DESIGNING A MODERN SUBSTATION TO MINIMISE COST AND TIME DURING FUTURE UPGRADES

By

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Dissertation submitted in fulfilment of the requirements for the degree:

Master of Engineering in Electrical Engineering

In the Department of Electrical, Electronic and Computer Engineering

Faculty of Engineering and Information Technology

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July 2019

Declaration

I, Sinclair Boy Pienaar, student number , do hereby declare that this research project, which has been submitted to the Central University of Technology Free State, for the degree: Master of Engineering in Electrical Engineering, is my independent work. This research project complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State. This project has not previously been submitted by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Signature

Date: 10/07/2019

Acknowledgements

I express my appreciation to the Omniscient force in the universe, Jehovah Jireh and the following amazing individuals:

- My supervisor, Professor Kanzumba Kusakana, thank you for the informative ideas, educational intelligence, continuous guidance and feedback.
- My co-supervisor, Doctor Patrick Maditereza, thank you for the comments, knowledge and advice.
- My family, thank you for your love and encouragement.
- My friends, especially my partner (Shermone), thank you for your patience and support.

Abstract

The Northern Cape Operating Unit in South Africa is experiencing load growth, due to residential developments, high electrification growth, agriculture and mining. The rural areas were previously not given sufficient attention, a result of slow developmental growth. The current 66 kV network experiences low voltages, under n-1 contingencies. The existing 66 kV network has no spare capacity to supply new customers. For additional capacity, Eskom should upgrade its distribution network from 66 kV to 132 kV. Eskom further upgrades their substations, due to equipment reaching their functional lifespans. The cost to maintain equipment regularly is high. Old apparatus interrupts security and continuity of supply to customers regularly.

The challenge with substation upgrades, on existing substations, is the cost involved to upgrade the 66 kV substations to 132 kV. Before substation, upgrades may take place. New and existing consumers who require additional capacity are not connected, due to capacity constraints in existing substations. Older protection schemes do not possess any data storage facilities, to be utilised during fault investigations. Phase one protection schemes solely retain the flag of the previous incident, which is not adequate when investigating faults for extended periods. During substation upgrades, continuity of supply to existing customers is necessary to improve customer satisfaction and network performance.

Electricity is generated and distributed instantaneously, by electricity utilities. There is occasionally an enormous amount of wasted capacity in electricity utilities. Illegal connections contribute to overloads and trips, as the network is carrying more users than initially designed. It is particularly critical to assess the economic practicability of BESS for diverse applications. The costs of energy storage systems, depend on the type of technology, the planned operation, and the hours of storage required.

This dissertation further proposed a Battery Energy Storage System (BESS) design, which leads to a costly network upgrade deferral and increased self-consumption. BESS reduces environmental pollution (Environmentally friendly), reduces consumer electricity prices (Creating value for customers), provides reliable back up supply, improve network performance and create sufficient capacity on the medium voltage network.

This dissertation compared different substation designs and the most cost-effective design, when upgrading modern substations, were preferred. The modern substation design reduced the complexity of substation upgrades, reduced substation upgrade expenses and improved network performance. Furthermore, the preferred modern substation upgrade designs had the lowest influence on network performance, during construction. The high voltage and medium voltage systems were reliable for n-1 contingencies. Finally, the same Control Plant schemes and cabling were re-used during substation upgrades.

Design, apparatus and construction expenses of a standard 66/22 kV, 40 MVA substation, were approximately R 39,946,427. The decommissioning cost of an existing 66/22 kV substation was approximately R18,540,602, per substation. The decommissioning cost escalated the cost to upgrade an existing 66/22 kV substation to R 58,487,029. The minimum energy storage system cost was approximately R4,931,500 for a 1 MW power conversion system and R4,931,500, for a 1 MWh battery system. The modern substation designs, including upgrade costs, reduced capital expenditure and operational expenditure to R 43,169,816, during substation upgrades. Substation upgrade cost comparison was to calculate the most cost-effective design for substation upgrades, when upgrading high voltage networks or deferring substation upgrades.

Keywords - Battery, Substation, Upgrade, Cost comparison

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Nomenclature

°C	Degrees Celsius
$	US Dollar
η	Charge and discharge efficiency
η_m	PV module efficiency
η_{pc}	Power conditioning efficiency
A	Total area of the PV panel (m2)
A	Ampere
C_r	Rated battery capacity in Ampere hour
C_s	Surface layer de-rating factor
D_f	Decrement factor for the entire duration of the fault
I_{dch}	Discharge current in ampere
m	Metre
MVA	Mega Volt Ampere
MW	Megawatt
MWh	Megawatt hour
P	Active Power
P_f	Packing factor

Q_n	Rated capacity of the battery
R	Rand
SOC_0	The initial state of battery at $t = 0$
V	Voltage

Abbreviations

BESS	Battery Energy Storage System
BMS	Battery Management System
CBNH	Circuit Breaker Not Healthy
CH	Charge
COUE	Cost of Unserved Energy
CT	Current Transformer
DOD	Depth of Discharge
EMS	Energy Management System
ES	Ethernet Switch
ESS	Electricity Storage System
GOOSE	Generic Object Oriented Substation Event
HMI	Human Machine Interface
HV	High voltage
IED	Intelligent Electronic Device
LCC	Life Cycle Cost
MVA	Mega Volt Ampere
PV	Photovoltaic

RE	Renewable Energy
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
VSR	Voltage Selection Relay
VT	Voltage Transformer

CHAPTER 1: INTRODUCTION

1.1 Background

The Northern Cape Operating Unit is experiencing load growth, due to residential developments, high electrification growth, agriculture and mining. For additional capacity, power utilities should upgrade its network from 66 kV to 132 kV [1]. The complexity of substation upgrades is due to safety working clearances between substation equipment. Eskom has built new power stations, expanding its generation capacity. Furthermore, power utilities upgrade their substations, due to material reaching its useful lifespan. The cost in maintaining old substation equipment is regularly high. Old substation apparatus interrupts security and continuity of supply to customers [2].

On the medium voltage feeder bays, the focus area is, to reduce the number of customers impacted. The power systems performance was improved, by installing a sufficient number of re-closers, splitting feeders, cutting the line length, and providing back-feeding capabilities. Electricity utilities installed voltage regulators and capacitor cans, increasing the voltage on the medium voltage network [3]. The existing reticulation networks cannot supply the forecasted load, without the requirement of substation upgrades.

Due to the diameter and capacity of Wolf conductor on the 66 kV network, under n-1 contingency, the voltage drops below allowable limits. Power utilities upgraded their conductors to a Tern conductor, that is larger in diameter and carries increased current, to supply customers under n-1 conditions. N-1 contingency further refers to steady supply. When municipalities apply for 10 MVA steady supply, power utilities will install two 10 MVA transformers. If one of the transformers is faulty, the additional 10 MVA transformer carries the load.

Eskom Distribution carries out Network Development Plans, which entails: analysing their networks and carrying out load forecasts over ten years. During the analysis and comparison of the proposed alternatives, technical requirements, environmental issues, design issues, constructability issues and operational issues, were considered.

There exist no methods in place to predict lightning, or prevent lightning from striking in certain servitudes. For lightning protection, power utilities used lightning masts, surge arresters, shield wires and earth mats. Earth mats are utilised, preventing damage to equipment and for safety to personnel during faulty conditions.

The proposed method of substation designs, for future substation upgrades, reduced the amount of steelwork used, foundations demolished, conductors installed, cabling used, labour and cost. The proposed modern substation design, using Micro-station V8i, ensured security and continuity of supply to customers. Installing by-pass isolators on the medium voltage feeder bays, provides security and continuity of supply to customers and ensures a steady supply to customers, improving the performance of the network.

1.2 Problem Statement

Methods used to carry out substation upgrades are costly, time-consuming and considerably multifaceted. Methods involve decommissioning of equipment, steelwork, Control Technology cabling, conductors and equipment foundations. Existing methods require interruption of the continuity of supply to customers, reducing the performance of the network. New substation designs incorporate an approach of overcoming these problems.

1.3 Objectives of the study

The aim of this research, is an investigation into the design of a new 66/22 kV substation, using Micro-station V8i, that will minimise cost and save time during future upgrades.

The objectives of this study were as follows:

- To review substation upgrades, existing substation designs, modern substation designs, Battery Energy Storage Systems, Solar Energy technologies with BESS integration designs, Wind Energy technologies with BESS integration designs, mobile substations, Power Plant technologies and Control Plant technologies.
- To design a new substation with BESS integration designs, using Micro-station V8i.
- To design a new substation for future substation upgrades, using Micro-station V8i.
- To carry out an economic analysis, using Power Delivery Engineering modules, Bill of quantities, Power Office software and the Black Pearl (ACNAC) software, to find the most cost-effective design for substation upgrades.

1.4 Research methodology

The following methodologies were used for this research:

1.4.1 Literature review:

The literature related to voltage upgrades, existing substation designs, modern substation designs, Battery Energy Storage Systems, Solar Energy technologies with BESS integration designs, Wind Energy technologies with BESS integration designs, Power Plant technologies and Control Plant technologies, were reviewed.

1.4.2 Micro-station V8i was utilised:

- To design a switching station with BESS and Wind Energy integration designs.
- To design a new substation with BESS integration designs.
- To design the modern 66/22 kV substation, for future upgrades.

A. Control plant designs that were designed using Micro-station V8i:

- High voltage impedance schemes (4FZD3920)
- Transformer schemes (4TM7101)
- Rural feeder protection schemes (4RF1101)
- Metering designs
- Direct current designs

B. Power Plant designs that were designed using Micro-station V8i:

- General arrangement designs
- Station electric diagrams
- Sections designs

1.4.3 Proposed substation design costing

- Power Delivery Engineering modules and cells were used for equipment selection.
- For an economic analysis of equipment, Power Office software was used.

- The total material cost and bill of quantities were used to populate the detail design cost, utilising the Black Pearl software, finding the most cost-effective design for substation upgrades.

1.5 Hypothesis

- The new substation design minimises cost and saves time, during future upgrades.
- The usage of Battery Energy Storage Systems increase self-consumption, improves solar technologies, enhance wind generation technologies and defer substation upgrades.

1.6 Limitation of the Study

The study was conducted, with the following limitations:

- The research focussed on substation designs and did not include high voltage and medium voltage line designs.
- The study focussed on alternative substation upgrade designs, using substation design software, Miro-station V8i.

1.7 Contribution to Knowledge

- The proposed modern substation designs, using Micro-station V8i, reduces capital expenditure and operational expenditure.
- The proposed modern substation designs utilised less control technology cabling, during substation upgrades and reduced the complexity of substation upgrades.

1.8 Research Output

The following papers were presented and published:

- Pienaar, S.B., Kusakana, K. and Manditereza P.T., "Proposed substation general arrangement on networks thateeds to be upgraded.", *26th Southern African Universities Power Engineering Conference* pp. 468-473, 24-26 January 2018.
- Pienaar, S.B., Kusakana, K. and Manditereza, P.T., "Usage of Battery Energy Storage Systems to Defer Substation Upgrades." *In 2018 Open Innovations Conference (OI)*, pp. 151-156, IEEE, 2018.

1.8.1 Scientific outcomes

- The new substation upgrade design improves the performance of the network.
- The high voltage and medium voltage bays are reliable during faulty conditions.
- New substation upgrades ensure available sufficient capacity on the medium voltage network for future growth.
- Micro-station V8i was utilised, designing the new substation with BESS integration designs, for energy storage.
- Solar Energy designs, with BESS and Wind Farm designs with BESS, were used to improve solar technologies and enhance wind generation technologies, in South African switching stations.

1.8.2 Social impact

- The modern substation design, for future upgrades, ensures economic growth in South Africa.
- Battery Energy Storage Systems stores energy and ensures reduced environmental pollution.

1.9 Outline of the Dissertation

Chapter 1 offers an introduction to the dissertation, which entails the problem statement, research objectives, methodology, hypothesis, limitations of the study, social impact, as well as scientific outcomes.

Chapter 2 reviews the literature on substation upgrades, existing substation designs, modern substation designs, Battery Energy Storage Systems, Solar Energy technologies with BESS integration designs, Wind Energy technologies with BESS integration designs, capacitor banks and mobile substations.

Chapter 3 presents the design methodology, using Micro-station V8i on existing substation upgrades, BESS integration designs in new substations and the proposed modern substation designs, for future upgrades.

Chapter 4 provides the economic analysis, using Power Delivery Engineering modules, Bill of quantities, Power Office software and the Black Pearl (ACNAC) software, for detailed design costs.

Chapter 5 presents the substation upgrade recommendations and concludes the dissertation.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The South African energy utilities upgrade their substations, due to substation equipment reaching their useful lifespan. The cost to maintain outdated apparatus, that interrupts security and continuity of supply to customers, is high. Before substation, upgrades may take place. New and existing consumers who require additional electricity are rejected, due to capacity constraints in existing substations [4].

Electricity is generated and distributed instantaneously by power utilities. In power utilities, producing and distributing power simultaneously is occasionally an enormous amount of wasted capacity. Illegal connections may contribute to overloads and trips, as the network is carrying more users than designed [56].

In 1970, conversion methods for the storage of alternating current were extraordinarily costly and unreliable. Hence, Battery Energy Storage Systems were not preferred. The fact that generated electricity is transmitted in AC, has led to the belief that energy cannot be stored in batteries [5].

Battery Energy Storage Systems may lead to costly network upgrade deferral and reduced demand charges. The installation of large scale Battery Energy Storage Systems (BESS), may support the long-term carbon mitigation strategy of South Africa, transitioning to a low carbon economy. The depletion of coal and concerns over environmental pollution, ensures that renewable energy continues to grow [6].

The objective of Chapter 2, is to carry out a literature review on existing substation upgrades, modern substation upgrade designs and alternate substations upgrade designs. This Chapter further reviews capacitor banks, the use of mobile substations during substation upgrades and renewable energy sources with BESS, to improve renewable energy and defer substation upgrades.

2.2 Existing substation upgrade design methods

General arrangements are for construction of new substations and refer to the physical layout of a substation. When designing the General Arrangement (GA) of a substation, it is necessary to develop the cable connection layout, considering the location of the control room. The consideration of the location of the control room is to save costs on control plant cables, while meeting the operating requirements [7].

Micro-station V8i, Power Delivery Engineering modules and Power Office software, was utilised to design the new substation for future upgrades. The proposed modern substation design improves safety in substations, by adhering to Power Delivery Engineering clearances between high voltage feeder bays, transformer bays and MV feeder bays, for various voltage and insulation levels. A cost-effective design was achieved, by using 132 kV clearances between 66 kV feeder bays and 66 kV transformer bays. On the 66 kV bus-bars, 66 kV voltage transformers and the 66 kV bus-section isolators 132 kV clearances prevent decommissioning of steelwork and demolishing of existing foundations. The 66 kV foundations and 66 kV steelwork were cast and erected, according to 132 kV steelwork and 132 kV foundation designs, according to the Power Delivery Engineering modules and cells. Reducing labour and cost during substation upgrades was achieved, by solely decommissioning the 66 kV apparatus and installing 132 kV apparatus.

The Single-line diagram, in Figure 2.1, is an existing 66/11 kV substation. The substation consists of two 66 kV feeder bays, two 66/11 kV transformer bays and five 11 kV feeder bays. The 66/11 kV substation supplies the existing five customers from the two 11 kV busbars.

