLPE 1Core	2.5	4.83	500 mm^2 Al XLPE_1	581
132 kV_1	132 kV_3	132 kV 500mm2 Al XLPE 1Core	2.5	5.84	500 mm^2 Al XLPE_2	581
33 kV_1	33 kV_3	33 kV 630mm2 Cu XLPE 1Core	0.5	15.88	630 mm^2 Cu XLPE_1	684
33 kV_2	33 kV_4	33 kV 630mm2 Cu XLPE 1Core	0.5	19.19	630 mm^2 Cu XLPE_2	684
11 kV_7	11 kV_8	11 kV 95mm2 Cu XLPE 1Core	0.72	0	95 mm^2 Cu XLPE Cu_2	290

11 kV_3	11 kV_7	11 kV 95mm2 Cu XLPE 1Core	1.8	0.56	95 mm^2 XLPE Cu_1	290
11 kV_4	11 kV_8	11 kV 95mm2 Cu XLPE 1Core	0.5	10.45	95 mm^2 XLPE Cu_5	290
132 kV_2	132 kV_3	SWCH	0	0	Bus Section 1	5000
33 kV_1	33 kV_2	SWCH	0	0	Bus Section 2	5000
33 kV_3	33 kV_4	SWCH	0	0	Bus Section 3	5000
11 kV_1	11 kV_2	SWCH	0	0	Bus Section 4	5000
11 kV_3	11 kV_4	SWCH	0	0	Bus Section 5	5000
400 V_1	400 V_2	SWCH	0	0	Bus Section 6	5000
33 kV STS1 SUB	33 kV_STS2 SUB	SWCH	0	0	Bus Section 7	5000
33 kV_DHI1 SUB	33 kV_DHI2 SUB	SWCH	0	0	Bus Section 8	5000
33 kV_AD1 SUB	33 kV_AD2 SUB	SWCH	0	0	Bus Section 9	5000

Scenario 2 : 5 Year Load Forecast - 1 x 40 MVA Trfs

From Bus Name	To Bus Name	Section Conductor Description	Total Length (km)	% Branch Loading A	Name	Branch Rating A (A)
11 kV_4	11 kV_115	11 kV 150mm2 Cu XLPE 1Core	0.5	8.84	150 mm^2 XLPE Cu_1	365
11 kV_10	11 kV_115	11 kV 150mm2 Cu XLPE 1Core	0.62	1.39	150 mm^2 XLPE Cu_2	365
11 kV_9	11 kV_10	11 kV 150mm2 Cu XLPE 1Core	0.62	0	150 mm^2 XLPE Cu_3	365
11 kV_3	11 kV_9	11 kV 150mm2 Cu XLPE 1Core	0.45	3.21	150 mm^2 XLPE Cu_4	365
11 kV_1	11 kV_3	300 XLPE 11kV Cu 1C Tre Gnd	0.5	4.76	300 mm^2 XLPE Cu 1 C	520
11 kV_2	11 kV_4	300 XLPE 11kV Cu 1C Tre Gnd	0.5	12.61	300 mm^2 XLPE Cu 1C	520
33 kV_4	33 kV_DHI2 SUB	33 kV 400mm2 Cu XLPE 1Core	4	1.3	400 mm^2 Cu XLPE_4	545
33 kV_4	33 kV_STS2 SUB	33 kV 400mm2 Cu XLPE 1Core	10.5	6.75	400 mm^2 Cu XLPE_2	545
33 kV_3	33 kV STS1 SUB	33 kV 400mm2 Cu XLPE 1Core	10.5	3.73	400 mm^2 Cu XLPE_1	545
33 kV_3	33 kV_DHI1 SUB	33 kV 400mm2 Cu XLPE 1Core	3.5	1.34	400 mm^2 Cu XLPE_3	545
33 kV_3	33 kV_AD1 SUB	33 kV 400mm2 Cu XLPE 1Core	2.5	4.76	400 mm^2 Cu XLPE_55	545

