NETWORK STUDIES AND MITIGATION OF HIGH 132 kV FAULT CURRENTS IN ETHEKWINI ELECTRICITY

by

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This thesis is dedicated is dedicated to my parents, my wife and daughter.

Acknowledgements

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Abbreviations and Acronyms

- EE EThekwini Electricity
- EM EThekwini Municipality
- ES Eskom
- FCL Fault current level
- KZN KwaZulu-Natal
- ADMD After diversified maximum demand
- FCLD Fault current limiting device
- NERSA National Current Regulator of South Africa
- SS/s Substation/s
- HV High voltage (≥ 33kV)
- MV Medium voltage (typically 11kV)
- LV Low voltage (single phase 220 V, three phase 380V)
- 1ph Single phase
- 3ph Three phase
- Intake Point at which Eskom supplies eThekwini Electricity
- CB's Circuit breakers
- ohtls Overhead transmission lines
- FCLR Fault current limiting reactor
- CFL Compact fluorescent lamp
- LED Light emitting diode
- GLF Geographic Load Forecast
- ADD After diversity demand
- KLA Klaarwater

ABSTRACT

The growth of the world population has led to an increase in the demand for electricity. This has resulted in the expansion of electric power networks and this evolution brought with it many challenges. One of which is that power networks are experiencing increased fault current levels. This is as a result of growth in demand which has led to interconnected networks and increases in generation capacity. Fault current levels have been increasing steadily and are at a point where mitigation measures have to be evaluated to ensure that equipment operate within designed limits. Alternatively, equipment would have to be replaced with adequately rated equipment. In some cases, replacement would have to take place prematurely, since equipment would not have reached their “end of life”. This study investigates the problem at a 132 kV sub-transmission voltage, and the various factors involved with increasing fault levels and mitigation methods being used. Essentially, mitigation measures increase the impedance in the network, thereby reducing fault currents. Mitigation measures are classified as passive or active, and have varied degrees of effectiveness, usage and network losses. Active measures do not have any effect on the network under normal operating conditions, and only operate during a fault. An example is the superconducting fault current limiter. Passive measures operate under normal and abnormal conditions and affect network parameters. These are usually topological changes which increase the system impedance. Passive measures were chosen for the network studies since active measures are in the developmental stage at the 132 kV voltage level. In this research investigation, the measures tested include: network splitting by creating sub-grids, network reduction, high impedance transformers, introducing a higher voltage network and current limiting reactors. Reducing the 132 kV interconnectivity by creating a northern, southern and central grid reduced the fault levels significantly and does not require any capital investment. However, under abnormal conditions the grids are reconnected to ensure that there is no loss of supply. A solution is to construct a network at a higher voltage level that will support the 132 kV sub grids. A reduction in 275/132 kV transformation lowers the fault levels, while a reduction in generation had little effect on the network. High impedance transformers and current limiting reactors increase the losses in the network, but can be used to limit fault currents to pre-determined values. Electric utilities have to investigate the various measures in order to ascertain the most beneficial to that particular network, given the high cost of infrastructure, the ability to experience outages, space constraints in substations, and the electrical losses that might be incurred. The results obtained from this study carried out on the 132kV eThekwini Network is presented and discussed.

CHAPTER 1 - INTRODUCTION

1.1 Background

EThekwini Electricity (EE) network is supplied at 275 kV by Eskom (ES) from the Western, Southern and Northern regions of the Municipality. Electric power is stepped down at these substations (SSs) to 132 kV and distributed through overhead transmission lines (ohtls) and underground cables to supply the 132/11 kV SSs. There are approximately a hundred SSs in the supply area [1] and EM is a major load centre in ES's Eastern Region.

The ES supply is a network of 400 kV and 275 kV overhead lines, with the major lines into KwaZulu-Natal (KZN) supplied from the North West of the province. These essentially carry power from the generation hub situated in Mpumalanga. The 275 kV network is now being phased out and replaced by 400 kV. Plans are also in place for 765 kV lines to be constructed to the region. The region has experienced steady growth over the last 20 years and as a result ES has strengthened the network in the region and will continue for the next 10-15 years [2].

EE has seen a steady and significant increase in fault current levels (FCLs) on the 132 kV network [3]. The increase is evident in the results of the fault level studies carried out across the EE network, and is higher at the ES point of supply to EE (known as the Intake points or substations). The EE network is currently operated fully inter-connected at 132 kV, between the regions, together with the bus-sections and couplers closed. In the event of a 132 kV fault occurring, equipment fault current ratings shall be exceeded at some of the 132/11 kV and 132/33 kV SSs. This problem exists at a number of EE's SSs, with the highest fault levels occurring at the 275/132 kV SSs.

1.2 Problem Statement

Globally, utility fault current levels have been increasing steadily as additional new generation and transmission infrastructure is commissioned and added to the existing networks [4]. Network strenghtening is required as a result of the increase in demand for electricity as more customers are connected to the grid. However, having under-rated equipment in a network poses a risk to personnel and equipment.

Electric power infrastructure typically has a lifespan of either 20 or 40 years [5]. Over the last decade, with the introduction of asset management, utilities have moved from a time-based maintenance regime to a condition-based one. This enables power utilities to, based on satisfactory conditions, extend service intervals. Condition assessments are carried out in order to determine expected life-span and assist in deciding whether or not to extend the life or replace equipment. However, with the increasing FCLs, utilities may have to do the opposite, by replacing equipment pre-maturely, before they reach their ‘end of life’. In some cases, equipment replacement would be required mid-way into its life. Apart from replacement, other measures need investigation for the under-rated equipment.

Various approaches have been used to solve the problem across networks globally [6]. These have been examined and tested in the network studies that have been carried out. The technical, financial and practical aspects, together with short, medium and long term increase in FCLs has been considered in the research.

1.3 Key Objectives of the Research

The objectives of the study are to:

- Establish the possible causes of FCLs
- Identify the areas in the network where high fault levels are prominent
- Investigate solutions to mitigate the FCLs
- Test mitigation measures on the 132 kV network by conducting network simulations or analysis
- Recommend solutions to mitigate the high 132 kV FCLs

1.4 Thesis Structure

Chapter 2 studies the increase in FCLs, analysis and the mitigation measures. It identifies suitable options to be simulated on the EE network.

Chapter 3 focuses on the existing EE as a utility and the challenges that it faces. The past and future growth is discussed together with the standards and operation of the network. The FCL problem is put in context with the network.

Chapter 4 discusses the study methodology, process, software and the study model.

Chapter 5 shares the results of the study and deliberates over them. The options studied are able to mitigate high FCLs, with a few having a greater effects than others.

Chapter 6 concludes the thesis, offers recommendations and future study alternatives.

CHAPTER 2 - LITERATURE REVIEW

The design of electric power networks or implementing major expansions to existing networks, factors a number of the key issues regarding the technical performance of the network at both transmission and distribution level must be ascertained. These include: voltage regulation, voltage fluctuations, electrical losses, distribution plant loading and utilisation, generation stability, harmonics, phase balancing, supply availability and security, and network fault levels.

2.1 Faults

Faults in an electrical system are undesirable, unpredictable and inevitable events that are the result of creation of unintentional conducting path and subsequent flow of current in that path or circuit. This is referred to a short-circuit fault and is the most common fault in electrical power networks [7]. Blockages can also occur, in which case there will be no flow and an open circuit will occur.

Faults are caused by the breakdown of the insulating medium which leads to an unwanted connection/s of parts of a circuit/s. These can be characterised by extremely high currents at a point, for a short period of time (milliseconds), until interruption takes place by the protection system. However, their effects can be devastating to personnel, plant, the power supply and the financial profitability of the utility. Networks cater for these events by having protection systems in place to protect equipment and utilise equipment rated with the correct specifications.