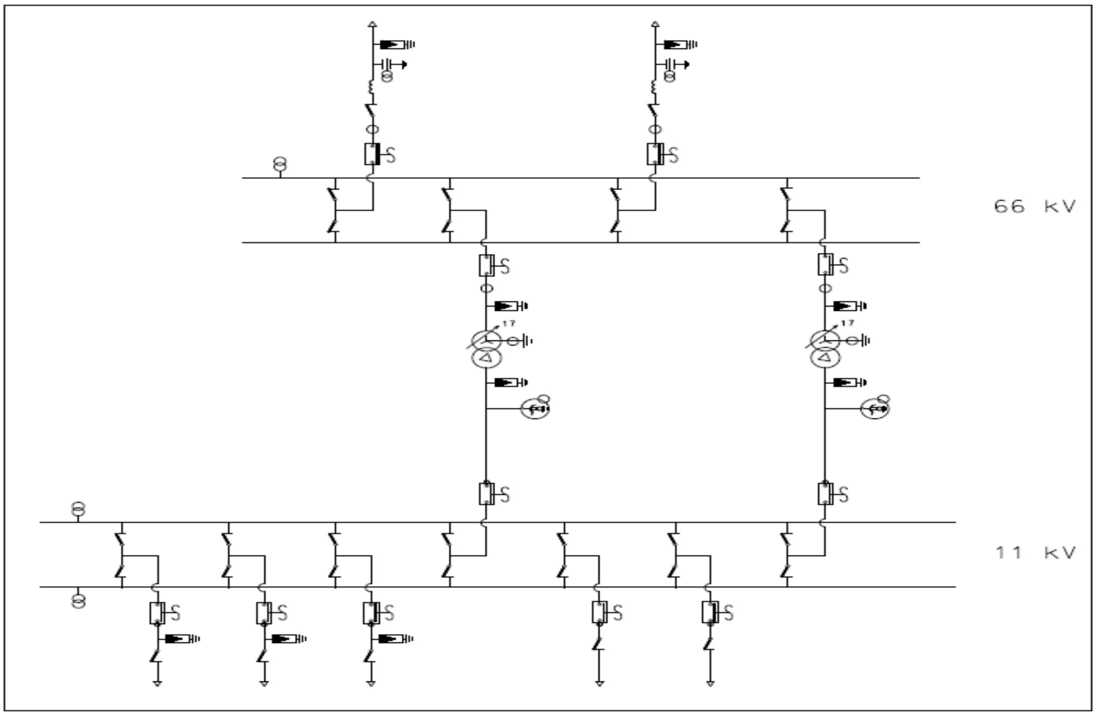


Figure 2.1: Existing 66/11 kV Single-line Diagram

The method in Figure 2.2 was applied during the Kuruman network upgrade, on the Eldoret substation and Moffat substation designs. The 66/11 kV general arrangement design, in Figure 2.2, is an example of how this substation was upgraded. The newly installed 66 kV feeder bay, 66 kV busbar and the 66/11 kV transformer bay area, is indicated on the right-hand side of the general arrangement, in Figure 2.2. The new 66 kV feeder bay, 66 kV busbar and the 66/11 kV transformer bay were installed in advance, under dead conditions, for safety. The existing 11 kV busbar does not require to be extended to connect the new 66/11 kV transformer bay. The newly installed 66/11 kV transformer bay connects to the existing 11 kV busbar, using live-work techniques, as indicated in Figure 2.2.

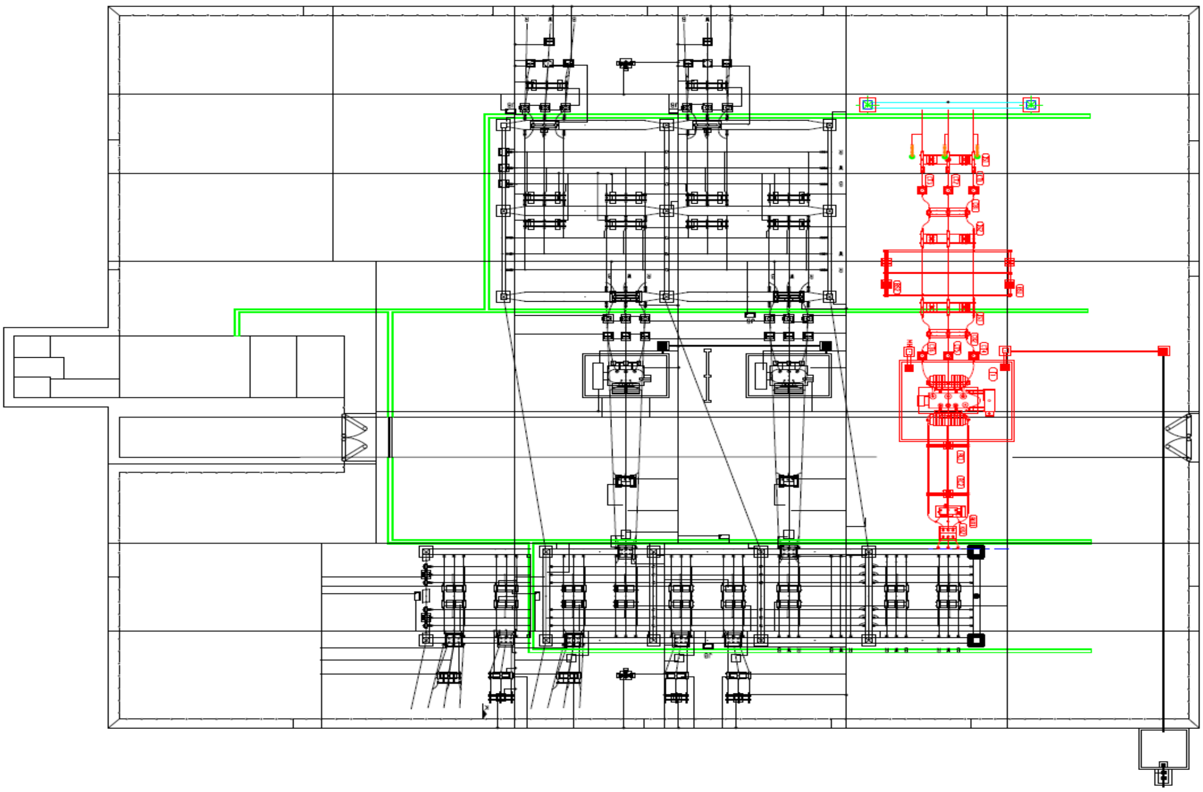


Figure 2.2: Existing 66/11 kV General Arrangement

The disadvantage of this method is that it should be executed, while the medium voltage side of the substation is live, ensuring back-up supply to existing customers, while the substation is upgraded. There is a risk of electrocution with this method of carrying out substation upgrades. The new substation general arrangement design incorporates a way of reducing this.

Figure 2.3 demonstrates the method used to extend the new 132 kV busbar, to install an additional 132 kV feeder bay and a second 132/22 kV transformer bay, while the substation is switched off. The second 132 kV feeder bay, 132 kV busbar and the 132/11 kV transformer bay was constructed in advance. A second line was built, energising the second 132 kV feeder bay, as well as the second 132/11 kV transformer bay. Eventually, premium supply was connected to the existing customers, using live work techniques.

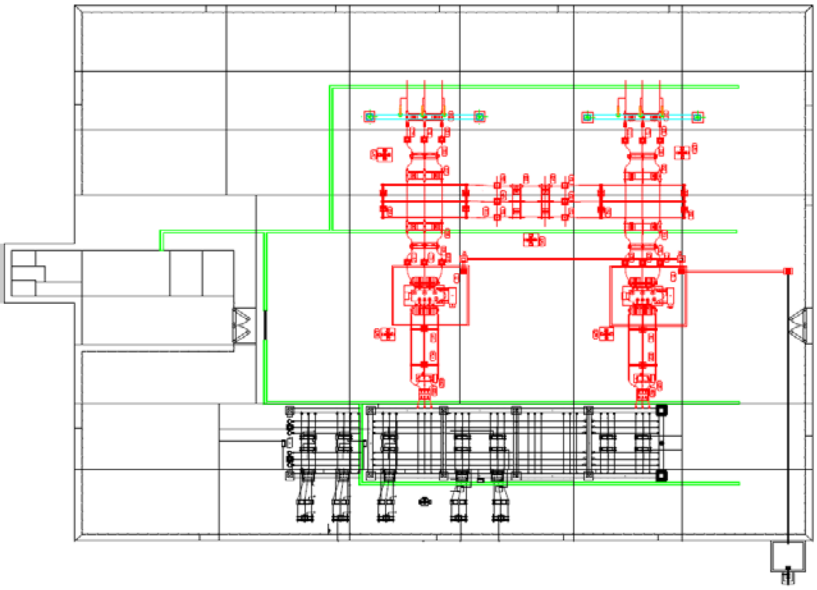


Figure 2.3: Upgraded 132/11 kV General Arrangement

The preferred method used to carry out substation upgrades, was for the Riries substation, Mothibistat substation and Valley substation. The procedure was to construct a new 132/22 kV substation, on a platform alongside the existing 66/22 kV substation yard. Building a new substation alongside an existing substation, is a safer method of carrying out substation upgrades, although significantly costly.

2.3 Control Plant Technologies

Electro-mechanical relays, used in existing substations, are not reliable and have no fault recording capabilities [4]. Analysing a fault from Electro-mechanical relays and Siemens Oscillo-store K recorders was difficult and the information gained from Electro-mechanical relays was insufficient for fault investigations. Over the years, testing electro-mechanical relays have become particularly challenging, since electro-mechanical relays have a single function. Non-directional over-current protection relays are not sensitive, when interconnected customers provide fault current to the protected feeder bay. Directional overcurrent relays are utilised, reducing the mal-functioning of non-directional relays [8].

In smart substations, substation designers should understand the substation configuration of the apparatus, while existing substations field technicians should understand the various electro-mechanical relay wiring [9]. Smart substations enable bay-level intelligent electronic equipment to communicate, meaning that the failure of one relay does not reflect the collapse of the entire bay [10].

Intelligent Electronic Devices (IEDs) in Figure 2.4, monitor, protect and control the primary equipment in a substation [11]. An IED is any device incorporating one or more processors, with the potential to receive sampled values from voltage and current transformers, sending data to circuit breakers [12]. Microprocessor-based, Intelligent Electronic Devices (IEDs), observe the state of the equipment and protection settings, taking action to ensure a steady supply to customers [13].

Figure 2.4: REF 615 IED

Due to technological advancements, manufacturers began using intelligent electronic devices with different protocols. The various protocols were used to distinguish the apparatus from that of seperate manufacturers. The problem with different protocols, was that they are incompatible with equipment from seperate manufacturers. Three tests are carried out for relays of different manufacturers to communicate with one another. The tests are: the system performance-oriented test, function-oriented test and communication service oriented test [14].

Intelligent Electronic Devices (IEDs), from different manufacturers, make use of the IEC61850 standard, ensuring interoperability between various relays [15]. Due to the IEC61850 standard, physical interfaces between the Primary Plant equipment and the intelligent electronic devices, are standardised. The IEC61850 standard, ensures that there are more manufacturers, of the same technology [16]. This standard reduces the cost of Microprocessor-based, intelligent electronic devices [17]. All the IEC61850 IED's communicate with primary plant equipment, bay level equipment and station level equipment, using a standard language called Substation Configuration Language [18]. The IEC61850 standard keeps up with technological advancements (updating of software, protection functions, and testing equipment), over the entire lifespan of the substation [19].

GOOSE (Generic Object Oriented Sub-station Event) messages, are the communication method used between intelligent electronic devices and the station level equipment. GOOSE messages have an interlocking function. The interlocking feature, is to prevent the substation equipment from operating, when they not required to [20].

The station level, refers to the Human Machine Interface, engineering workstation and gateways, to connect to the substation control centre. The station bus enables information exchange between intelligent electronic devices and the SCADA (Supervisory Control and Data Acquisition) system [21]. Protection IEDs will conduct calculations and a trip signal will be sent to the breaker, via the process bus [22].

Wireless communications within the IEC61850, could be considered as a cost-saving initiative, reducing control plant cabling and wiring costs [23]. Wireless data acquisition systems, based on the IEC61850, may monitor plant equipment wirelessly [24].

2.4 Capacitor bank bays

Most of the customer loads are inductive, which results in lagging power factors, further corresponding to power losses between the consumer and the electricity utility. Capacitor bank bays, in Figure 2.5, installed on substation busbars, improve power factor correction and assist with voltage upgrades, during peak load periods. The placement of capacitor banks plays an essential role in ensuring minimum system power losses and improves the overall power distribution efficiency [25].

Capacitor banks, in Figure 2.5, cause high frequency and high current transients during the switching of the breakers. The peak transient current is more than six times the nominal current and this may damage equipment in the capacitor bank bay.

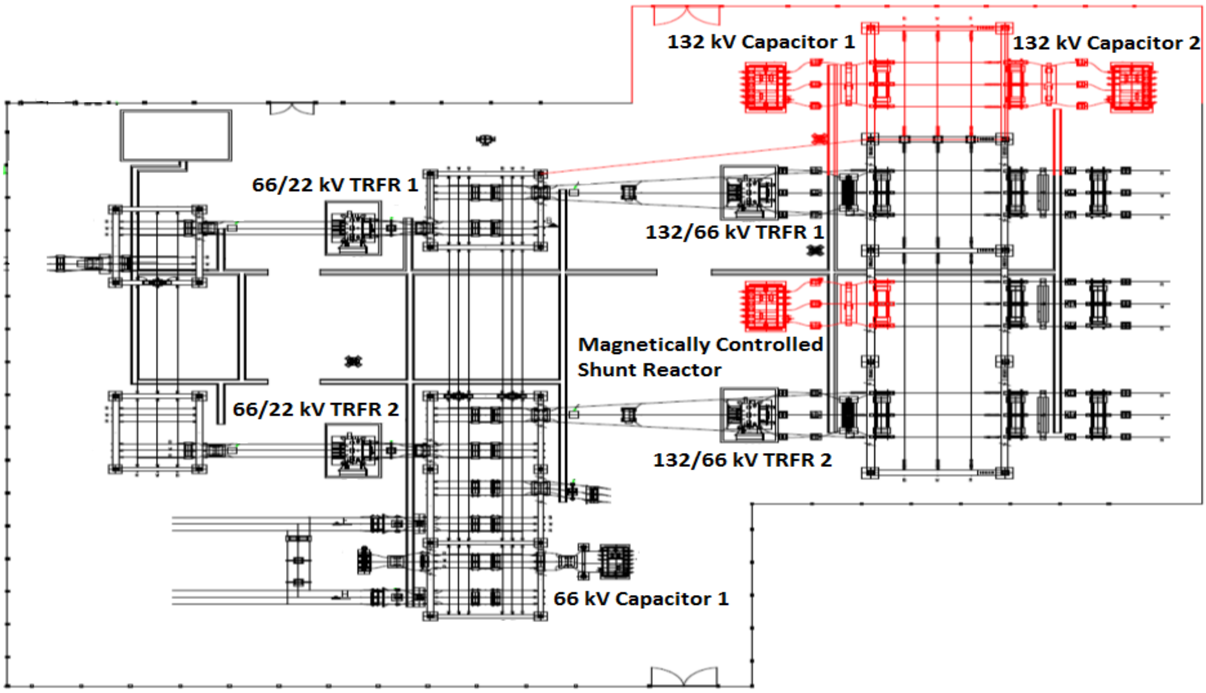


Figure 2.5: Capacitor bank bays using Micro-station V8i

The Magnetically Controlled Shunt Reactor relieve the Ferranti effect, when the feeders are lightly loaded. To reduce the peak transient flow, a passive element, such as a resistor, is installed in the capacitor bank bay [26]. Failure of capacitor banks could result in a voltage drop at the substation busbar and affects the balance of the network [27].