33 kV_4	33 kV_AD2 SUB	33 kV 400mm2 Cu XLPE 1Core	3.5	0.82	400 mm^2 Cu XLPE_66	545
11 kV_3	11 kV_5	11 kV 50mm2 Cu XLPE 1Core	0.5	4.1	50 mm^2 XLPE Cu _1	200
11 kV_5	11 kV_6	11 kV 50mm2 Cu XLPE 1Core	0	0	50 mm^2 XLPE Cu_2	200
11 kV_4	11 kV_6	11 kV 50mm2 Cu XLPE 1Core	0.5	0.9	50 mm^2 XLPE Cu_3	200
132 kV_1	132 kV_2	132 kV 500mm2 Al XLPE 1Core	2.5	10.78	500 mm^2 Al XLPE_1	581
132 kV_1	132 kV_3	132 kV 500mm2 Al XLPE 1Core	2.5	0	500 mm^2 Al XLPE_2	581
33 kV_1	33 kV_3	33 kV 630mm2 Cu XLPE 1Core	0.5	15.96	630 mm^2 Cu XLPE_1	684
33 kV_2	33 kV_4	33 kV 630mm2 Cu XLPE 1Core	0.5	19.27	630 mm^2 Cu XLPE_2	684
11 kV_7	11 kV_8	11 kV 95mm2 Cu XLPE 1Core	0.72	0	95 mm^2 Cu XLPE Cu_2	290
11 kV_3	11 kV_7	11 kV 95mm2 Cu XLPE 1Core	1.8	0.56	95 mm^2 XLPE Cu_1	290
11 kV_4	11 kV_8	11 kV 95mm2 Cu XLPE 1Core	0.5	10.5	95 mm^2 XLPE Cu_5	290
132 kV_2	132 kV_3	SWCH	0	0	Bus Section 1	5000
33 kV_1	33 kV_2	SWCH	0	2.64	Bus Section 2	5000
33 kV_3	33 kV_4	SWCH	0	0	Bus Section 3	5000
11 kV_1	11 kV_2	SWCH	0	0	Bus Section 4	5000
11 kV_3	11 kV_4	SWCH	0	0	Bus Section 5	5000
400 V_1	400 V_2	SWCH	0	0	Bus Section 6	5000
33 kV STS1 SUB	33 kV_STS2 SUB	SWCH	0	0	Bus Section 7	5000
33 kV_DHI1 SUB	33 kV_DHI2 SUB	SWCH	0	0	Bus Section 8	5000
33 kV_AD1 SUB	33 kV_AD2 SUB	SWCH	0	0	Bus Section 9	5000

ANNEXURE E – INTELLIGENT ELECTRONIC DEVICES USED

A. IEDs Compliant to IEC 61850

GE Industrial Systems

F35 Multiple Feeder Management Relay

UR Series Instruction Manual

F35 Revision: 4.9x

Manual P/N: 1601-0106-M2 (GEK-113205A)

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LISTED MEASURING EQUIP. 20GN

GE Multilin's Quality Management System is registered to ISO9001:2000

QMI # 005094

UL # A3775

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B. Legacy IEDs

P12x/EN FT/Fc6 — User Guide

Page 4/64 — MiCOM P120/P121/P122/P123

1.1 USER INTERFACE

1.1.1 Relay Overview

The next figures show the MiCOM P120, P121, P122 and P123 relays.

The table shows the case size for the relays.

Height	Depth	Width
4U (177mm)	226mm	20 TE

The hinged covers at the top and bottom of the relay are shown closed. Extra physical protection for the front panel can be provided by an optional transparent front cover; this allows read only access to the relays settings and data but does not affect the relays IP rating. When full access to the relay keypad is required to edit the settings, the transparent cover can be unclipped and removed when the top and bottom hinged covers are open.

C. Remote Terminal Unit

Product data sheet
Characteristics

C264C1-------0----
MiCOM C264 Bay Controller and RTU with LCD Display 40TE size

Main

Range of product	MiCOM C264
Device short name	C264
Display resolution	128 x 128 pixels
Display type	LCD display LED indicator
User machine interface type	Mimic-based
[Us] rated supply voltage	24 V DC - 20...10 % 40 W 48...60 V DC - 20...10 % 40 W 220 V DC - 20...10 % 40 W 110 V AC 50/60 Hz - 20...10 % 40 W 230 V AC 50/60 Hz - 20...10 % 40 W
IP degree of protection	Case: IP50 conforming to IEC 60255-27 Front panel: IP52 conforming to IEC 60255-27