When a fault occurs, it generates exceptionally high currents that lead to high dynamic and thermal stresses on the equipment such as overhead lines, cables, transformers and switchgear. The protection systems must be activated timeously in these events to prevent or minimise the damage, at the same time isolate, the area in which the fault has occurred.

Furthermore, the equipment must withstand the stresses placed upon them until the protection system becomes operational [8]. The different types of faults that can occur in a power system are shown in figure 1-1. The most common fault is the single line to ground or earth and is shown in figure 1-1(a) [9]. The path to earth might contain resistance, Rf, shown in figure 1-1(f)

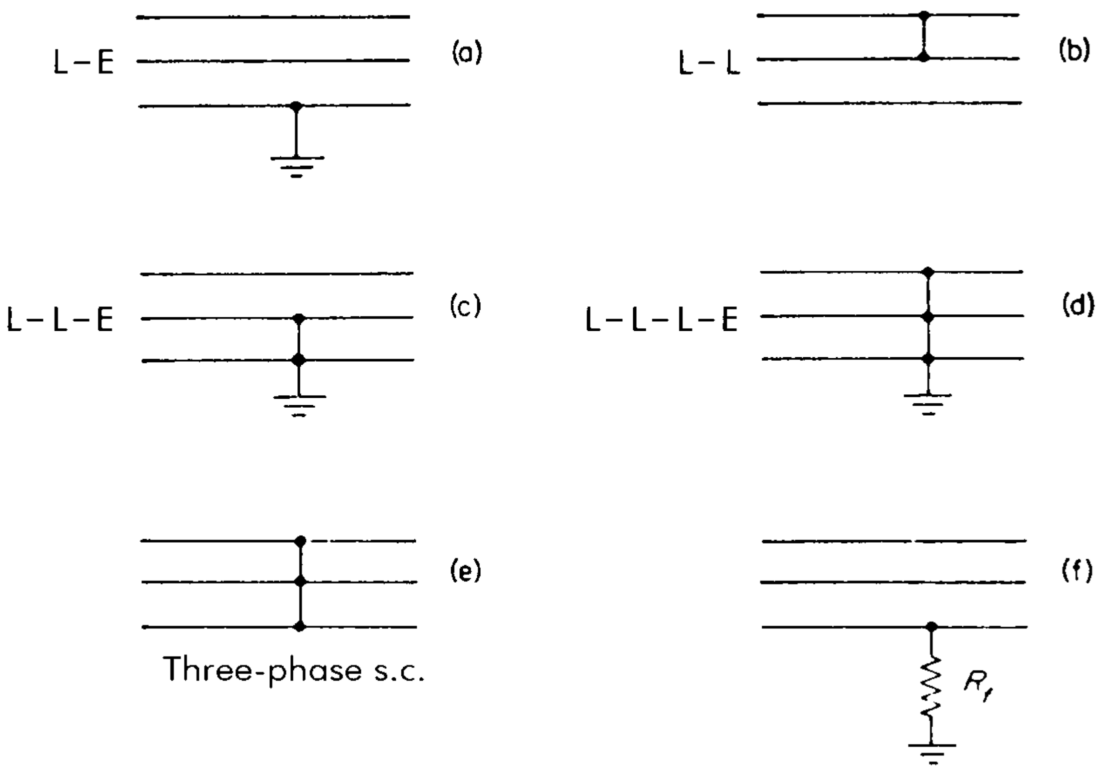

Figure 1: Types of faults where L = line or phase, E = earth [9]

Faults that occur across all 3 phases when the network is electrically balanced are termed balanced faults and normal single circuit equivalents may be used. Other faults will be unbalanced and are calculated using symmetrical components [9].

The most common types of faults occur due to corrosion, lightning, smoke from cane fires, bird streamers, damage to cables or lines and mechanical failure of the equipment [8]. The effects of faults on the network are as follows:

- Voltage sag (or dip)
- Very short interruptions
- Long interruptions
- Voltage spike
- Voltage swell
- Harmonic distortion
- Voltage fluctuation
- Noise
- Voltage Unbalance

Faults can cause immense damage to equipment and injury to personnel. Customers can be affected by loss of supply and production and damage to appliances and machinery.

2.2 Fault Current Levels (FCL)

FCLs in networks have been increasing steadily and have increased across utilities globally [10]. The Cigre Working Group A3.16 conducted a study to ascertain the effects on networks 2003. The results are shown in figure 2 [10]. When compared to a similar survey carried out in 1996 [10], the results show that FCLs have increased to levels where many utilities require fault current limitation at voltages between 110 kV and 145 kV.

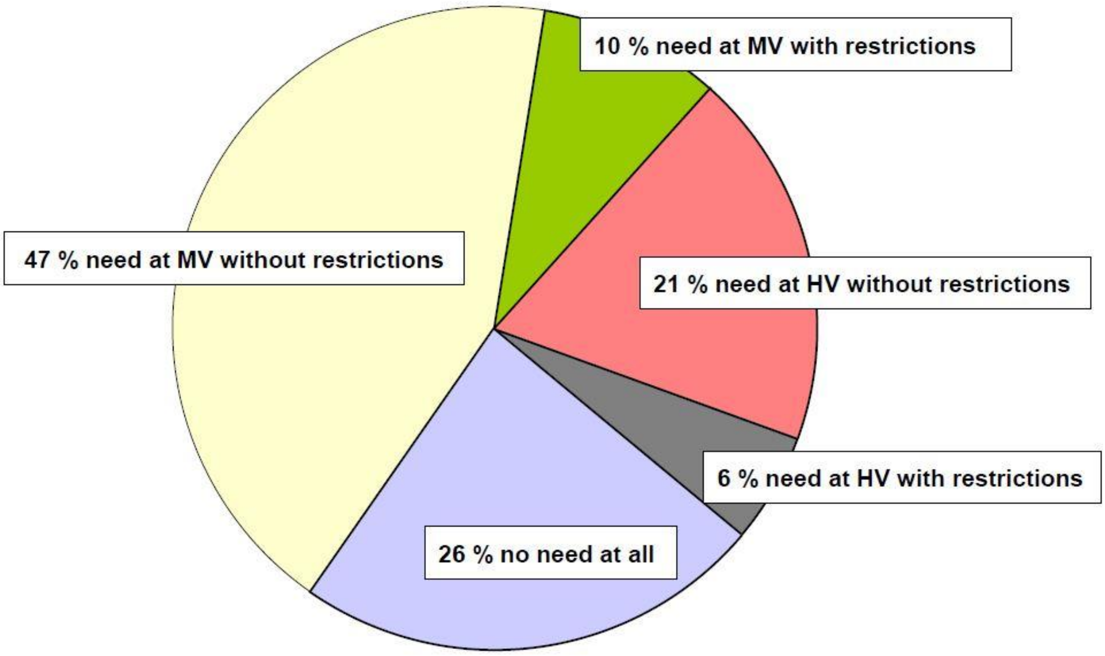

Figure 2: FCL survey results [10]

Electricite de France (EDF), a French utility, uses the FCL specifications as shown in table 1. EE uses different voltages, but the FCLs for equipment matches the equivalent transmission and distribution voltage levels. It can be seen that there has been an increase in the FCL specifications of equipment, which is also the case in EE, FCL specification for 132 kV switchgear was 31.5 and has now been increased to 40kA.