2.5 Mobile substations

Mobile substations may refer to an entire substation on wheels, or simply a transformer bay. Mobile substations provide a steady supply to existing customers, if one transformer bay fails or during substation upgrades. However, mobile substations should adhere to the safe working clearances, required for operators to operate [28].

The mobile substation in Figure 2.6, may supply customers, whilst the existing 66 kV feeder bays and the 66/22 kV transformer bays, are decommissioned [29]. Portable substations should adhere to safe working clearances on the general arrangement designs. Mobile unit substations may increase the operational flexibility of substations [30].

Figure 2.6: 132-66 kV/22-11 kV Mobile Substation

The purpose of transportable substations is to further provide power supply to customers, during natural disasters or equipment failure [31]. It is challenging to improve the performance of the network, if mobile substations are installed without the necessary lifting equipment [32]. Lightning protection of the mobile substation, is independent of the lightning protection provided on the general arrangement of a substation [33]. The equipment on mobile transformer trailers should be earthed with a copper conductor, that carries the maximum fault current. Due to limited space in substations, transportable substations are designed to retain sizeable apparent power on light trailers [34]. Movable substations damage roads as a result of weight and block traffic, due to size [35].

The 4TM7100 scheme, in Table 2.1, protects the mobile substation and the 4TC-5200 tap changer protection scheme controls the On-Load Tap Changer of the mobile substation. The current circulating system uses the REG-DA voltage-regulating relay for on-load tap changing applications.

Table 2.1: Mobile substation protection scheme

4TM7100 Protection Scheme	**Intelligent Electronic Devices**
Two terminal differential protection	SEL487E
HV and MV O/C	SEL487E
E/F and breaker fail	SEL487E
High impedance HV REF	RMS 2V73K1
High impedance MV REF	RMS 2V73K1

The unhealthy protection alarm, is any situation implying that the protection system is not proficient in performing the intended function. The harmful protection alarm may further be activated, by the busbar VT or line VT supply fails.

The 'Circuit-breaker not healthy' alarm, refers to any situation indicating that the circuit breaker is not capable of executing its intended function. The trip circuit supervision monitors each phase of the circuit breaker trip circuit independently. The trip circuit supervision blocks the closing of the circuit breaker, when the trip circuit has failed. The main station layer, located in the control centre, is responsible for fault-finding, tripping breakers of faulty bays and remote reclosing of switches on the mobile substation [36].

2.6 Distributed Battery Energy Storage

Battery energy storage has been used in China, Germany and the United States, as one of the preferred alternatives for energy storage [37]. Distributed battery energy storage is further used to improve network capacity, quality of supply and to defer costly substation upgrades [38, 39]. No Battery Energy Storage Systems, from 1 MWh or higher, are in service in South African electrical utilities. Battery Energy Storage Systems remain costly; this being the reason as to why the demand is not high.

As presented in Table 2.2, Battery Energy Storage Systems are installed on the power system, at a substation, or by electricity consumers. Calculating the size and placement of Battery Energy Storage Systems on the distribution network, is dependent on the battery technology and the purpose of the storage system [40].

Table 2.2: Grid-Related Energy Storage Applications [41, 42]

Category	**Placement**	**Application**
A	Battery energy storage systems connect as close as possible to consumers (230V-400 V).	• Voltage support • Solar smoothing • Stabilising, Frequency
B	Battery Energy Storage Systems ties to the medium voltage busbars and the medium voltage feeders (3.3 kV-33 kV).	• Peak shifting • Substation upgrades deferral • Back-up supply
C	Battery Energy Storage Systems connect to the high voltage busbars and the HV feeders (44 kV - 132 kV).	• Reliability of supply • Substations upgrades deferral • Back-up energy
D	Renewables Integration	• Renewables Energy Time-shift

		• Renewable energy capacity firming • Wind Generation Grid Integration

2.7 Radial distribution feeders

The concern, on a radial distribution feeder, is that the end of the feeder lacks consistent back-up supply connection from other feeders. Back-up supply decreases the interruption time and reliability methods are challenging to achieve. Battery energy storage offers one possibility to reduce the outage times, experienced by consumers [43]. The customer loads connect to the network, using Battery Energy Storage Systems, located close to loads, as it is not possible to foresee as to where future disturbances will materialise [44, 45].

The purpose of BESS installations in the distribution network, is to reduce network constraints for the efficient operation of the network [46]. BESS reduce stress on equipment in the network, consequently improving their lifetime. Energy storage systems further improve reliability, as an alternative to more costly distribution line capacity upgrades [47]. The concern with feeder designs with BESS, is that power utilities are not certain as to which feeder interruptions are likely to occur.

2.8 A Wind Energy Farm with BESS

Wind Energy Farms (WEFs), are more environmentally friendly and cost-effective, than the traditional approach of centralised grids [48]. Renewable energy sources operated in both grid-connected mode and islanded mode. The Wind Turbine Transformer (WTT), connects as closely as possible to the wind turbine, at the bottom of the wind turbine structure [49]. Wind Turbine Transformer failure leads to high economic loss, including Cost of Unserved Energy (COUE) and a high cost of transformer refurbishment [50].

The output of wind power generation is unable to maintain stability, like that of traditional coal generation stations, to operate precisely, according to the generation schedule [51]. The challenge with renewable energy, is that the amount and timing of energy production by the wind plant, is unknown [52]. Wind Energy Farms generate electricity as the wind is blowing and the power output depends on the wind speed and type of generator [53]. Energy generated by a wind farm is calculated, as follows [54]:

$$E_w = 0.5 * \rho * A * v^3 * C_p * \eta_g * \eta_t * f(t) \tag{2.1}$$

Where: ρ = density of wind (1.225Kg/m^3);

A = wind turbine swept area (m^2);

v = wind velocity (m/s);

C_p = power coefficient of a wind turbine performance;

η_g = generator efficiency;

η_t = turbine efficiency;

$f(t)$ = wind probability density function.

The Micro-station V8i design, in Figure 2.7, consists of a Wind Energy Farm (WEF), Battery Energy Storage (BES) and a Power Conversion System (PCS). The 2 MWh Battery Energy Storage System and the 20 MW WEF are connected, in parallel to the power grid [55]. BESS, with wind generation, improves the function of renewables and overall generation. BESS is further used to avoid the cost of coal and carbon emissions by coal generating stations [56]. The aim of using BESS, in Figure 2.7, is to increase self-consumption and achieve cost savings from the decrease of energy import, during peak price periods [57].

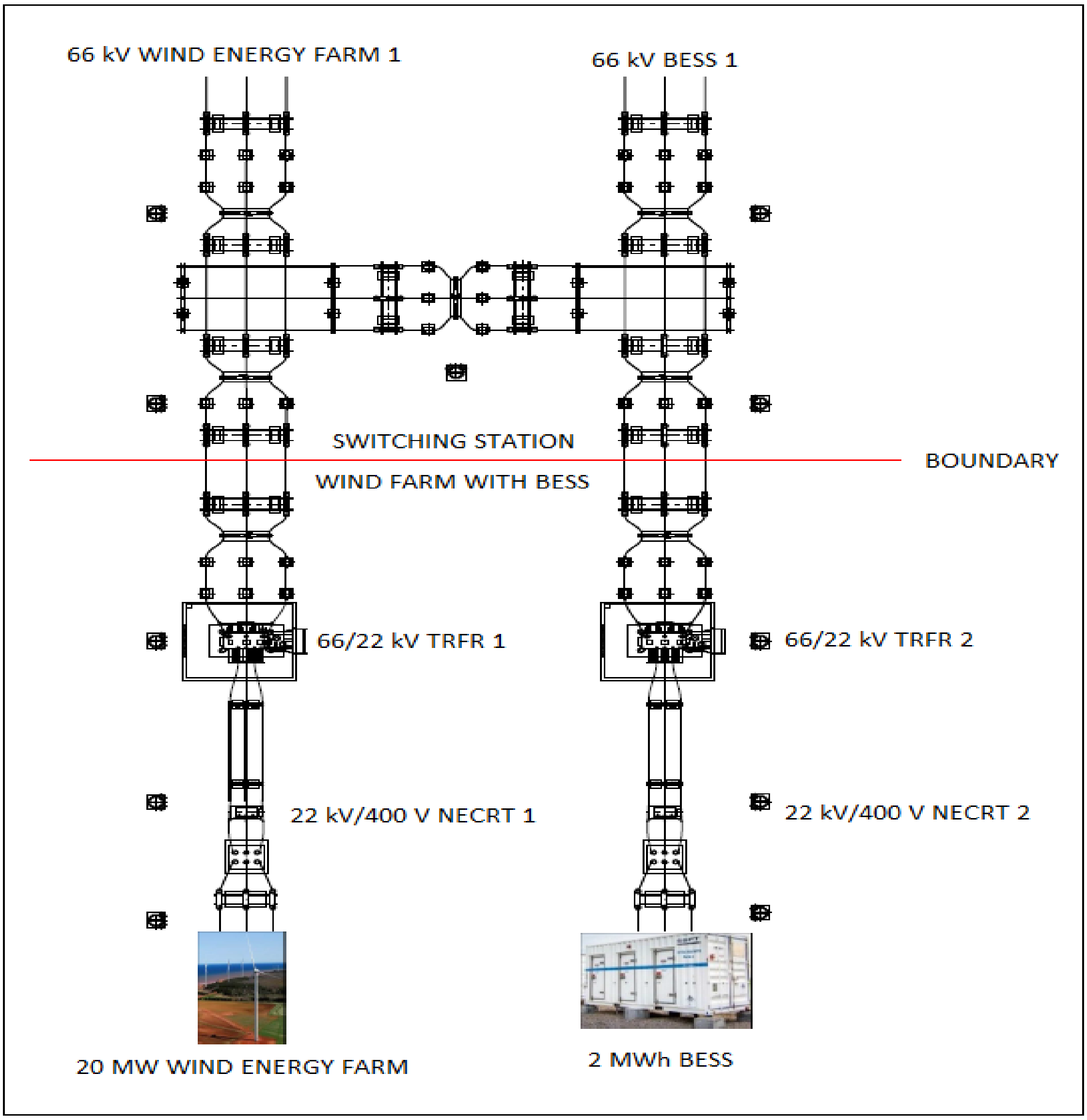


Figure 2.7: Wind Energy Farm with BESS integration design

With the improvement of renewable power prediction technology, it is possible to calculate an optimal SOC, to smooth wind power fluctuations [58, 59]. The State of Charge (SOC), is an important parameter, indicating the battery state during discharge, as compared to its charged state [60]. The battery management system calculates the state of charge (SOC), implement balance control and diagnose the fault [61, 62]. The SOC of a battery is calculated as follows [61]:

$$SOC = SOC_0 - \frac{1}{Q_N}\int_0^t \eta I dt \tag{2.2}$$

Where: SOC_0 = the initial SOC;

η = the charge and discharge efficiency;

I = the discharge current;

Q_n = the rated capacity of the battery.

SOC in [68] is further calculated, as follows:

$$SOC = SOC_0 - \frac{\int_0^t i_{dch} dt}{C_r} \tag{2.3}$$

Where: I_{dch} = discharge current in ampere;

C_r = Rated battery capacity in Ampere-hour (Ah);

SOC_0 = the initial state of battery at t = zero.

The calendrical ageing is due to three main factors: temperature, state of charge and the non-operating duration of the energy storage system [63]. However, the lifespan increases exponentially, as the depth of discharge decreases. The actual lifecycle is heavily dependent on plate design and active material composition, for most battery types, used for energy storage [64]. Higher DOD (depth of discharge), means more energy is discharged from the battery, during the discharging process, however, at the same time, higher DOD reduces battery life [65]. Therefore, the depth of discharge is calculated as follows:

$$DOD = 1 - SOC_{\min} \tag{2.4}$$

Where: DOD = Depth of Discharge;

SOC_{min} = SOC at its minimum value.

Depth of discharge is an important parameter, influencing battery lifetime [65]. Therefore, battery lifetime is calculated as shown:

$$E_{Lifetime} = Mean * [F * (DOD) * (DOD * C_r * V_{nom}] \tag{2.5}$$

Where: F = the number of cycles which is a function of DOD;

C_r = Nominal battery capacity in Ah;

$V_{nominal}$ = Nominal battery voltage.

2.9 Solar Power with BESS

Solar energy is an inexhaustible renewable resource; the disadvantage of solar energy is that there is a lack of solar power at night. BESS is used to store energy, to be utilised through network peaks, allowing for more consumers to be connected to the grid. Charging the batteries during load off-peak times, when the price of electricity is low and discharging the stored energy during load peak evening time, is an alternative method of deferring substation upgrades [66].

The size of PV systems, with battery energy storage, should be calculated, so that the PV, with BESS, will be sufficient in supplying the load. The output energy of a solar PV is calculated as follows [67]:

$$E_{pv} = A * \eta_m * \eta_{pc} * P_f * I \tag{2.6}$$

Where: A = total area of the PV panel (m^2);

η_m = PV module efficiency;

η_{pc} = power conditioning efficiency (0.86);

P_f = packing factor (0.9);

I = hourly irradiance (kWh/m^2).

The Battery Management System, is the control hub in the Battery Energy Storage System, with voltage regulation and peak load saving functions [68]. The Battery Management System (BMS), monitors and measures the power system's performance parameters, such as voltages, currents and temperatures [69]. The BMS communicates with the PCS (Power Conversion System), the state of the Battery Energy Storage System [70]. The four quadrants, Power Conversion System, release capacity back to the utility system, providing active and reactive power control [71]. The Battery Management System prevents any stray currents, or electrical problems, from affecting the grid [72, 73, 74].

The illumination levels required for all the lights in the Wind Farm, with BESS, are indicated in Table 2.3. Lighting protection is provided by multiple 400-Watt High-

Pressure Sodium (HPS) floodlights, placed within the switching station yard and mounted on lightning masts. The floodlights are fed from the AC module installed in the yard AC distribution box.

Table 2.3: Illumination levels

Illumination level	**Level (Lux)**
Control panels front	200
Control panels rear	100
Lavatory	100
Transformer areas	20
Substation yard	10

Micro-station V8i was utilised for a Solar Energy Farm, with BESS and 66/22 kV switching station lightning protection, (Figure 2.8). The equipment is protected from direct lightning strikes, using 21-meter lightning masts. Lighting and lightning protection was carried out, keeping in mind 132 kV safe working clearances, 132 kV phase to ground clearances, access to equipment and lighting and lightning coverage, for future switching station upgrades. Lightning strikes may cause damage to substation equipment, due to over-voltages, in the event where lightning protection is not carried out according to specifications [75].