Table 1: FCL specifications for the French utility, EDF [10]

Substation voltage	20 kV	63-90 kV	225 kV	400 kV
Max short circuit current	12.5 kA	31.5 kA (20 kA)	31.5 kA	63 kA (40 kA)

2.3 Fault Analysis

Fault analysis is carried out to determine the magnitude of fault currents in the components within the network. This information is essential in the grading of protection systems and rating the equipment. In complex networks fault analysis is carried out using power system packages. These essentially make use of methods, such as Newton Rapson [11], to solve parameters at the various nodes. It is essential that the model resembles the actual equipment in the field and that all the equipment parameters are considered. Analysis will be carried out using the Power System Simulator for Engineering (PSS®E) which is a power system software analysis tool.

2.4 Causes of the High Network Fault Currents

Over the past two decades, Utilities have seen a steady increase in the fault current levels in their medium and high voltage networks. These have significant impacts on power quality, operation and maintenance, protection, reliability and availability and replacement. These factors ultimately affects the delivery of power to the end user. High FCLs indicate the ability of the network to supply power and are a measure of its robustness. Essentially a reduction of the source impedance will cause an increase in the FCLs in the network. High FCLs are desirable given that the equipment in the network has sufficient capacity to withstand the stress and strain during a fault. FCLs generally increase as a result of network evolution and there are a few factors surrounding this phenomenon.

2.4.1 Increased Utilisation and Demand for Power

The increased demand in power utilisation has resulted in some utilities not being able to supply customers [40]. This is driven by higher consumption patterns and large parts of the world that have not been electrified. Governments are under pressure to provide this basic necessity. Apart from being a basic service, cheap and efficient power is a driver for economic growth in most developing countries [11].

China has now over taken USA to become the biggest economy in the world. In doing so, China has been constructing power capacity approximately the equivalent to that of South Africa’s (SA) installed capacity in a single year. ES, is one of the largest in the world and the leader in Africa and is responsible for almost all in generation capacity. The utility generated 35 819 MW on the 27 February 2016 with the estimated installed capacity estimated at 44 GW [12]. The demand in KZN was 6799 MW and this number is expected rise to 8045 MW by the year 2025 as shown in figure 3 [10].

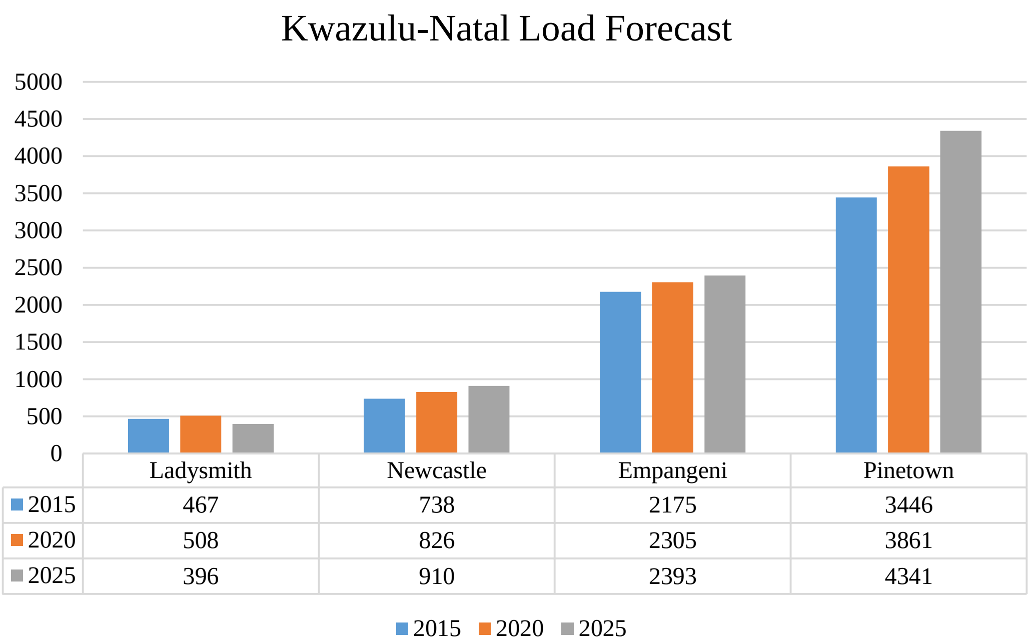

Figure 3: KwaZulu-Natal Load Forecast [10]

The internet has become a necessity in most parts of the world as consumers live in a more connected and interactive society. These, together with the wide usage of smartphones has enabled individuals and businesses to grow their income in many new ways. Small businesses are able to connect to global market and offer their products services to literally anywhere in the world. Medium to large businesses have introduced more automation on their processes. These interventions require uninterrupted supply of power to operate and compete effectively in the global market place.

There has been a steady increase in power utilisation in households with more appliances being utilised on a daily basis. Some households, for instance, have 2-3 or even 4 television sets, as a television set per room is becoming the norm. Additionally, the changes in the weather patterns have led to extreme temperatures being experienced, and this has warranted the use of air conditioners in summer and heaters in winter. The global temperature rise in February 2016 was the highest recorded at 1.35°C and higher than the rise experienced last year of 1.15°C [13]. As a result, utilities are experiencing an increase in the notified maximum demands (NMD) of the household subclasses (low, medium and high income household levels).

Massive electrification projects are being commissioned locally to provide power for all citizens living in both formal and informal sectors. These are households that have low average diversification maximum demands (ADMD) but are being electrified in large numbers and can be supplied quickly using economical designs. EE had a target of 40 000 new connections in the 2015/16 financial year [14].

A Geographical Load Forecast carried out by EE indicates that there will be fifty percent increase in the City's power consumption over the next 20-30 years. The forecast was based on an Economic Development Study [15] and is dependent on the economy factors of the city and the country. A growth between 1-2% was used to calculate this figure [15]. The demand is expected to increase at an average of 2.9% per year [16].

Cities are becoming denser with more people moving into cities and it is predicted that in the 20-30 years a larger percentage of the world's population will be living in cities. EM is planning to increase the population from 75 000 to 400 000. This is expected within the inner city in the next 30 years [17] with EM adopting the live, work and play concept. This would mean that the resident would be reliant on public transport system. The concept is in line with the Integrated Rapid Public Transport Network (IRPTN) that in planned. The first of these projects is the Bus Rapid Transport (BRT), of which, a few routes are nearing completion. The BRT link the major residential, industrial and commercials hubs of the city. The effects of these projects are to open up areas within the city to be developed.

2.4.2 Increase in generation capacity

The increase in generation capacity increases the FCL downstream in the network [18]. In some cases, the fault current limiting devices (FCLDs) have to be installed on the feeders from generators onto the busbars. An increase in generation reduces the source impedance which results in an increase in the FCL. The shortage of power that the country has experienced from 2008 to 2014 has led to the need for more generation capacity to be installed. As a result ES has rolled out major generation plans, including, renewables, combined cycle gas turbines and pump storage schemes [19]. The effect of more generation capacity increases the fault current downstream. There is also a very strong drive for clean energy. This has resulted in move towards renewable energy generation [20]. Renewable energy generation is injected within high-voltage and medium voltage network of the utility and is known as Embedded Generation (EG). The 20 year power generation capacity mix is shown table 2 [21].

Renewables are expected to be make up 20% of the generation capacity by 2030, the total amounting to 17.8 GW [21]. The closest and most significant new generation source to EE is the Avon Peaking Plant that is situated alongside ES's Avon SS and feeds directly into SS at 275 kV. This is a peaking plant that has a maximum output of 670 MVA. EE is supplied by 2 circuits at 275 kV from this SS. The Ingula Pump Storage scheme is being completed and has one of the 6 generators operating currently. This would supply a total of 1300 MVA during peak hours. The plant supplies the KZN from the north west of the province.

Table 2: South African Generation Capacity [21]

Energy Source	**Existing Generation**		**20 year generation mix**
	Capacity (MW)	**Energy (GWh)**	**Integrated Resource (MW)**
Coal fired	37 715	218 212	6 250
Hydro-electric	661	1 904	2 609
Pump storage	1400	2 962	
Gas turbines	2 426	709	6 280
Nuclear	1 910	23 502	9 600
Renewable energy	3.15	2	**17 800**
Available Capacity	44 115	237 291	
Foreign imports		13 038	
Local IPP & co-gen		4 107	

2.4.3 Network interconnection and grid expansion

With the additional generation capacity being added to the grid more transmission lines are being planned and constructed. Since the formation of power grids, there have been more and more interconnection of power sources, transmission lines and underground cables and substation. This has provided utilities with secure, stable source of power, flexible and robust network [22]. Although most networks are planned for redundancy (n-1), modern networks are highly meshed and have may have dual or triple redundancy (n-2 or n-3).

ES has planned network strengthening by introducing 765 kV voltage level into KZN. These transmission lines will supply the proposed Isundu SS, situated at north-west of EM, and the proposed Mbewu SS, to be situated along the coast, north of EE. These are planned to be 765/400 kV SS and will be interconnected by 400 kV transmission lines. EE will be obtaining supply to the proposed 400/132 kV Inyaninga SS from these transmission lines. Further strengthening of the ES network will be achieved by the construction of 400 kV transmission lines between the existing Venus and Ariadne SSs [19].

Investigations into the rising faults levels have revealed that the utility has a few options to choose from and that the best solution for the utility cannot be determined without an assessment of each of the possible solutions [5]. An economic evaluation has to be included in the study together with the operational cost incurred, once the solution is implemented. This factor could ultimately decide whether the solution is to be implemented or not.

2.3.3 Higher network voltage levels

With higher demands being place on utilities, voltage transmission have been increasing steadily to reduce the incurred losses. These become strong sources and when connected to a highly meshed network, result in significant increases in fault currents. Urban areas in South Africa are becoming dense and the ability to obtain servitudes is extremely difficult and time consuming. This has led to utilities having to construct overhead lines at higher voltages and capacities from the outset, re-cycling existing servitudes with higher capacity conductors (conventional or high temperature), introducing high transmission and distribution voltages and phasing out intermediary voltages. Standardization of voltage levels to a single voltage level at distribution and sub-transmission levels is a logical option to reduce spares holding, simplify operation and skills sets and ensure inter-changeability between SSs. This has led to higher voltage levels being adopted due to the reduction in network losses. Most utilities prefer 11 kV at distribution and 132 kV at sub-transmission level. Intermediate voltages such as 33, 66 and 88 kV are being phased out.

2.3.4 Embedded Generation

Kyoto Protocol requires many countries to reduce greenhouse gas emissions. This has resulted in a massive drive towards green energy sources over the past few years. In 2015, the investment in renewables globally, peaked with $ 285 billion being invested. This added new generation capacity of a total of 118 GW [23]. SA experienced generation capacity constraints, from 2008-2015, with planned load shedding being implemented across the country. This resulted in calls for energy efficiency and more generation capacity. Eskom initiated a Renewable Energy Bid Process (REBID), where Independent Power Producers (IPP) could produce and sell power to Eskom [24]. Currently, 3392 MW of power is being supplied by IPPs, with 2145 MW being produced from renewables. These energy sources increase the fault levels, especially when they are close to the load due to the source impedance being low [20].

2.4 Safety

Utilities have an obligation to ensure that their networks are planned, constructed, maintained and operated safely and this is a statutory requirement. It is thus vital that the power systems' reaction to abnormal events is planned and have the necessary controls in place to restore the power system back to its normal state [25]. This includes ensuring that the fault currents in a network are maintained below those of the equipment ratings.

2.5 High Fault Current Mitigation Measures

The mitigation of FCLs can be classified into two categories, passive and active. Passive measures are in operation in the network at any given time and become part of the network. These operate under normal and abnormal conditions with all voltage and currents seen. Active measures involve mechanisms which would operate under fault conditions to reduce the fault currents. During normal conditions they are dormant and do not have any effects on the network. The aim of these devices are to introduce an impedance into the faulted circuit, reduce connectivity and in doing so reduce interconnection, or disconnect one or more of the sources of supply to the fault once the fault has occurred, thereby reducing the FCL. Passive and active measures are illustrated in figure 4 [6]. The total life cycle costing has to be carried out before the measure are chosen.

2.5.1 Passive measures

The conventional measures that have been adopted in networks are multiple breaker upgrades, high impedance transformers, bus-slitting and impedance grounding. These measures can be classified into topological and apparatus measures. These two measures will ultimately increase the source impedance that is experienced by the fault and hence reduce the current. Topological measures involve configuring the grid to reduce the fault levels and can be achieved by introducing a higher voltage level, splitting of the network into sub-grids, and splitting of the bus-bars. Apparatus measures introduce equipment in the network that are permanently connected, such as reactors and high impedance transformers.

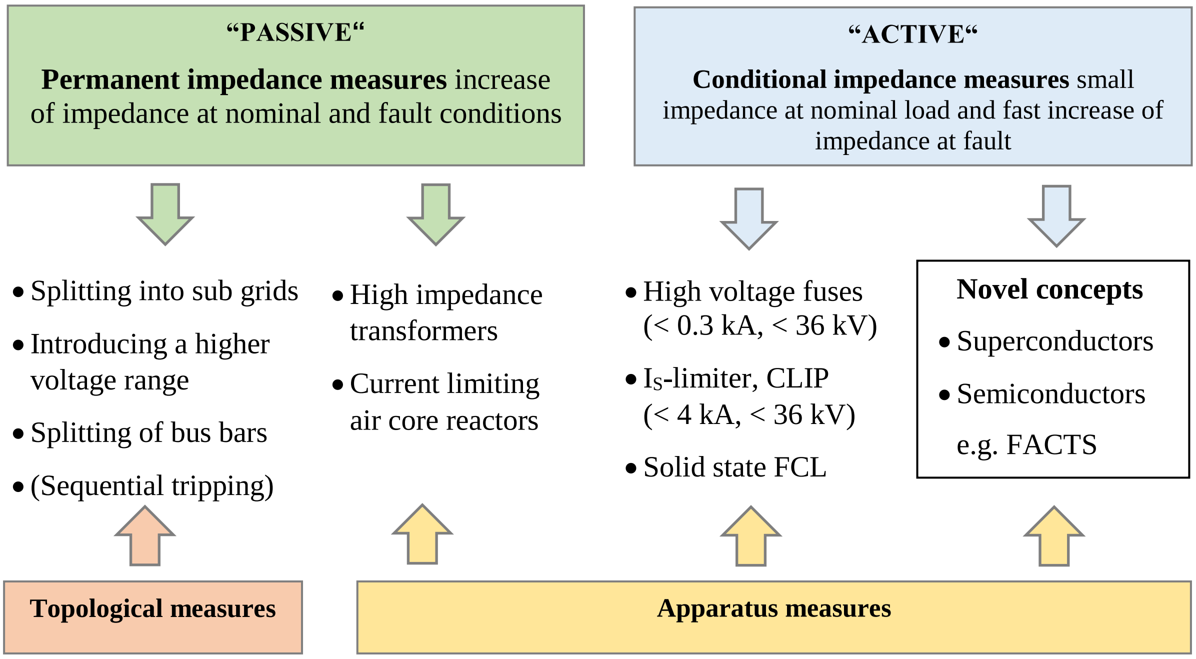

Figure 4: Passive and active fault current mitigation measures [6]

At voltages below 36 kV(<0.3 kA), high voltage fuses are an effective method of managing FCLs.