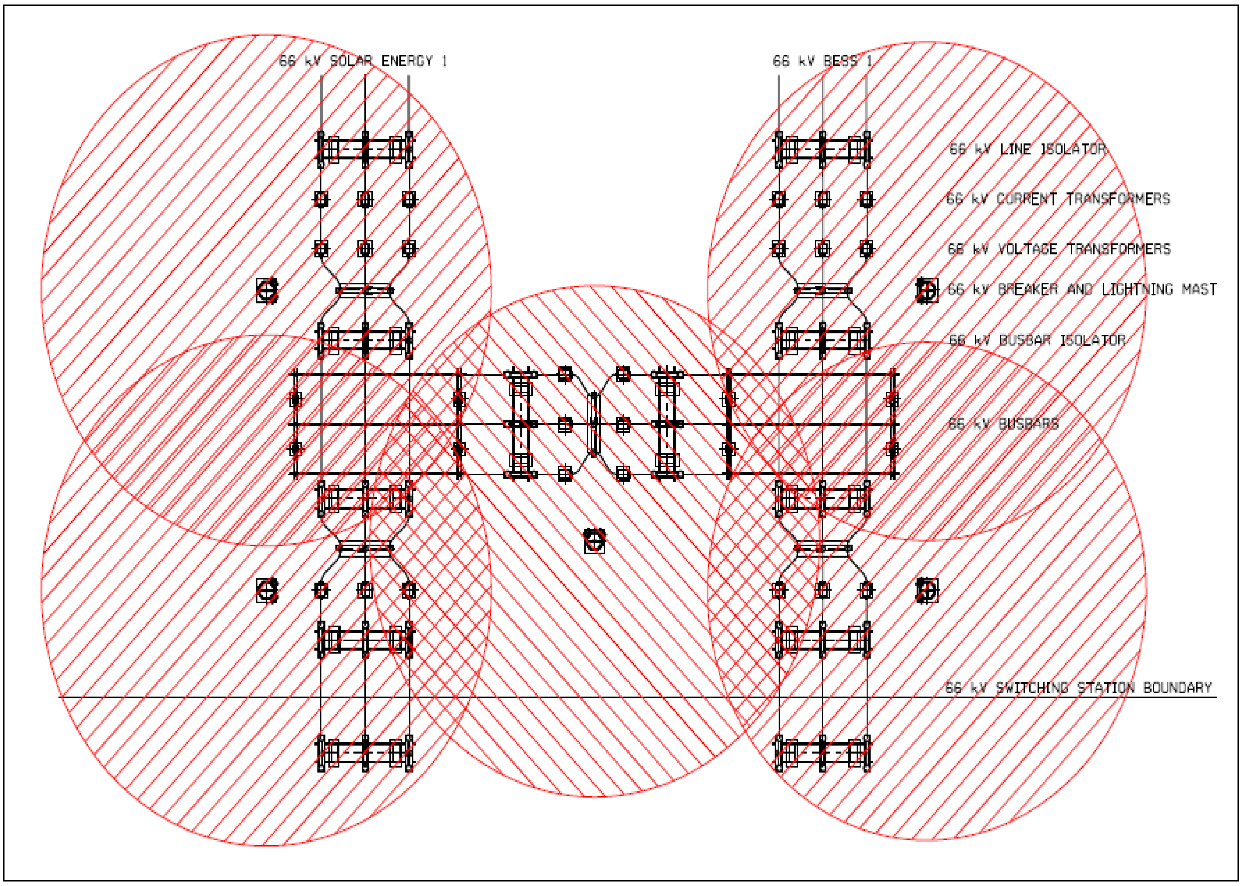


Figure 2.8: Switching Station Lightning Protection

The equation below, determines how far apart and the amount of lightning masts were applied, for 66/22 kV switching station lightning protection:

$$X = \sqrt{H * (2R - H)} - \sqrt{H1 * (2R - H1)} \qquad (2.7)$$

Where: X = The protective distance from mast for height H1;

H = Mast height;

R = lighting attractive radius 45m;

H1 = height of the equipment to be protected.

2.10 Conclusion

Due to capacity constraints, low voltage conditions are experienced on the high voltage and medium voltage feeders. Electro-mechanical relays, used in existing substations, are less reliable, with no fault recording capability. The cost in maintaining outdated equipment, that interrupts security and continuity of supply to customers, is high. Before substation upgrades may take place, new and existing consumers, requiring additional electricity are rejected, due to capacity constraints in existing substations. Substation upgrades aim to improve the capacity, connecting outstanding and new electrification customers in the area.

Mobile unit substations may increase the operational flexibility of substations, and consequently, ensure continuity of power supply to customers, during substation upgrades. Capacitor bank bays, installed on substation busbars, improve power factor corrections and assist with voltage upgrades, thereby improving the overall power distribution efficiency. The 4TM7100 scheme protects the mobile substation and the 4TC-5200 tap changer protection scheme controls the On-Load Tap Changer of the mobile substation.

The output of solar and wind power generation is unable to maintain stability, like that of traditional coal generation stations, to operate precisely according to the generation schedule. The challenge with renewable energy, is that the amount and timing of energy production by solar and wind plants, is unknown. Wind Energy Farms generate electricity when the wind is blowing and the power output depends on the wind speed and the type of generator.

The aim of using BESS, is to defer substation upgrades, increase self-consumption and achieve cost savings, from the reduction of energy import, during peak price periods. BESS, with renewable generation, should improve the function of renewables and overall generation. Financial losses, incurred by customers due to load shedding, should be less, due to Battery Energy Storage Systems and improved network performance. The cost of un-served energy, incurred by power utilities is less, due to a firm, reliable supply. BESS will reduce environmental pollution (Environmentally friendly), provide secure backup supply and improve network performance (Reduce SAIDI and SAIFI).

CHAPTER 3: MODERN SUBSTATION UPGRADE DESIGNS

3.1 Introduction

Chapter 3 presents modern substation upgrade designs in the Northern Cape Operating Unit, in South Africa. Substations in the Northern Cape are experiencing load-growth, due to residential developments, high electrification growth, agriculture and mining. Consumers requiring electricity are not connected, due to capacity constraints. The methods used to carry out substation upgrades are costly and time-consuming. Network upgrades require the interruption of the steady supply to customers and power supply interruptions reduce the performance of the power system. New substation design considers safety, reliability, maintenance, increased supervisory control, interoperability, environmental compliance and reduced capital expenditure [76].

Chapter 3 further illustrates alternate methods of substation upgrade designs and integration designs of Battery Energy Storage Systems. Battery Energy Storage System designs lead to costly network upgrade deferral, reduced demand charges, back-up supply, peak shaving, peak shifting, voltage support, reliability of supply and improved quality of supply.

3.2 Modern substation designs for upgrades

The modern substation design solution was to discover safe, reliable and cost-effective methods of carrying out substation upgrades, paying attention to:

- Safety of personnel and equipment.
- Environmental compliance.
- Passive fire protection.
- Re-use of Control Plant schemes and cabling during substation upgrades to save cost.
- Network performance.

3.2.1 Control Technology Designs

Electromechanical relays have a longer lifespan than microprocessor-based relays. However, Electromechanical relays require an outage for testing and maintenance, which reduces network performance and the cost of unserved energy is exceedingly high-priced [77, 78]. Microprocessor-based relays may be tested while the substation is in service and have more protection and monitoring functions than phase one relays [79].

A. Protection scheme designs

The two feeder protection schemes (4FZD3920), protect the two incoming 66 kV feeders in the modern substation. The RED670 relay provides distance protection, breaker fail, ARC functionality and synchro-check. The REF615 relay offers directional back-up O/C, E/F, overvoltage protection, under-voltage protection and thermal overload protection. Sensitive, selective and high-speed busbar protection is required to clear busbar faults in the modern substation. Busbar protection limits damage to equipment, maintains the system stability and continuity of supply.

The bus-zone protection scheme (4BZ5800), in Figure 3.1, protects the 132 kV sectionalised busbars. The two voltage transformers, on the 132 kV busbars, are for directionality and synchronisation check. The protection remains operative during VT supply selection, to detect busbar isolator closure onto a fault or isolator flashover, whilst under operation.

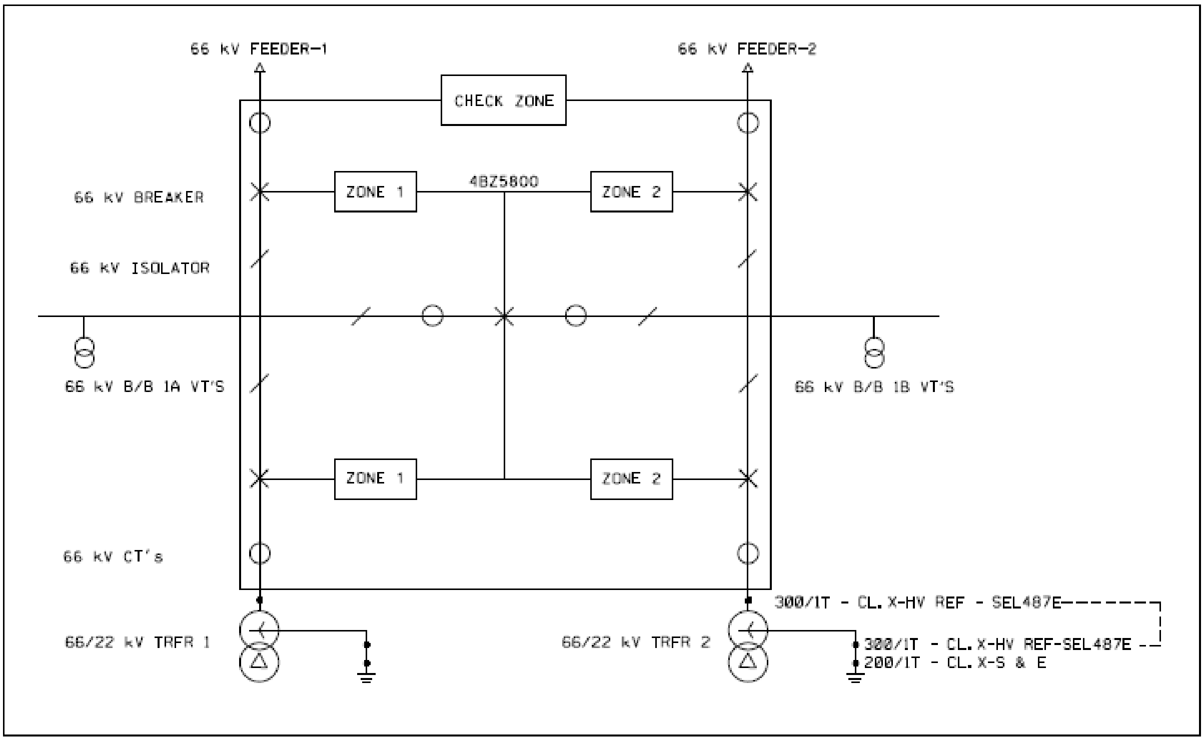


Figure 3.1: 66 kV Bus-zone Protection Scheme (4BZ5800)

B. *Metering designs*

Mount two metering modules with four ZMD405 meters for the two incoming high voltage feeder bays and the two transformer bays. Tariff metering modules, with ZMD402 meters, were for the 22 kV feeder bays. Meter module one, may consist of 66 kV feeder one and 66 kV feeder two. Meter module two will consist of 66/22kV transformer one and 66/22kV transformer two. All the metering equipment was connected to the IDF. All the meters were connected to the cell modem and the GSM kit (Truteq), enabling remote metering.

C. *Direct Current designs*

The total DC drain current for schemes, in Table 3.1, is the total drain current for the panels, plus 20% for circuit breaker operations, which resulted to 3.466 A. Travelling time to the furthest substation, is approximately 24 hours. Therefore, battery sizing was calculated as 24 hours * 3.466 A = 83 Ah. However, the standard battery bank rating is 85 Ah. The preferred battery charger, recharges flat batteries to 80% capacity, within 5 hours. Therefore, the charge current required was calculated as 0.8 * 85/5 = 13.6 A. The rating for the battery charger to carry the substation load, was calculated as 3.466 A + 13.6 A = 17.1 Ampere. The standard battery charger rating was 20 A.

Table 3.1: 110 V DC drain current for schemes

Schemes	**Description**	**Quantity**	**Total drain current (A)**
4FZD3920	HV feeder protection scheme	2	0.8
4TM7101	Transformer protection scheme	2	0.812
4TC5200	Tap changer scheme	2	0.306
4RF1101	MV feeder protection scheme	4	0.4
D20 RTU	Remote terminal unit	1	0.47
4LS1100	Under frequency load shedding scheme	1	0.1
Total			2.888

The load requirements of the complete electrical system were 150 Ah, providing the required 24-hour standby power. The DC supply module, installed in the relay room, provided DC supply to all the protection, control, communication and metering equipment. The 110 Volt direct current batteries ensure that the primary and back-up protective relays remain stable during an Alternating Current fail condition.

D. SCADA design

The challenge with hardwiring, is that the connections to the protection schemes are different; the data transferred is slow and cannot be compared [80]. The communication failure reports locally at the protection IED and remotely to the station HMI.

Each Control Plant scheme was provided with a 110 V DC supply for the protection system, back-up protection system, Ethernet switch and breaker spring rewind circuits. The 240 V AC supply was used to illuminate the amber Protection Not Healthy alarm on each protection module and to supply mechanism box heaters. The rear of the new scheme modules is, open to ease access to the internal components and improve heat dissipation. The modern substation protection schemes were designed for a minimum operational lifespan of 20 years.

The suitable protocol for the serial link is DNP 3.0 (Data Network Protocol), with proven compatibility to the Remote Terminal Unit, in Figure 3.2. The data communication connection shall be via copper RS485 and optical RS232. A new D20 RTU, with serial RS-485 communication ports, as illustrated in Figure 3.2, was utilised for the modern substation. The D20 RTU interfaces serially with the substation IED's, such as the transformer protection scheme, the On Load Tap Changer scheme, high voltage feeder back-up protection (REF 615) and the medium voltage feeder protection scheme (P145).

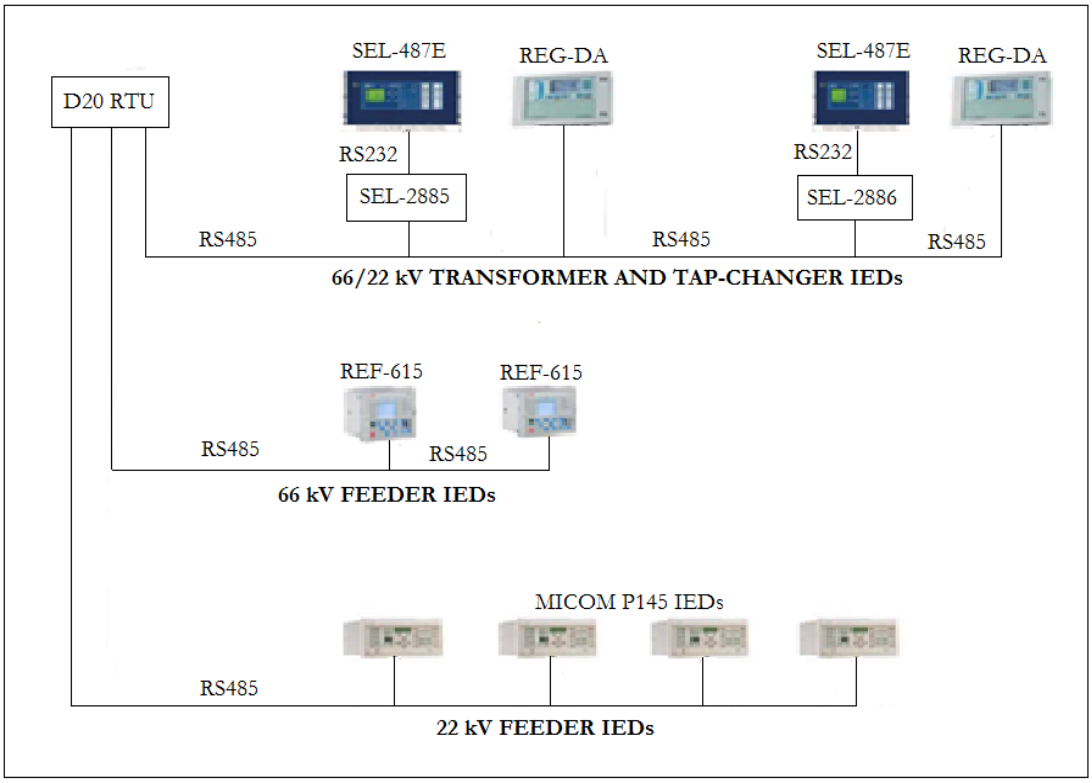


Figure 3.2: Substation RS-485/DNP 3.0 serial communication architecture

The serial RS485 connection reduces the cost of hardwiring. The RS485 communications standard has up to 32 intelligent electronic devices (IED), that are connected on one port and the devices connect up to a distance of approximately 1200 meters. The serial interfaces reduce the amount of hardwiring between IEDs and the RTU. All inputs and outputs are relayed, via serial communication (DNP3 protocol), to and from protection schemes, which reduced the complexity of wiring and installation time. Therefore, the size of the required IDF is smaller.

E. *Control Plant cabling*

Secondary Plant, multi-core thermoplastic insulated cables, have a voltage rating of 600 to 1000 V and current ratings dependent on the cross-sectional area. During the installation of Control Plant cabling, provision was provided for sufficient slack to reach the furthest point on the terminals. A 10% spare capacity factor was used for all long run cables, when selecting cables for an application. The reason for the additional cores, is to provide provision for damaged cores, should modifications be necessary at a later stage. The cable block diagram, as in Figure 3.3, indicates the cable number and destination of each cable.

The purpose of the modern substation design, is to prevent decommissioning of all the Control Plant cabling, during substation upgrades, to save costs. All the control cables were installed from the 66/22kV transformer panels, 66 kV feeder panels and the 22 kV feeder panels to the respective equipment in the substation yard. All the cabling used in Figure 3.3 below, is the very same cabling that will be used during substation upgrades.

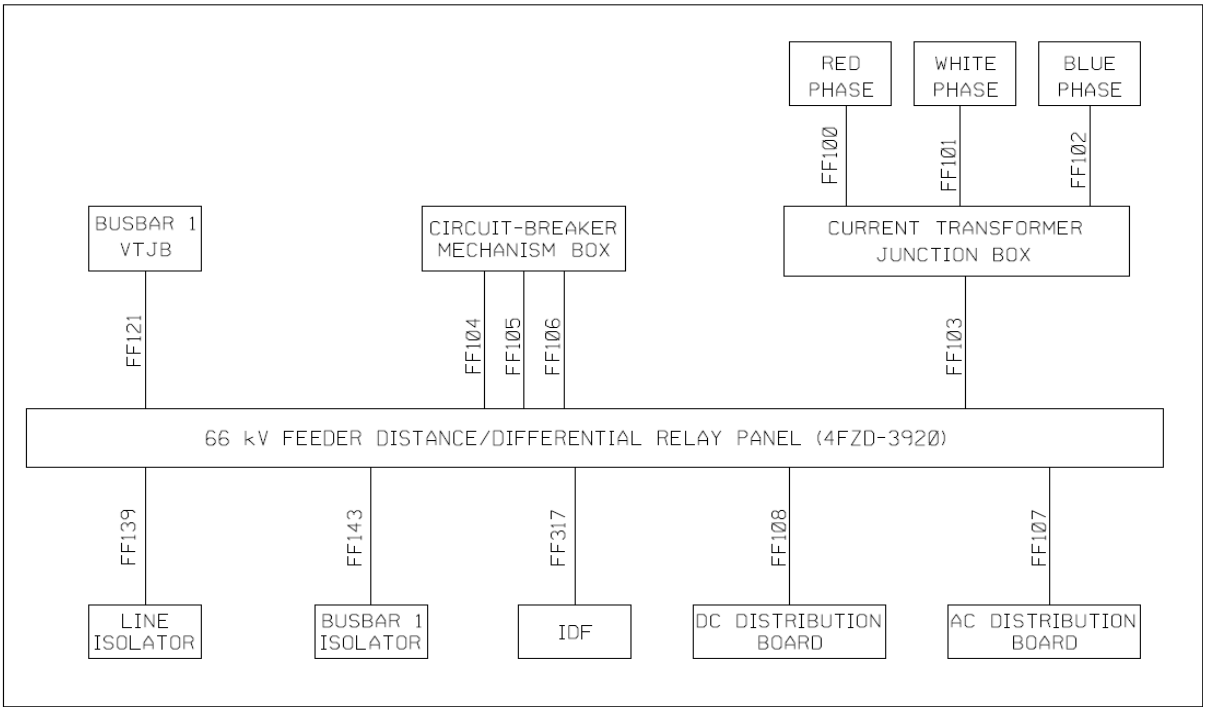


Figure 3.3: 66 kV feeder scheme cabling (4FZD3920)

All the safety clearances, foundations, conductor lengths, type of clamps used, steelwork and equipment heights, for future upgrades, were taken into consideration while designing the new 66/22 kV modern substation. Cable racks are provided, such that every cable is adequately supported, throughout its run. The cable trays were installed, so that there will be a minimum of 400 mm between the cable tray and the control panels.

3.2.2 Power Plant designs

A. General Arrangement designs

The General Arrangement design, in Figure 3.4, ensures operability, maintainability and extendibility. Operability indicates that substation equipment may safely be opened, isolated, tested and earthed, for maintenance and refurbishment of equipment. The modern substation design improves safety and operability in substations, by adhering to safety clearances. The control room on the General Arrangement design, in Figure 3.4, is close to the transformers in conserving costs on Control Plant cabling.

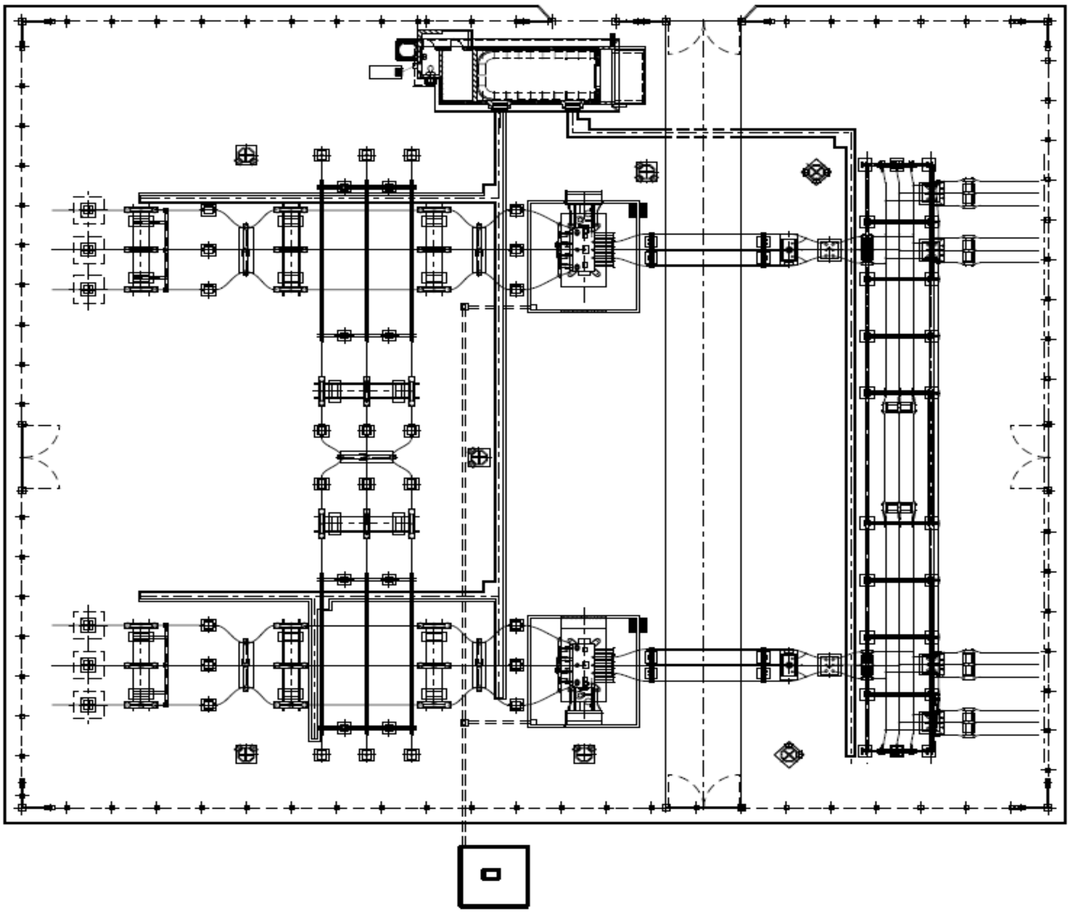


Figure 3.4: 66/22 kV design for future upgrades

On the two 66 kV feeder bays and the two 66/22 kV transformer bays, the decommissioning of the following equipment, foundations and steelwork, were prevented during substation upgrades, to save cost and time:

- Two sets of 132 kV terminal supports,
- Two sets of 132 kV line isolators,
- Two sets of 132 kV current transformers,
- Four sets of 132 kV breakers,
- Four sets of 132 kV busbar isolators,
- Twelve 132 kV current transformers.

The complexity of substation upgrades, was due to safety clearances between equipment on General Arrangement designs. Power Delivery Engineering software uses designs for safe working clearances, in Table 3.2, for the high voltage feeder bay, transformer bay and medium voltage feeder bay equipment, with different voltage and insulation levels.

Table 3.2: Electrical and Working Clearances

System Nominal Voltage (kV)	**System Highest Voltage (kV)**	**Minimum Electrical Clearance**		**Working Clearance**	
		Phase to Earth (mm)	**Phase to Phase (mm)**	**Vertical (m)**	**Horizontal (m)**
3,3	3,6	80	110	2,5	1,2
6,6	7,2	150	200	2,6	1,2
11	12	200	270	2,7	1,3
22	24	320	430	2,8	1,4
33	36	430	580	2,9	1,5
44	48	450	730	3,0	1,6
66	72	770	1 050	3,2	1,8
88*	100	840	1 150	3,3	1,9
132	145	1200	1650	3,7	2,3

B. 66 kV feeder bay section

For the 66 kV feeder bay section, in Figure 3.5, 132 kV clearances were used. With an increase in voltage, the further apart the safe working clearances, phase-to-phase clearances and phase to ground clearances. Phase-to-phase and phase-to-ground clearance, is for preventing voltage flashovers. Safe working clearances, prescribe distances that should be adhered to, depending on apparatus voltage level. Safe working clearances are for allowing work to be carried out safely on isolated and earthed primary plant apparatus, whilst adjacent equipment is in service. All the equipment on the 66 kV incoming feeder bays was strung with a Centipede conductor. The 66 kV section design, in Figure 3.5, has 132 kV clearances on the high voltage side, saving on labour and cost, during substation upgrades. Reducing labour and cost during substation upgrades was achieved, by decommissioning the 66 kV voltage carrying apparatus and installing the 132 kV apparatus.

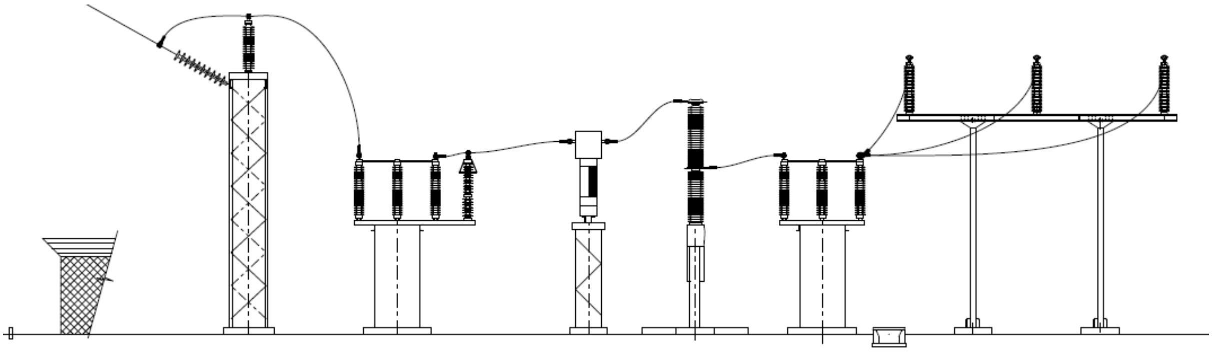


Figure 3.5: 66 kV feeder bay (132 kV clearances)

Alternatively, dual voltage equipment may be used with off-load selector switches, alleviating labour, reducing upgrade costs and improving substation performance. Since the high voltage winding of the multi-winding transformer is partially graded, a neutral 66 kV surge arrester was installed on the neutral of the primary winding. The 22 kV neutral earthing resistor, limits the secondary earth fault current to 360 A, irrespective of the high voltage level selected.

C. Sectionalised busbar with bus-section breaker

For busbar selection, tubular busbar and high-strung busbar, using columns and beams, were considered. The preferred option, was to use low profile tubular busbars, as they are more cost-effective and compact, with limited visual impact. One of the factors that determine the requirement for busbar protection, is the importance of the substation. A substation may be an essential link to the network, maintaining system stability, or the substation may be feeding a critical load. A substation design, with two incoming high voltage feeders, with a single split busbar and two transformer bays, were considered for high voltage busbar protection.

Tube vibration damping for high wind conditions was considered for the 120 mm diameter aluminium alloy tubes, exceeding 5.5 meters. Tube vibration damping was carried out by installing a single centipede conductor, two-thirds the length of the tube and fixing it at both ends. A drain hole of 10 mm diameter was drilled at the bottom centre point of the aluminium alloy tubes, facilitating drainage of condensate moisture.

D. 66/22 kV transformer bay section

The 20 MVA, 66/22 kV transformer bay, in Figure 3.6, has a full-load current of 175 A, on the 66 kV side of the transformer bay. All the stringing on the high voltage side was carried out with the Centipede conductor. Centipede has a rating of 833 A, suitable for future 40 MVA transformers.

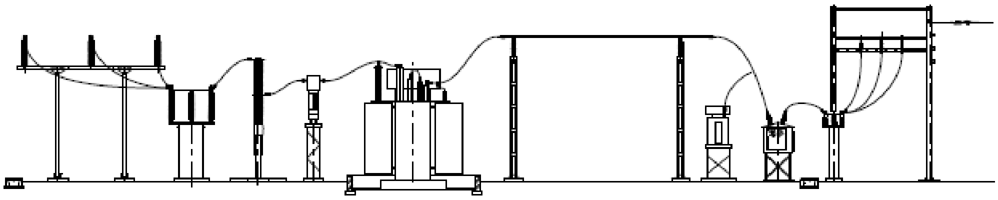


Figure 3.6: Transformer bay section design (132 kV clearances)

On the 22 kV side, the maximum continuous current from the 20 MVA, 66/22 kV transformer, is 525 A. The maximum single-phase fault current on the 22 kV busbar, is limited to 720 A by the integrated resistors, in the neutral electromagnetic coupling resistors, with auxiliary transformers.