2.5.1.1 High impedance transformers and fault current limiting reactors

The most common mitigation measure is the use of high impedance transformers [6]. The advantage of this is that it could reduce fault levels at many substations down-stream. The cost of replacement would have to be considered together with the losses as a result of having more impedance than required for the life of the transformer. The greatest drawback is the introduction of a higher impedance in the circuit that would not normally be present, now becomes permanent in the network. As a result volt drops and power losses would be incurred. These would have to be simulated and assessed technically and financially to determine if the solution is viable.

2.5.1.2 Fault current limiters

Figure 5 [6] illustrates the waveforms with and without fault current limitation. Without fault current limiting, the load will see the entire fault current which will be cleared within the periods prescribed by the protection system. This would usually be 60-100ms. Fault current limiters add additional impedance into the circuit to limit the current to a safe value that the equipment in the circuit would be specified to withstand. With current limitation the shape, phase and amplitude of the waves are changed, which can have significant impacts on the power system. The impacts to be evaluated are:

- Transient Stability
- Protection system
- Transient response (TRV)
- Power quality (volt drop-fault recovery)
- Thermal losses

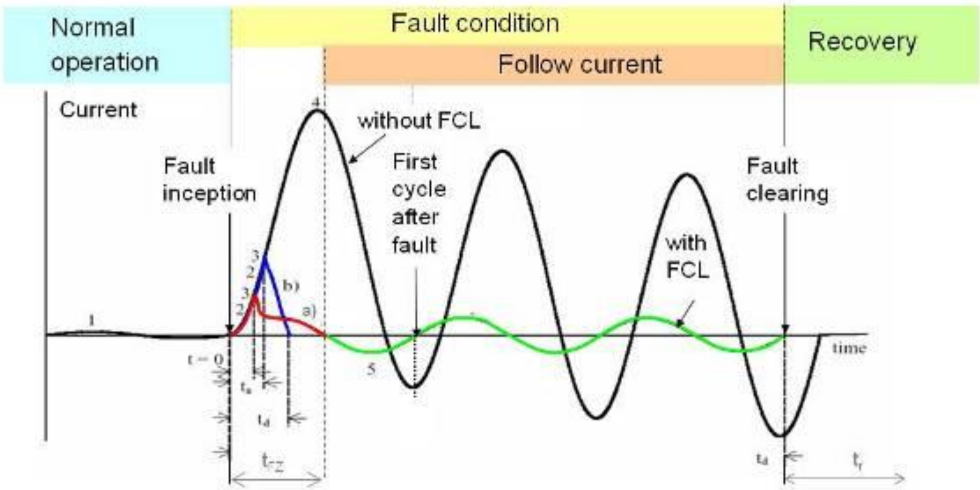

Figure 5: Fault current with and without fault current limiting [6]

When used in line with a transformer feeder, the fault current limiting reactor (FCLR) would have the same effect of using a high impedance transformer. It is not an economical solution since the maximum load current passes through the FCLR and there will be huge losses incurred. FCLRs are considered as a solution between bus-ties or bus-sections, should it be required that these be operated closed. The faults current with a bus-section open is the minimum that is expected on the busbars, while the FCLR manages the power transfer between the bars and thus the FCLs. 132 kV FCLRs are massive devices

(5-6m in length) that are installed as single phase units. The components of the air core FCLR is shown in Figure 6 [26].

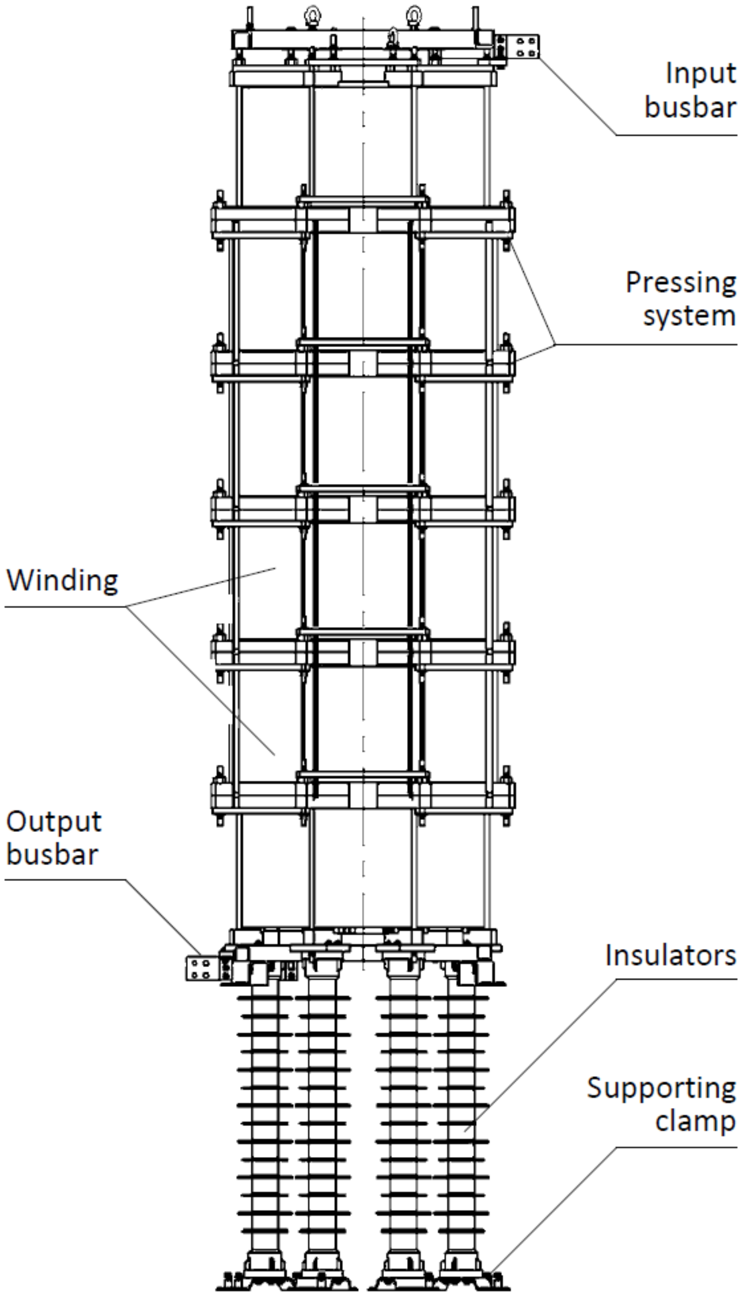

Figure 6: Air core FCLR components [26]

The FCLR unit comprises of air core winding that are stacked together to obtain the required impedance and then mounted on an insulating base. FCLRs are installed in an enclosed area that is deemed to be live, while the height of the device is much greater than that of other conventional SS equipment. Installation in existing SSs is thus a challenge. An FCLR is shown in Figure 7 [26] during testing.

Figure 7: The FCLR during testing [26]

Apart from the losses, the space required for the installation would have to be evaluated together with the complexity of the integration into the existing system, if the FCLRs are to be considered as an option.

2.5.1.3 Busbar and network splitting.

Spitting of busbars and networks is one of the most cost effective means of reducing the fault levels. It involves identifying the problematic areas and then reduce the number of sources supplying the portion of network. Traditionally bus-sections or bus ties have been kept closed due the flexibility, security and robustness. Opening of bus-sections reduce the number of sources and thus the fault level. In contingencies when busbars have to be connected, FCLD can be used between busbars and bus- sections hence the bus-section can be closed for contingencies. FCLD losses will be limited to contingencies events.

A similar concept to that of bus-splitting is the splitting of the network. Over the years as networks grew, they have become highly meshed at sub transmission and distribution voltages. This increases flexibility of operating the network, improves the voltage stability and the quality of supply. Splitting the network is the creation of sub-grids with a limited number of sources of supply. The split network must be simulated and a contingency plan put in place for other sources of supply to be re-connected as required. The re-connection should be carried out through FCLRs, to maintain the required levels. The main disadvantage of this is that there is a loss of operational flexibility. The network operators would have to respond to losses of supply according to a pre-determined plan. A challenge in the implementation of such a strategy in existing substations and networks is the additional space required for the new equipment.

2.5.1.4 Higher voltage networks

FCLs have increased at lower voltage levels. Should other measures not be possible or feasible, the strategy is to construct a network at a higher voltage level than what is affected. This then allows for the network splitting and interconnection at the high voltage level. This option would be more costly, but would benefit the network in the long term by improving the flexibility and robustness of the network. The new network will maintain the FCL at the affected voltage level. The losses of the overall network will improve as a result of more power transferred at a higher voltage.

2.5.1.5 Construction of new substations and equipment change out

Construction of new SSs with equipment specified to meet the future FCLs is an option that is rarely considered [27]. This is the most expensive and time consuming of the solutions to implement. If a SS is close to its end of life or individual items are known to be problematic, a replacement plan should be put in place.

2.5.2 Active measures

Active Measures are those that will only operate in the event of a fault, and will under normal conditions have no effect on the network. Thus, the power quality and losses of the network will not be effected. The use of equipment is thus limited to fault or abnormal conditions in the network which will be detected by the device [6]. At the medium voltage (MV) level many of these devices are utilised. These are voltage levels from 11 kV to 69 kV. Utilities in Germany, United Kingdom and USA have implemented the apparatus in the network to limit fault currents. The existing literature is based on the different methods that the utilities or researchers have studied and in some cases implemented, in networks. Most of the literature for active methods have been focused on MV network [6]. At the High Voltage (HV) level, many utilities have preferred to adopt passive methods. Active devices at the 132 kV voltage level are in their infancy stage with ongoing research and development taking place.

2.5.2.1 Sequential tripping

Sequential tripping is a method whereby sources that contribute to the high FCL are disconnected from the circuit in the event of a fault by upstream circuit breakers that are adequately rated [6]. In figure 8, the new source (Source N) would have higher breaking capacity than Source A and B. For a fault at Feeder C, Source N will disconnect itself from the circuit to reduce the fault current (by the amount that it contributes) by operating the adequately rated breaker N1. Once the fault levels drop to a safe value, breaker C1 operates to clear the fault as shown in the figure 8.

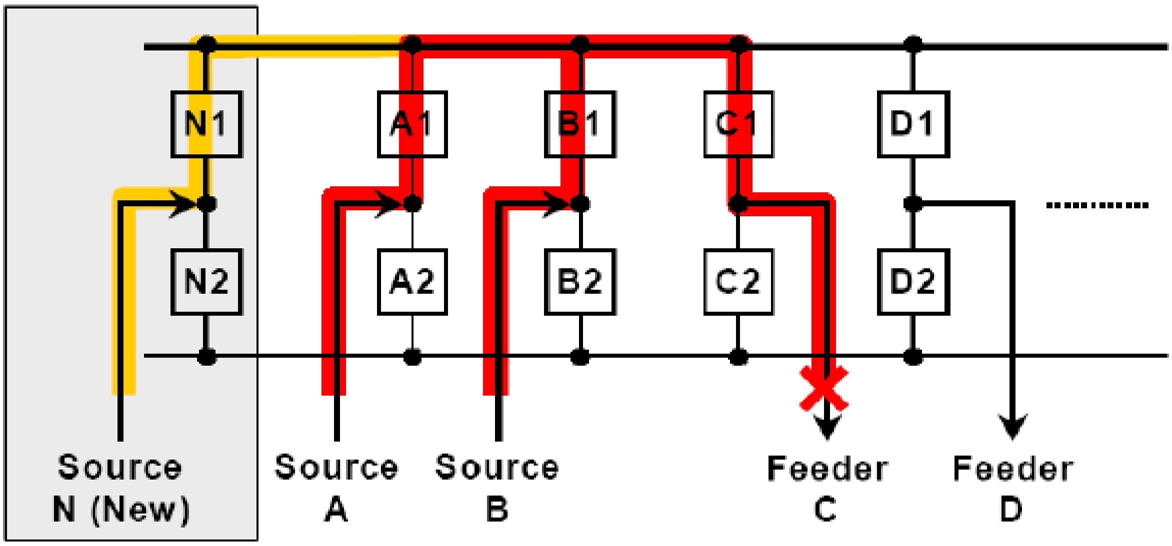

Figure 8: Sequential tripping for a fault at Feeder C [6]

The network remains interconnected under normal conditions. Fault conditions are simulated in the network and methodologies are formulated. These are them programed into relays. This is a cost effective solution, but the underrated equipment will experience the high FCL until the FCLs are reduced to a level that will allow the circuit breaker to trip safely. This method does not reduce the FCLs and is generally not considered as a solution since it might over stress the equipment over time.

2.6 Network Performance and Power Quality

Utilities are governed by standard in terms of their system availability and quality of power. These standards are becoming key factors in determining pricing and network investment. It is thus important to fully understand the introduction of new equipment in the network. It is important that volt drop, harmonics and ferroresonance are studied in the network when fault current limiting devices (FCLD) is be considered.

2.6.1 Volt drop and Regulation

One of the first criteria that is checked in any network is the voltage at various junctions and customers. FCLDs must have low impedance in order to reduce the voltage drop across it during normal operation. This would reduce the energy losses and be a strong motivation factor in the selection process of FCL mitigation measure. This is the key factor in the choice of passive devices while active ones will generally not have this problem. The low or no energy consumption and better voltage quality of active devices will be weighed against the high costs of the device and installation. FCLD location will have an effect on the voltage regulation in the network. During a fault, FCLD can cause voltage sags in other part of the system. Feeders downstream to the FCLD will be effected more than those adjacent to it.

2.6.2 Ferroresonance

This is a phenomenon that occur in networks with non-linear inductance properties. This could lead to overvoltage and overcurrent in the network. The response characteristics of the FCLD has to be examined at the voltage using actual test results. No ferroresonance will occur if the FCLD displays linear inductance characteristics. If not, a capacitor will have to be used in series with the reactor.

2.7 Impacts of Fault Current Limitation on Existing Protection Schemes

Protection systems play one of the most important roles in power networks by ensuring that equipment only experience stresses within their designed limits [28]. In order to ensure that the criteria is met, protection co-ordination settings will ensure that equipment deliver the necessary power under normal conditions. Should abnormal conditions in the network arise due to disturbances or circuit parameters shifting out of the specified ranges, then the areas or zones that have been affected, will need to be isolated. High FCL make protection devices sense abnormal conditions quicker and can thus take action faster.

When FCLs change in a network the protection grading would thus have to change accordingly. The effects of fault current limiters have to be fully investigated and their effects on the network quantified. In a protection scheme, the pickup processing and the co-ordination can be influenced for different types of protection schemes and investigates the effect of the FCLD being located within the zone of protection or outside. These are summarised in table 3.