The new type CTB36 22 kV vacuum circuit breaker, in Figure 3.7, may be used for future substation upgrades. Vacuum insulation circuit breakers are environmentally friendly and do not require oil. The CTB36 vacuum insulation circuit breaker has two trip coils, ensuring tripping of 22 kV feeder bays, during faulty conditions. However, electricity utilities continue to have operational challenges with the new outdoor vacuum insulation circuit breakers.

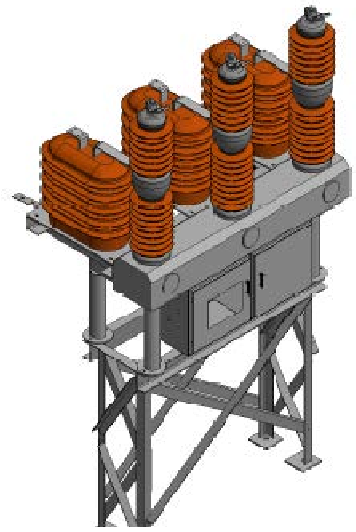


Figure 3.7: CTB36 Vacuum Circuit Breaker

3.3 Modern substation designs with BESS

General arrangements are utilised, for the construction of new substations and refer to the physical layout of a substation. When designing the General Arrangement (GA) of a substation, it is necessary to design the cable connection layout, considering the location of the control room. Considering cable connection layout, is to save costs on control plant cables, while meeting the operating requirements [81].

3.3.1 BESS integration designs

The Battery Energy Storage System (BESS) integration design, in Figure 3.8, was designed for substations with more than one constrained medium voltage feeder. Kiosk circuit breakers are three-pole operated circuit breakers, with integrated protection and current measurement transformers. The kiosk circuit breakers were used for control, measuring, indication, maintenance and protection purposes.

The BESS integration design, used for energy storage, utilises two kiosk breakers on both sides of the 400 V/22 kV step-up transformers, as designed in Figure 3.8. The current transformers of the kiosk breakers were used for over-current, earth fault, differential protection and restricted earth fault protection.

Connecting the Direct Current (DC) batteries to the 22 kV/400 V transformers, was carried out through DC to AC inverters [82]. A 400 V yard distribution box, with a chop-over module was installed, to provide auxiliary supply for more than one of the Energy Storage Systems (ESS).

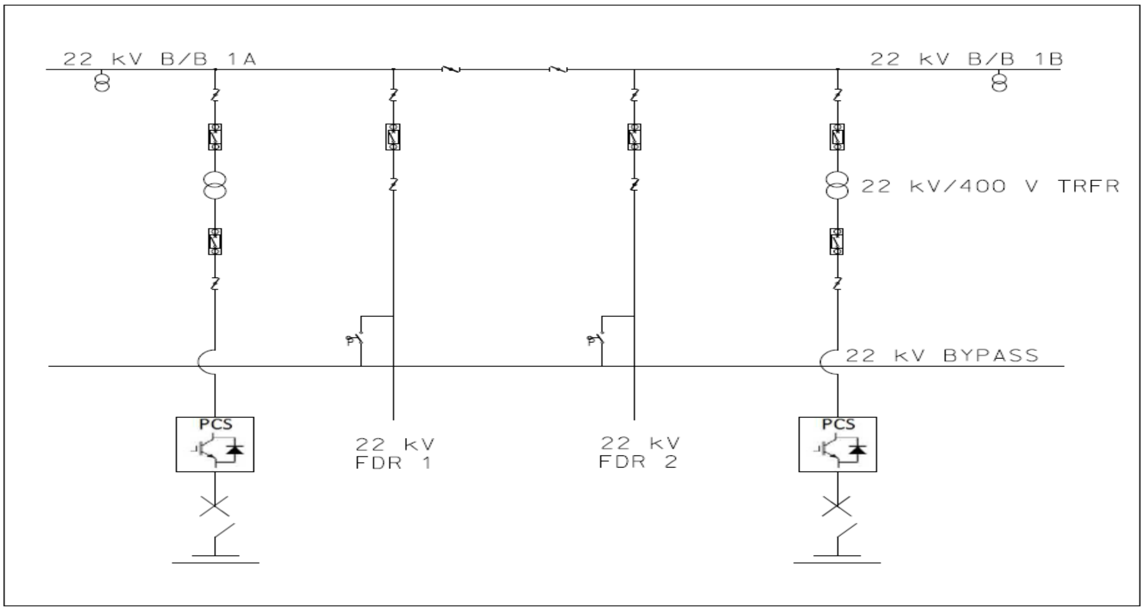


Figure 3.8: BESS integration design

The SEL-487E two terminal differential protection relay, in Figure 3.9, was used when two kiosk breakers were utilised. The on-load tap changer of the step-up transformer, is protected and controlled by the 4TC-5200 Tap Changer protection scheme.

Figure 3.9: SEL-487E relay

The BESS section design was strung with a Bull conductor and connected to the 22 kV bypass Isolators, as designed in Figure 3.10, below. The bypass of the protected bay, refers to the complete switching out of the protected bay, including the protected equipment. The bypassed feeder bay is rerouted to a fully equipped bay, which has a protection scheme and revenue metering. The bypass of a faulty bay, was to improve network performance and ensure customer satisfaction, while the faulty bay was repaired.

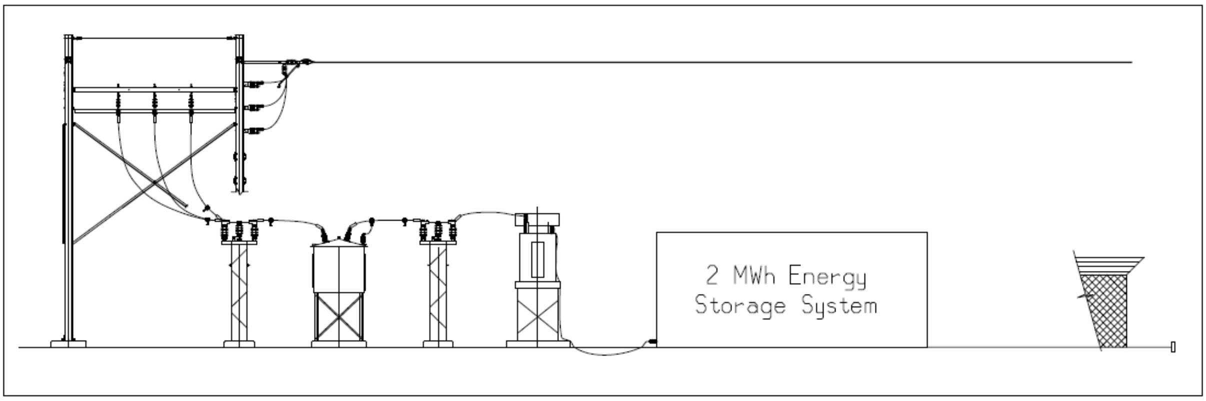


Figure 3.10: BESS section design

The 4RF1100 scheme, in Figure 3.11, for Embedded Generators in power utilities, were utilised. A three-phase voltage transformer input is included for measurements, direction determination and synchronism checks.

Figure 3.11: MiCOM P145 relay

The 4RF1100 scheme was used, protecting the medium voltage power system and the consumers, from possible adverse effects of the BESS. The 4RF1100 protection scheme utilises the MiCOM P145 feeder management relay. The 4RF1100 scheme provides over-current, earth fault and sensitive earth fault protection. Sensitive earth fault protection, is a low-set exact time protection function, used on medium voltage overhead lines.

3.3.2 Yard AC Distribution Box

Two 100 kVA NEC/R/T's (Neutral Electro-magnetic Couplers with neutral earthing resistors and auxiliary transformers), were used as a source of AC power for the substation. A yard AC distribution box, complete with a chop-over module and a termination module, was installed in the substation high voltage yard. The yard AC distribution box were utilised to supply power to the yard lights, AC/DC panel and the tap changer motors. The yard AC Distribution box will be no further than 30 meters from any apparatus of the plant in the substation, to save on cabling costs. The AC distribution module further provides an electrical supply for maintenance, breakdown or testing purposes.

The chop-over operates in a manner that, the breaking contacts break, before the making contacts close (and vice versa), in order to prevent paralleling of the voltage sources. The chop-over function includes a short time delay, before chopping-over or chopping-back between supplies, providing provision to block the frequency protection, for a short time, after a chop-over operation. The chop-over will operate, based on a complete loss of voltage on one transformer supply.

3.4 Environmental compliance

Three items should be present to start a fire: oxygen, transformer oil and heat [83]. Fire sensors provide quick alarming for fires to be extinguished, before they start [84]. Major substation fires will result in revenue losses, due to loss of supply to customers or asset losses. Due to winds, fire spreads to the rest of the equipment in substations; fire may further affect nearby buildings. Therefore, an appropriate risk assessment was carried out, before Passive Fire Protection was considered for the modern substation. Passive fire protection was set in place, providing a cost-effective fire protection system, to reduce fire damage in substations and to minimise environmental pollution, due to oil. Electricity utility transformers use oil for cooling, which may cause oil spills in the incident of distributing a leak.

Electrical companies previously used crushed stone-filled pits around the transformers. The crushed stone-filled pits prevented fires from spreading to the entire substation [85]. Installing oil-holding dams ensured that oil will not spread and cause environmental pollution. A single oil dam was designed, to accommodate both transformer 1 and transformer 2. The dimensions of the oil dam are 3.9 m x 3.9 m x 2.8 m. The oil dam is capable of holding 18 000 litres of oil, which exceeds the capacity of the largest transformer, plus 20%. The transformer bund wall areas, are drained via 300 mm diameter concrete pipes leading to the oil dam. The bund walls should be 1.5 meters away from the oil-filled equipment, so that oil spills within the bund wall. Bund walls are between 200 mm to 500 mm above the concrete runway. The use of ester oil in transformers, illuminates the use of bund walls, as ester oil is environmentally friendly [86].

Substation, construction activities are not permitted within 100 meters of memorial sites and 20 meters from heritage sites. If clearing of plant species of protected trees (Conservation importance), is unavoidable, a removal permit from the relevant authority must be obtained. Environmental concerns were considered during the design of the new substation, for the safety of animals and consumers [87].

With the worldwide concerns on global warming and the target of reducing carbon emissions, renewable energy technologies, such as Battery Energy Storage Systems, were introduced in electric power networks. Renewable Energy Sources are considered to steer clear of the harmful and dangerous effects of climate change [88].

The BESS container was designed for the harshest expected environmental conditions, being coastal environments, with a creepage distance of 31 mm/kV. Renewable Energy Sources (RES's), solar energy, wind energy and Battery Energy Storage Systems, provide a solution for additional energy, with reduced environmental pollution [89]. The standard creepage distances, for high voltage electrical equipment, are 20 mm/kV and 31mm/kV, for medium to very high pollution levels. The Northern Cape is located close to mining activities, leading to pollution on the substation insulators. The pollution levels of substations, near mining activities and coastal areas, are high. As a result, all insulators for the modern substation design, have a creepage distance of 31 mm/kV.

3.5 Conclusion

The current 66 kV network experiences low voltages, under n-1 contingencies. The existing 66 kV network does not aquire spare capacity to supply new customers. For additional capacity, Eskom should upgrade its distribution network from 66 kV to 132 kV. The challenge with substation upgrades on existing substations, is the cost involved to upgrade the 66 kV substations to 132 kV. The methods used to carry out substation upgrades are costly and time-consuming. Network upgrades require the interruption of a steady supply to customers, reducing the performance of the power system.

The modern substation upgrade utilises less control technology cabling. The very same Control Plant schemes and cabling were re-used, during substation upgrades. The yard AC Distribution box, with an AC distribution module, will be no further than 30 meters from any apparatus of the plant in the substation, to save on cabling costs. The AC distribution module will provide an electrical supply for maintenance, breakdown, or testing purposes.

Electromechanical relays requiring an outage for testing and maintenance, which reduces network performance and cost of unserved energy, is exceedingly costly. Microprocessor-based, Intelligent Electronic Devices (IED's), observe the state of the equipment and protection settings and take action to ensure a steady supply to customers. Microprocessor-based relays may be tested, while the substation is in service.

The 4BZ5800 Bus-zone scheme was applied on single busbar arrangements, with two bus-section isolators and a circuit breaker. The busbars have two-zone busbar protection, with a check zone. The 4BZ5800 busbar arrangement will provide discriminate isolation of the faulted bus-section, ensuring security and continuity of supply to customers. Steady supply to customers will improve the performance of the network and reduce the cost of unserved energy.

Power Delivery Engineering, drawing modules for high voltage feeder bays and transformer bays, should be adhering equipment for various voltage and insulation levels. On the 66 kV feeder bays and the 66 kV high voltage transformer bays, 132 kV safe working clearances was applied, reducing cost and labour, during substation upgrades. The modern substation solution for future upgrades, will reduce the complexity of substation upgrades and improve network performance.

All the safety clearances, foundations, conductor lengths, type of clamps used, steelwork and equipment heights for future upgrades, were taken into consideration, while designing the new 66/22 kV modern substation. The design of the conductors and clamps, caters for the highest anticipated load currents and the maximum expected fault currents, during substation upgrades. Sufficient capacity was created on the medium voltage network for future growth, by applying the new substation upgrade solutions. Sufficient capacity was achieved, by installing the loop-in loop-out configurations, on the high voltage feeder bays and by-pass isolators, on the medium voltage feeder bays.

CHAPTER 4: COMPARATIVE ECONOMIC ANALYSIS

4.1 Introduction

The primary objective of this Chapter, was to demonstrate the economic investments between the various methods of substations upgrade designs. The selection of the optimal substation upgrade design requires a comparative economic analysis. The economic analysis was performed, using literature review expenses, PowerOffice 14 material expenses, supplier budget quotes and the Black Pearl (ACNAC) detail design costs.

Energy consumption expenses were presented, in terms of the levelized annual cost ($/kW per year) and revenue requirements (cents/kWh). The levelized annual cost, is that which an electricity utility would expect to pay yearly, for all the construction work of the proposed substation, including repaying a loan and interest, for the up-front capital cost. The revenue requirement is the amount, in ¢/kWh, that an energy utility would require to charge for each kWh of energy consumed, covering all costs for operating and owning the energy storage system. The revenue requirement value applies to utilities, that expect to sell the energy stored, during peak load periods.

The BESS (Battery Energy Storage System) may be used in reducing the overestimation and underestimation costs of electricity utilities [90]. BESS ageing affects the operational and maintenance cost of the equipment. To prolong the life of the BESS, the cycle ageing and calendar ageing process of the BESS was, revised in the forecast and cost minimisation algorithm [91]. BESS installation cost may be as high as 2.5 times the cost of an equivalent on-grid system [92]. Literature review and comparative cost analysis revealed that, Battery Energy Storage Systems are noticeably more expensive, than the proposed modern substation upgrades [93].

4.2 BESS Capital Cost

System cost depends on many factors, including the battery system and the Power Conversion System equipment, necessary for the Battery Energy Storage System. The most critical factors influencing total life-cycle cost are the capital cost of the equipment, followed by the replacement costs, losses, charging and discharging energy costs. The frequency of operation, application of the BESS and planned discharge cycles, are essential parameters for calculating the life-cycle cost, or present worth of life-cycle cost [94]. The system capital cost, is the sum of the component costs, plus construction costs, for a Battery Energy Storage System, which operates in both the discharge and charge modes [95]. The capital cost calculation for the Power Conversion System and the Battery System are mathematically expressed as follows [96]:

$$Cost_{total}(\$) = Cost_{pcs}(\$) + Cost_{storage}(\$) \tag{4.1}$$

The cost of the power conversion equipment was multiplied to the power rating of the system, as shown by Equation 4.2 [96]:

$$Cost_{pcs}(\$) = Unit\ Cost_{pcs}(\$/kW) * P(kW) \tag{4.2}$$

The cost of the storage unit, is related to the amount of energy stored, as shown by Equation 4.3 [96]:

$$Cost_{storage}(\$) = Unit\ \ Cost_{storage}(\$/kWh) * E(kWh) \tag{4.3}$$

With: $E = P * t$

Where: P = Power;

t = the discharge or storage time;

E = the stored energy capacity.

To account for Battery Energy Storage System inefficiency cost, the storage cost equation was modified as follows:

$$Cost_{storage}(\$) = Unit\ \ Cost_{storage}(\$/kWh) * (E(kWh)/\eta) \tag{4.4}$$

Where: η = the efficiency.

The power conversion systems and the battery systems provide various functions and utilise different ratings. The Power Conversion Systems in Table 4.1, for Long-Term Operation, were priced in $/kW. Battery units are priced in $/kWh. Energy storage systems expenditure depend not only on the type of technology, but further on the planned operation, round-trip efficiency and particularly the hours of storage required.

Table 4.1: PCS Costs for Long-Term Operation [95]

Technology	**250 kW**		**1 MW**		**5 MW**		**20 MW**	
	1st unit	10th unit	1st unit	10th unit	1st unit	10th unit	1st unit	10th unit
Battery	500	225	300	175	200	150	150	125
Note: Power rating is based on continuous operation. Note: All costs are in $/kW.								

Battery technology costs, in Table 4.2, were considered for most energy storage batteries and the costs reflect development costs. Costs of Battery Energy Storage Systems are limited and the costs are power and time-dependent [97].

Table 4.2: BESS technology expenses and performance [96]

Battery Technology	**Power Subsystem Cost ($/kW)**	**Energy Storage Subsystem Cost ($/kWh)**	**Round-trip Efficiency (%)**	**Cycles**
Sodium/ Sulfur Batteries	350	350	75	3000
Vanadium Redox Batteries	400	600	65	5000
Lithium-ion Batteries (large)	400	600	85	4000

4.3 Existing Substation Upgrade

Bill of quantities and the ACNAC program were used for the decommissioning costs of existing substations. Bill of quantities was further used for supply and installation of steelwork. Most existing substations are standard connection substations, meeting the most cost-effective design. Furthermore, standard connection substations meet the Quality of Supply and technical performance specifications. Electricity utilities generally contract with customers on the Standard Option. Specific voltage dip or interruption limits were not specified in the standard contract. Large power consumers may, however, contract the Power Quality Service Option or premium power option. Steady supply option entails costs to be recovered, for the measuring device and operating costs thereof.

From the detailed costing in Table 4.3 above, the cost of upgrading an existing 66/22 kV substation, is more costly than constructing a new substation. While constructing new substations, there are design issues and lessons learnt, that escalate costs. Nevertheless, the cost to upgrade the modern 66/22 kV substation is more affordable, compared to the existing substation upgrade methods, currently used by electricity utilities.

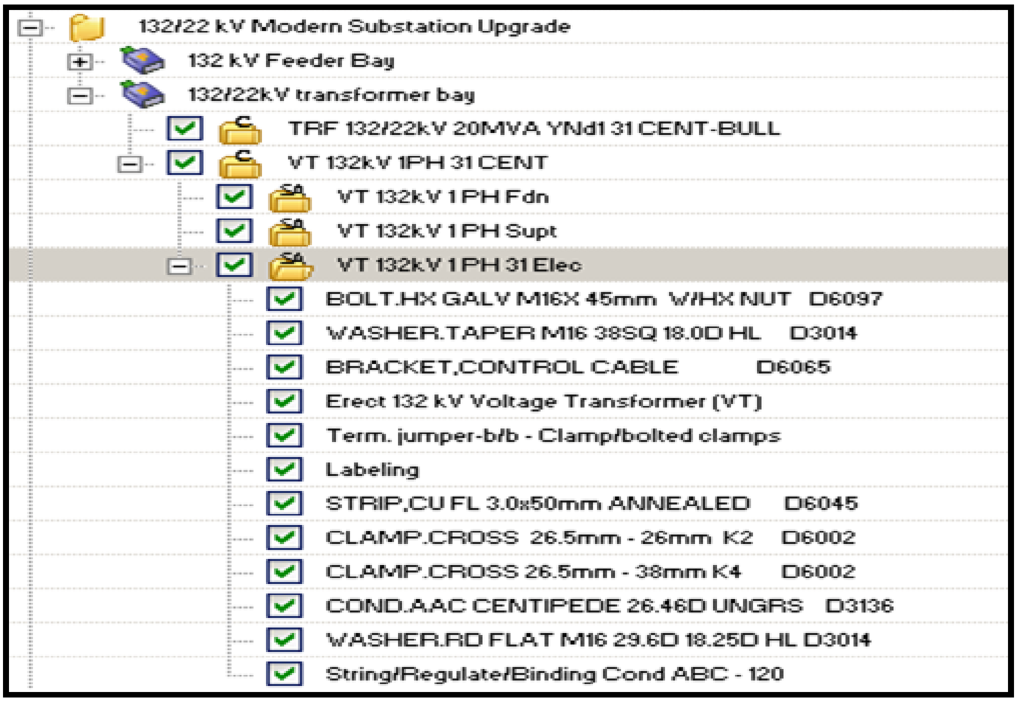
Table 4.3: Upgrading of an existing 66/22 kV substation

Description	**Upgrading expenditure (Rand)**
Engineering (E)	2,605,513
Material (M)	19,395,513
Internal Contracts	87,531
External Contracts	14,543,896
Commissioning (T)	594,543
Overheads (7.5%)	R 2 684 071
IDC (0 %)	0.00
Land and Rights	35,361
Substation Total Capital cost	**39,946,427**
Existing 66/22 kV substation decommissioning costs	18,540,602
Total Substation Upgrade Cost	**58,487,029**

4.4 Modern Substation Expenditure

PowerOffice 14 was, utilised for the costing of a new standard 66/22 kV substation and the modern 66/22 kV substation, for future upgrades. The PowerOffice 14 software makes use of design modules from the Power Delivery Engineering program, for the costing of substations.

The PowerOffice 14 software, in Figure 4.1, consists of Power Delivery Engineering design cells and design modules, used for equipment selection. PowerOffice 14 use standard prices for all the equipment required to design substations. The total material cost and bill of quantities were used, populating the detail design cost on ACNAC (Black Pearl, costing program). Detail costing sheets were used to compare the standard 66/22 kV substation to the proposed 66/22 kV substation, for substation upgrades.



- 132/22 kV Modern Substation Upgrade
  - 132 kV Feeder Bay
  - 132/22kV transformer bay
    - ☑ TRF 132/22kV 20MVA YNd1 31 CENT-BULL
    - ☑ VT 132kV 1PH 31 CENT
      - ☑ VT 132kV 1 PH Fdn
      - ☑ VT 132kV 1 PH Supt
      - ☑ VT 132kV 1 PH 31 Elec
        - ☑ BOLT.HX GALV M16X 45mm W/HX NUT D6097
        - ☑ WASHER.TAPER M16 38SQ 18.0D HL D3014
        - ☑ BRACKET,CONTROL CABLE D6065
        - ☑ Erect 132 kV Voltage Transformer (VT)
        - ☑ Term. jumper-b/b - Clamp/bolted clamps
        - ☑ Labeling
        - ☑ STRIP,CU FL 3.0x50mm ANNEALED D6045
        - ☑ CLAMP.CROSS 26.5mm - 26mm K2 D6002
        - ☑ CLAMP.CROSS 26.5mm - 38mm K4 D6002
        - ☑ COND.AAC CENTIPEDE 26.46D UNGRS D3136
        - ☑ WASHER.RD FLAT M16 29.6D 18.25D HL D3014
        - ☑ String/Regulate/Binding Cond ABC - 120

Figure 4.1: PowerOffice 14 software

4.4.1 Control Technology expenditure

The Control Plant expenses were to procure and install two new 66 kV feeder protection schemes, two new 66/22 kV transformer protection schemes, two new tap changer schemes and four new 22 kV rural feeder schemes. Expenditure includes: pre-commissioning and commissioning of protection schemes, SCADA circuits, metering modules, direct current and telecommunication circuits.

A. High Voltage Feeder Protection schemes (4FZD3920)

The REF615 supports the IEC61850 standard, for inter-device communication in substations. The IEC61850 remote engineering access, via Ethernet and the local testing option, were added to the protection schemes. The 66 kV high voltage feeder protective relay, the RED670 offer an Ethernet module, using the IEC61850 protocol, for communication with station bus equipment. The high voltage feeder schemes expenditure, in Table 4.4, included digital transducers, for current measurements.

Table 4.4: 66 kV Feeder Protection schemes (4FZD3920) expenditure

Description	**Quantity**	**SAP no.**	**Total cost (Rand)**
4FZD3920 schemes	2	0248558	294,210
Supervisory binary output cards 1MRK000614-AB for ABB RED670 relay	2	0248568	6,490
IEC 61850 remote engineering access Ethernet switch	1	0248625	31,468
Digital transducers - universal, stand-alone	2	0183360	16,004
Box scheme in a wooden crate for shipping	2	0248565	3,278
Total			351,450

B. Transformer Protection schemes (4TM7101)

The economic expenses for the two 66/22 kV transformer bays, in Table 4.5, were for the two transformer protection schemes (4TM7101), restricted earth fault protection and the Ethernet communication interfaces. Two neutral electromagnetic couplers, with auxiliary transformers, are for the auxiliary supply of the substation.

Table 4.5: Transformer Protection schemes (4TM7101) expenses

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
4TM-7101 three winding transformer protection schemes (110V DC)	2	0246026	278,428
High impedance restricted earth fault protection relays	2	0246035	50,740
Ethernet communication interfaces supporting the IEC 61850 PROTOCOL	2	0246044	26,468
Total Cost			355,636

The single-phase fault current is restricted to 720 A, by the two 360 A, 22 kV neutral electromagnetic couplers with auxiliary transformers, installed on the 22 kV side of the transformer. The high impedance, high voltage and medium voltage restricted earth fault protection, is provided by the RMS 2V73K1 relay.

C. *Tap Changer protection schemes (4TC5200)*

The two tap changer protection schemes (4TC5200) expenditure, in Table 4.6, were allocated to the two 66/22 kV transformer tap changers. The REG-DA IED controls the voltage, by using the minimum circulating current principle.

Table 4.6: Tap changer protection schemes (4TC5200) costs

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
4TC-5200 tap changer protection and control schemes (110 V DC)	2	0246077	99,531
REG-PED (ETHERNET) supervisory communication interface	2	0246086	12,263

Total			111,794

D. Bus-zone scheme (4BZ5800)

The Bus-zone scheme (4BZ5800) expenditure, in Table 4.7, was allocated to the high voltage bus-zone protection. High voltage bus-zone protection is in between the high voltage feeder bays and the transformer bays.

Table 4.7: Bus-zone scheme (4BZ5800) expenses

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
Bus-zone Protection Scheme including cabinet	1	Buy out	44,385
Single phase current transducers	2	224937	1,266
Total			45,651

E. Medium Voltage Protection scheme (4RF1101)

Capital expenditure for equipment, in Table 4.8, was set aside for the four rural feeder protection schemes (4RF1100), on the outgoing 22 kV feeder bays. The four feeder protection schemes, in the control room, were mounted and earthed, as per the proposed control room layout drawings.

Table 4.8: 22 kV Protection scheme (4RF1101) expenses

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
Rural feeder bays, including cabinet (4RF1100)	4	0224944	152,596
Communication ports, for MiCOM P145 relay.	4	0224955	7,084
Single phase current transducers	4	0224937	2,532

Total			162,212

F. *Metering expenses*

Costing was calculated for twelve new meters, as indicated in Table 4.9, for the two metering panels. The meters are for 66 kV statistical metering and 22kV tariff metering. The Smartoo GPRS modem is for remote downloading of statistical and revenue metering data. The GSM modem is connected onto the MV90 network. The Vecto II meters, in the quality of the supply module, were for the quality of supply measurements.

Table 4.9: Metering expenditure

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
3MM02C meter modules	6	0175685	56,070
Voltage Selection Module D	2	0175688	10,896
GSM Cellular patch antenna	1	0246200	2,000
ABB Vision meters 1A type A1700 class 0.5 PB3KAARCTPRNC	12	0242582	54,000
Smartoo GPRS Modem	1	0223364	3,598
Swing frame cabinets	2		22,416
Quality of supply modules	2	0230644	9,908
Total			158,888

G. *AC/DC supply*

The AC/DC supply expenses, in Table 4.10, were allocated to the dual control yard AC distribution board, the single-phase AC module, AC supply module, DC supply module, DC interface module and the AC/DC panel.

Table 4.10: AC/DC supply charges

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
Dual control yard AC distribution board	1	185222	38,508
The single phase AC modules	2	216215	7,306
AC supply module	1	175669	3,387
DC supply modules	2	216216	10,580
DC interface module	1	185229	3,533
AC/DC panel including cabinet	1	Buy out	3,269
Total			66,583

H. *Direct Current expenditure*

Expenses for integrated battery chargers and NiCad battery cells, in Table 4.11, were allocated to the protection schemes and telecommunication equipment.

Table 4.11: Direct Current equipment costs

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
110 V, 20 A integrated battery charger	1	0212980	71,519
50 V, 30 A integrated battery charger	1	0212993	69,657
88C SA TYPE 3, cabinet with fixed steps, suitable for 88 cells	1	0256354	16,655
40C SA Cabinet with Fixed Steps, Suitable for 40 cells	1	0209840	16,655
1.2 V, 150 Ah NiCad Cells	38	0256102	31,170
1.2 V, 100 Ah NiCad Cells	85	0256104	102,191
Suitable for 85-88 VTX1 L95-110 Ah, VTX1 M75-100Ah Cells (Link set)	1	0256348	675.00
Suitable for 85-88 VTX1 L140-185 Ah, VTX1 M125-170Ah Cells (Link set)	1	0256349	675.00

Total			309,197

I. *SCADA and Telecommunications*

The SCADA system and telecommunications expenses, in Table 4.12, were allocated to the supervisory control of substation breakers and alarms, of substation equipment.

Table 4.12: SCADA and Telecommunications equipment expenses

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
DRTU	1	Buy out	220,000
Polyphasor lighting arrester	1	4543	1,200
Ten pair 80 way back mount frame	1	11136	180.00
Corner reflector cr400 & brackets	1	11714	1,100
Fixed label holder, 10 pair (16mm)	1	115067	6.00
Fixed label holder, 10 pair (22mm)	1	115068	2.00
LSA profile, 10pr disconnect module	1	164810	238.00
Earthing kit for coaxial cable	1	165520	275.00
Radio, mobile dash mount UHF TAIT T2015	1	174711	3,309
MODEM, radio FFSK 1200/2400/4800 baud	1	174778	750.00
Sundries, Krone	1	Buy out	6,500
Fibre Optic patch panel	1	Buy out	11,000
KabelFlex underground cable	500 m	Buy out	1,042
Total			245,602

J. *Under-frequency Load Shedding scheme*

Rotational load shedding scheme expenses, for under-frequency load-shedding, is shown in Table 4.13 below. Load shedding is a last resort, once no emergency reserves are available to maintain the frequency and voltage, at acceptable levels [98].