Table 3: The effects of Fault Current Limiters on protection schemes [28]

<table>
<tr><th rowspan="2">Protection principles</th><th colspan="2">Pickup</th><th colspan="2">Processing</th><th colspan="2">Coordination</th></tr>
<tr><td>FCL Inside</td><td>FCL outside</td><td>FCL Inside</td><td>FCL outside</td><td>FCL Inside</td><td>FCL outside</td></tr>
<tr><td>Overcurrent 50/51</td><td colspan="2">1 :
overcurrent pickup: $I_{SC\ FCL} > I_{Pickup}$</td><td colspan="2">6 :
FCL fault duration > processing time, additionally delay due to inverse-time characteristics</td><td>12 :
current grading, current blinding</td><td>13 :
source-impedance ratio (SIR) - grading</td></tr>
<tr><td>Directional functionality 67</td><td colspan="2">2 :
zone impedance pickup (refer to 3)</td><td>6, 7, 8 :
range of line phase angles including FCL, signal distortion</td><td>6, 8, 9 :
determination of direction based on source impedance</td><td colspan="2">No coordination, because the directional stage is added to overcurrent or distance function</td></tr>
<tr><td>Distance 21</td><td>1, 3 :
overcurrent pickup, impedance pickup $Z_{Fault} < Z_{Pickup}$</td><td>1 :
overcurrent pickup, no influence on impedance pickup</td><td>3b, 6,8:
zone impedance sensing</td><td>6, 8, 9 :
determination of direction based on source impedance</td><td>14 :
Inter-in-feed effect</td><td>15 :
Source-impedance ratio (SIR) – accuracy</td></tr>
<tr><td>Differential 87-Low impedance</td><td colspan="2">1, 4 :
Overcurrent pickup or overcurrent grading</td><td colspan="2">6, 10 :
lower fault current, check for sensitivity</td><td colspan="2" rowspan="2">16 :
No coordination with other types of protection, only some unusual exceptions</td></tr>
<tr><td>Differential 87-High impedance</td><td colspan="2">5 :
No overcurrent pickup facility, differential current measurement only</td><td colspan="2">6, 11 :
Lower fault current, check for sensitivity</td></tr>
</table>

Protection schemes may have to change once fault currents limiters have been installed. A study has to be carried out to determine the effect on the existing protection schemes and what changes, if any would have to take place.

2.8 Fault Current Limiter Location

FCLDs can be used at various locations within a network as shown in the figure 9 [29]. Position A is at the busbar that supplies the transformers at the primary voltage.

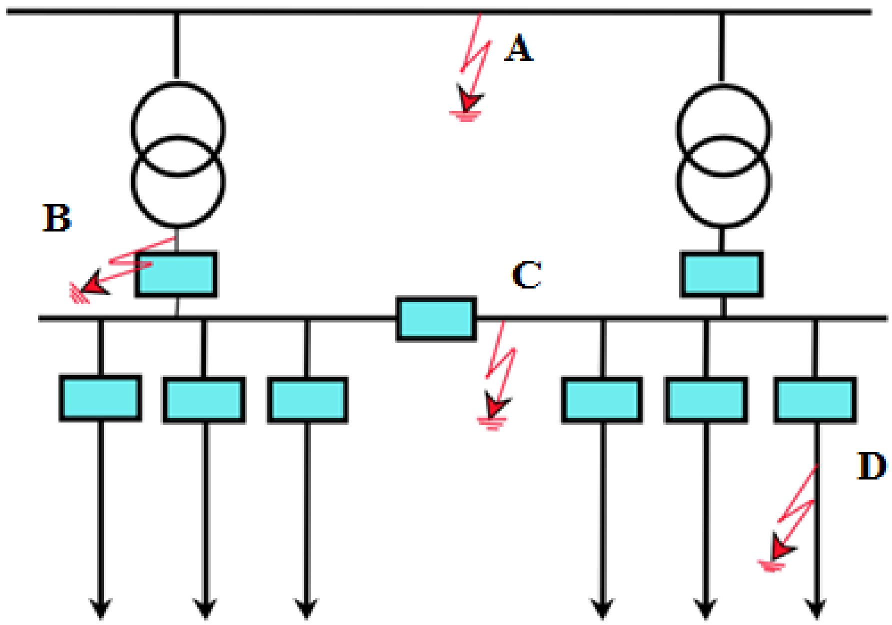

Figure 9: FCLDs shown at locations A, B, C and D [29]

In the HV context, at the 275 kV voltage level, it is a rare occurrence to experience high FCLs [30]. It is likely to occur in a highly inter-connected 275 kV network with large generation capacity being supplied by short lines. Installing FCLDs at position B is avoided due to the losses volt drop that would be experienced. The most optimal position is between the bus bars at position C. The bus-section is operated open and the FCLD is used when the bus-section has to be closed. D shows the FCLD on used to supply out of the SS, which might be a portion of the network where high FLCs are a problem.

2.9 Analysis of Fault Levels in HV networks

The accuracy of fault levels is dependent on the model parameters used. When using simulation packages, the results obtained give an approximation of the network behaviour in the event of a fault level. The introduction of new plant, generation and the growing trends of embedded generation have shown to increase fault current levels. The drive toward introducing Smart Guide Technology also makes the determination of accurate fault current calculation more significant.

The pre-fault voltage level has great impact on the calculated fault level. The following factor affects the fault voltage level [31]

- Operating conditions of generators (power factor)
- Tap changer positions of transformers
- Network impedances of lines and cables
- The estimated load demand on the network at the time of the study

2.10 Chapter Summary

The mitigation of high fault currents at the 132 kV voltage level is complex due to:

- The large number of consumers that are supplied downstream
- The robustness required.
- The high availability requirements.
- The interconnectivity of the network.
- The high impact of faults on the network and personnel.

Table 4 summarises the mitigation options, together factors that have to be considered.

Table 4 : A summary of the mitigation options [29]

Solution	Advantages	Disadvantages	Investment
New Substation	Solves all fault issues and accommodates future growth	Expensive and lengthy to install	Very high
Bus Splitting	Separates source of fault current from over-duty breakers	Also separates sources of load current from load centers and undermines system reliability	High, if breakers to split bus are not already installed
Multiple Breaker Upgrades	Most direct solution to problem with no adverse side effects.	Most direct solution to problem with no adverse side	High to medium, depending on number of breakers involved
Current Limiting Reactors	Easy to install	Voltage drop and power loss; potentially cause instability and the need to install compensating capacitors; large space requirements	Medium to Low
Sequential Breaker Tripping	No major hardware installation involved	Expands impact of fault to wider range of wider range of the system and undermines reliability	Low
Higher voltage network	Stability provided by the higher voltage network; no adverse effects on power quality;	Expensive and lengthy to construct	High

The total cost of an option must include the operation cost which include the maintenance and the cost of the additional losses. Utilities have to carry out studies to evaluate which of the methods can be applied and offers the most benefit for the capital invested.

CHAPTER 3 - THE ETHEKWINI ELECTRICITY NETWORK

EE is the licenced electricity operator within the EThekwini Municipality and provides power to the majority of the municipality. There are few areas on the outskirts of the municipality where Eskom is the supply authority. The high voltage (HV) network is shown in figure 10 [32].This is due to Eskom having the available capacity in the area. The Municipal boundary is greater than the area of supply (AOS) of the EE and there is intent to align the two boundaries in time and as the opportunity arises. The AOS spans approximately 2000 km^2 and provides power to approximated 740 000 customers.