Table 4.13: Under-frequency Load Shedding scheme charges

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
4LS1101 Under-frequency Load Shedding protection scheme	1	0404060	44,976
4LS-1101 protection scheme module, with enclosure for transport	1	404076	1,636
Total			46,612

K. Control Plant cabling and glands

The purpose of the multi-purpose substation design, was to further prevent decommissioning of all the Control Plant cabling, during substation upgrades, to spare costs. All of the control cables, in Table 4.14, were installed from the 66/22 kV transformer panels, 66 kV feeder panels and the 22 kV feeder panels, to the respective equipment in the substation yard.

Table 4.14: Control Plant cabling and glands expenditure

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
Cable 1kV 4c 4 mm² Cu BVX4ECV	6000 m	014475	129,000
Cable 1kV 12c 2.5mm² Cu BVX12DCV	1500 m	0014469	74,145
Cable 1kV 19c 2.5mm² Cu BVX19DCV	900 m	0014484	60,786
Cable 1kV 4c 16mm² Cu BVX4HCV	300 m	0014476	15,726

Cable telephone 10pr 0.5mm diameter TPH10AX	300 m	0014666	6,900
CAT5E FTP (Shielded) Solid Core (4pair)	400 m	0243301	5,600
Gland No 1 & Shroud	336	0168367	5,796
Gland No 2 & Shroud	96	0168279	2,415
TPH 10AX Cable Gland No.1	160	0010910	3,755
Total costs			304,123

L. *Junction boxes*

The voltage transformer and current transformer junction boxes installed, were for metering and protection functions. The costing for junction boxes, in Table 4.15, was allocated to the 66 kV feeder bays and the 66/22 kV transformer bays.

Table 4.15: Junction box expenses

Description	**Quantity**	**SAP number**	**Total cost (Rand)**
VRW20 junction boxes, with 8 circuit VT insert	4	0186950	28,188
VRW20 junction boxes, with 6 circuit CT insert	4	0186961	22,543
Total			50,731

M. *Total Control Technology expenses*

The total Control Technology expenditure, in Table 4.16 was, for the Control Technology designs, Control Plant schemes, Control Plant cabling as per cable block diagrams, installation and earthing of Control Plant panels, as well as the pre-commissioning and commissioning of Control Plant panels.

Table 4.16: Total Control Technology expenses

Description	**Total Control Technology Cost (Rand)**
Engineering design costs	263,000
Secondary Plant material costs	2,543,265
Installation and earthing of schemes	463,352
Commissioning costs	974,532
Total	4,244,149

4.4.2 Power Plant design expenditure

The period from budget quote approval, to the connection of a Battery Energy Storage System, may be brought down to one year. The time frames, from load forecasting to the construction and commissioning of new high voltage networks and substation upgrades, may take up to a decade. The financial benefit for network upgrade deferral, lasts for approximately one year, due to energy demand. Thereafter, it becomes cost-effective to proceed with the network and substation upgrades [99].

A. Proposed 66/22 kV substation equipment

For the substation equipment expenses, in Table 4.17, 132 kV current carrying equipment was used to save costs and time, during substation upgrades.

Table 4.17: 66/22 kV substation equipment expenses

DESCRIPTION	**SAP number**	**Quantity**	**Material costs (Rand)**
Isolator, hand operated, 132 KV, AC, 2500 A, 40 kA	0527586	8	567,434
BKR, 132 kV, 3150 A, 40 kA, 3P, 110 VDC, 31 mm/kV	0218735	5	519,459

CT, 132 kV, 2500 A, 40 kA, 2P2M2B1600, 31 mm/kV	0180034	18	1,332,772
66 KV SURGE ARRESTER, MCOV 84 kV, 31 mm/kV	0004562	12	43,252
TRFR 20 MVA, 66/22 kV, OLTC, YNd1	0185767	2	10,096,332
22 KV SURGE ARRESTER, MCOV 24 kV, 31 mm/kV	0400391	18	28,352
NEC/NER/AUX TRFR 22 kV, 360 A, 31 mm/kV	0182732	2	164,789
BKR KIOSK 22 kV, 1250 A, 20 kA, 31 mm/kV	0170218	6	623,351
ISOLATOR 22 kV, 2500 A, 25 kA, hand operated	0012904	8	672,059
ISOLATOR 22 kV, 400 A, 12 kA	0170064	24	40,368
VT 1PH, 66 kV/110 V, 100/50 VA, 31 mm/kV	0180091	6	157,104
VT 1PH, 22 kV/110 V, 100/50 VA, 31 mm/kV	0008746	6	79,336
Total cost			4,228 276

B. *66/22 kV substation steelwork*

Steelwork expenditure, in Table 4.18, was for standard equipment supports, designed according to distribution technology cells and modules. The labour and transport costs were incorporated in the quoted rate.

Table 4.18: Supply and installation of substation steelwork costs

DESCRIPTION	**SAP number**	**Quantity**	**Material expenses (Rand)**
6m Terminal supports pad type	D-DT-5210	6	59,040
132 kV Surge Arrestor brackets	0559307	2	13,996
132 kV Manual Isolator lattice supports	0186033	8	136,144
132 kV Circuit breaker tubular supports	0182927	5	72,680
132 kV CT lattice supports	0182752	18	68,886

132 kV CT lattice support caps	0182753	18	3,780
22 kV NECRT lattice supports	0185520	2	14,026
22 kV Kiosk breaker lattice supports	0402740	6	34,650
132 kV Twin tubular Busbar supports	0220125	4	108,244
132 kV Busbar tubes AL 120mm x 4 mm	0206318	6	1,752
22 kV Road crossing Tubular Busbar supports	D-DT-5221	4	24,000
22 kV Box structure column supports	0182776	20	265,000
22 kV Box structure, Extension bays	0183871	10	471,670
22 kV VT lattice support structures	0186034	2	7,654
22 kV VT lattice support structure caps	0227047	2	4,502
22 kV Manual isolator lattice supports	0182592	8	41,928
21 m Lighting / Lightning Masts	0214509	6	293,076
Total cost			1,621,028

C. Proposed 66/22 kV substation foundations

The expenses, in Table 4.19, were allocated to foundation material, foundation excavations, reinforcements, holding down bolts, backfilling and casting of foundations, according to distribution technology designs, including compaction around the foundations. Compaction is required to increase the stability of the foundations; the fill was compacted to a density of 93% Mod AASHTO. The expenses include shoring for foundations larger than 1.5 metres, where the subgrade tends to collapse.

Table 4.19: Supply and installation of substation foundations expenses

DESCRIPTION	**DDT number**	**Quantity**	**Material costs (Rand)**
6m Terminal support pad type foundations	D-DT-5210	6	55,074

132 kV Isolator support foundations	D-DT-5202	8	60,408
132 kV Circuit breaker foundations	D-DT-5200	5	60,725
Medium Equipment Support foundations	D-DT-5206	24	111,120
132 kV Tubular Busbar Twin support foundations	D-DT-5225	8	56,984
22 kV Road crossing Tubular Busbar support foundations	D-DT-5221	8	56,984
22 kV NECRT foundations	D-DT-5207	2	12,382
22 kV Kiosk circuit breaker foundations	D-DT-5216	6	30,534
22 kV Isolator foundations	D-DT-5205	8	24,760
22 kV Box structure support foundations	D-DT-5223	20	88,840
21m Lightning/lighting mast foundations	D-DT-5217	6	66,798
Concrete Trenches (m)	D-DT-5254	193	123,906
Concrete Covers	D-DT-5254	643	83,590
Total cost			832,105

D. *Proposed 66/22 kV substation conductors*

The conductor stringing expenses, in Table 4.20, was carried out, by using Sections layout designs. The two incoming 132 kV line bays were strung with a Bull conductor. The 132 kV Busbars, have a 120 mm outer diameter aluminium tube. The medium voltage feeder bays were strung with a Hornet conductor.

Table 4.20: Substation conductors expenditure

Description	**SAP number**	**Quantity**	**Material costs (Rand)**
Cond, AAC Centipede 26.46 mm diameter	14447	291	12,288

Cond, AAC Bull 38.25 mm diameter	14452	654	70,030
Tube AL 120 mm outer diameter x 4 mm W thick and 12 m long	206318	6	1,752
All Aluminium Conductor Hornet 16.25 mm diameter ungreased	14446	484	19,639
Copper round 10 mm diameter conductor	0400769	4815	72,090
Conductor, flat 50 x 3 mm	0400772	568	87,607
All Conductor Steel Re-enforced, Hare 14.16 mm diameter ungreased	14441	32	3,872
Total costs			267,278

4.4.3 Total modern substation design expenditure

Total acquisition expenditure, in Table 4.21, include: contractor site establishment, transport of equipment from the factory to the substation, design expenses and material expenses. Futhermore, acquisition expenditures include: servitude of substation, survey, civil works, construction and commissioning of substations.

Table 4.21: Modern 40 MVA substation cost breakdown

Description	**Modern Substation expenditure (Rand)**
Engineering design	3,316,603
Material	22,063,659
Internal Contracts	97,252
External Contracts	13,478,602
Commissioning	693,493

Overheads (7.5%)	2,973,721
IDC (0%)	0.00
Land and Rights	31,170
Total Project expenses	42,654,500

4.4.4 132/22 kV Upgrade expenditure

In Table 4.22, substation equipment upgrade expenses were allocated to 132 kV voltage carrying equipment, only.

Table 4.22: Substation equipment upgrade expenses

DESCRIPTION	**SAP number**	**Quantity**	**Material costs (Rand)**
S/ARR S/CL 132 kV, MCOV 84 kV, 31 mm/kV	0400380	12	82,988
TRFR 20 MVA, 132/22 kV, OLTC, YNd1, 31 mm/kV	0185670	2	10,746,632
VT 1PH, 132 kV/110 V, 100/50 VA, 31 mm/kV	0180089	6	285,128
Total			368,116

Factors that contributed to substation upgrade expenses, in Table 4.23, were:

- Labour expenses: Labour costs on the modern substation design was economical. Considering that the steelwork, as well as cabling and foundations, will not be decommissioned during substation upgrades.
- Cable expenses: The control plant cabling, from the control room to the Primary Plant equipment, was re-used. The cable lengths, from the Control Plant schemes to the Primary Plant equipment, were designed for 132kV clearances.

- Land development costs: There are no additional Land Development expenses; the same servitude was re-used.

Table 4.23: Total modern substation upgrade costs

Description	**Modern Substation expenditure (Rand)**
Engineering	3,316,603
Material	22,063,659
Internal Contracts	97,252
External Contracts	13,478,602
Commissioning	693,493
Overheads (7.5%)	2,973,721
IDC (0%)	0.00
Land and Rights	31,170
Total Project Costs	**42,654,500**
Upgrade equipment costs	368,116
Upgrade labour cost	147,200
Total 132/22 kV modern substation upgrade costs	**43,169,816**

4.5 Conclusion

Energy storage systems were used to defer substation upgrades, as well as to avoid the cost of coal and carbon emissions, by coal generating stations. Literature review and comparative cost analysis, revealed that Battery Energy Storage Systems and existing substation upgrade designs, are noticeably more costly, than the modern substation design for future upgrades.

Design, apparatus and construction expenses of a standard 66/22 kV, 40 MVA substation, were approximately R 39,946,427. The decommissioning cost of an existing 66/22 kV substation, was approximately R18,540,602, per substation. The decommissioning cost, escalated the cost to upgrade an existing 66/22 kV substation, to R 58,487,029. The minimum Battery Energy Storage System cost, was approximately R4,931,500, for a 1 MW power conversion system and R4,931,500, for a 1 MWh battery system. The modern substation designs, including upgrade costs, reduced capital expenditure and operational expenditure to R 43,169,816, during substation upgrades. Substation upgrade cost comparison was for calculating the most cost-effective design, for substation upgrades.

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Conclusion

The aim of this research was an investigation into the design of a new substation, using Micro-station V8i, minimizing cost and saving time, during future upgrades. Chapter 2 shows that, mobile unit substations may increase the operational flexibility of substations and consequently, ensure continuity of power supply to customers, during substation upgrades. Capacitor bank bays installed on substation busbars, improve power factor correction and assist with voltage upgrades, thereby, improving the overall power distribution efficiency.

The challenge with renewable energy is that the amount and timing of energy production, by solar and wind plants, is unknown. BESS, with renewable generation, will improve the function of renewables and overall generation. The cost of un-served energy, incurred by power utilities is less, due to firm reliable supply. BESS will reduce environmental pollution (Environmentally friendly), defer substation upgrades, provide secure backup supply, improve network performance and create sufficient capacity on the medium voltage network, during peak periods.

Chapter 3 presents the design methodology, using Micro-station V8i on existing substation upgrades and the modern substation designs, for future upgrades. The methods used to carry out substation upgrades, are costly and time-consuming. Network upgrades require the interruption of steady supply to customers and this reduces the performance of the power system.

Power Delivery Engineering, drawing modules for high voltage feeder bays and transformer bays, should be adhering equipment, for various voltage and insulation levels. On the 66 kV feeder bays and the 66 kV high voltage transformer bays, 132 kV safe working clearances were applied, reducing cost and labour, during substation upgrades.

The modern substation solution, for future upgrades, will reduce the complexity of substation upgrades and improve network performance. All the safety clearances, foundations, conductor lengths, type of clamps used, steelwork and equipment heights for future upgrades, were taken into consideration, whilst designing the new 66/22 kV modern substation.

The modern substation upgrade utilised less control technology cabling. The very same Control Plant schemes and cabling were re-used during substation upgrades. The yard AC Distribution box, with an AC distribution module, was not further than 30 meters from any apparatus of the plant in the substation, to save on cabling costs. The 4BZ5800 Busbar arrangement, provided discriminate isolation of the faulted bus-section, ensuring security and continuity of supply to customers. A steady supply to customers, will improve the performance of the network and reduce the cost of unserved energy.

Chapter 4 provides the economic analysis, using Power Delivery Engineering modules, Bill of quantities, Power Office software and the Black Pearl (ACNAC) software, for detailed design costs. Design, apparatus and construction expenses of a standard 66/22 kV, 40 MVA substation, were approximately R 39,946,427. The decommissioning cost of an existing 66/22 kV substation, was approximately

R18,540,602, per substation. The decommissioning cost, escalated the cost to upgrade an existing 66/22 kV substation, to R 58,487,029. The minimum Battery Energy Storage System cost, was approximately R4,931,500, for a 1 MW power conversion system and R4,931,500 for a 1 MWh battery system. Substation lifespan is approximately 50 years and the BESS life span, is approximately 20 years.

The modern substation designs, including upgrade costs, reduced capital expenditure and operational expenditure to R 43,169,816, during substation upgrades. The optimum economic results obtained for substation upgrades, were by comparing the most cost-effective designs for substation upgrades, when upgrading high voltage networks, or deferring substation upgrades.

5.2 Future recommendations

The study has discovered the following future recommendations:

- Methods of reducing the cost of Battery Systems and Power Conversion Systems for electricity utilities and large power users.
- Recommending the use of condition-based maintenance on all Control Plant schemes and mobile substations, ensuring a steady supply to customers.
- Cost-effective methods of deferring substation upgrades and high voltage network upgrades, should be explored.

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