The AOS is shown in orange with the 275 kV and 132 kV shown in red and turquoise respectively with the overhead lines shown as solid lines and underground cables in dashed lines. There are 275 kV lines from the Northern, Central and Southern regions of EM and an interconnection between the central and southern regions. In the mid 80's, EE introduced 132 kV as the supply voltage to the distribution SSs and support the 33 kV network that is being phased out.

3.1 Existing Network Design

EE has now standardised on 132/11 kV substations with a firm capacity of 60 MVA. This was an increase from the 33 kV substation which were generally a firm of 25 MVA and made use of 25 MVA transformers. The overhead lines and underground cables used to supply the substations have redundancy and have n-1. There are 2 supplies to each substation and the both supplies will be rated to carry the full capacity of the station. The failure of a single cable will affect substation's ability to supply the entire load. The same principle is applied to the transformers in the substation with 2 transformers being utilised, each rated to supply the entire load.

The 132 kV network is supplied by five 275/132kV substations and are the points of supply from ES shown in Table 5. These five substations provide supply to the approximately 101 substations at either 132 kV or 33 kV. There is a single 132 kV SS, Kingsburgh SS, that is fed directly from Eskom in the south of the EM. Tables 5, 6 and 7 [33]provide a breakdown of the infrastructure within the EE HV network, with table indicating the ES supply point to EE.

Table 5: eThekwini Electricity Intake Substations [33]

Eskom Supply Points	**Station Size**
Klaarwater	275/132kV, 750MVA
Durban South	275/132kV, 630MVA
Durban North	275/132kV, 315MVA

Eskom Supply Points	Station Size
Lotus Park	275/132kV, 315MVA
Ottawa	275/132kV, 315MVA
Kingsburgh	132/11 kV, 30 MVA

Table 6: eThekwini Electricity HV Network [33]

Transmission Circuit Voltage	Total Circuit Length (km)
275 kV Transmission Lines	141
132 kV Transmission Lines	492
33 kV Transmission Lines	11
132 kV Transmission Cables	125
33 kV Transmission Cables	237

Table 7: eThekwini Electricity Substations [33]

Substation Configuration	Number of Stations
275/132 kV Substation	5
132 kV Switching Substation	7
132kV Sealing End Sites	12
132/33 kV Substation	6
132/11 kV Substation	52
33/11 kV Substation	13

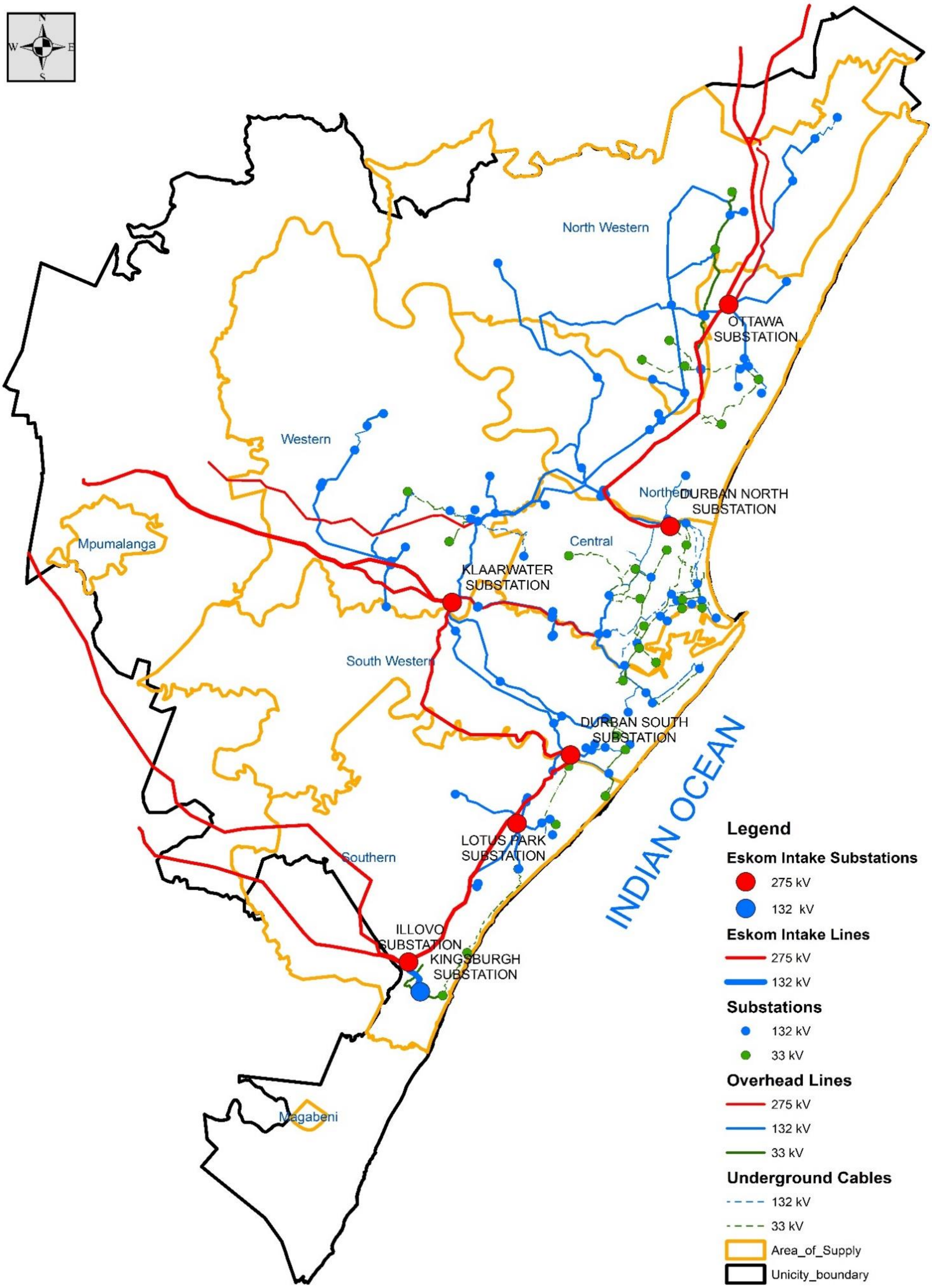

Figure 10: The EE Power Network [32]

The research investigation focusses on the fault current levels at the 275/132 kV and the 132/11 kV SSs and analysing the FCLs experienced at the 132 kV busbars.

3.2 Demand Forecast

3.2.1 Historical data and current demand

The aim of the EE's Demand Forecast is thus to determine the present and future electricity requirements of electrical end-users within eThekwini in order to reconcile this with the available resources and electrical services. The Demand Forecast presents a dynamic assessment in terms of historic and the most probable future trends. The focus throughout the forecast falls on the electricity needs and requirements of the various user sectors as determined by the characteristics and trends of each sector. The forecast therefore highlights where and when imbalances between electricity requirements and supply are most likely to occur.

In order to meet the long and short term power consumption requirements, the demands placed on the network have to be analysed and forecasted and is known as Demand Forecasting. The historical growth in the Maximum Demand (MD) in EE is shown in figure 11. The graph shows a steady and significant growth the 34 year period. The MD has increased from 464 MW in 1972 to an MD of 1712 MW that has been recorded 2016, thus far. The maximum demand is plotted against an S-Curve. This is used for demand forecasting, and is used to trend a load.

The gradient of the curve increases slowly over time and then reaches a period where the load increases proportionally (the centre) over time. It then tapers off towards the later stages as the load reaches a point of saturation. The graph shows a steady increase in the load from 1972 until the late seventies when there was a dip in demand.

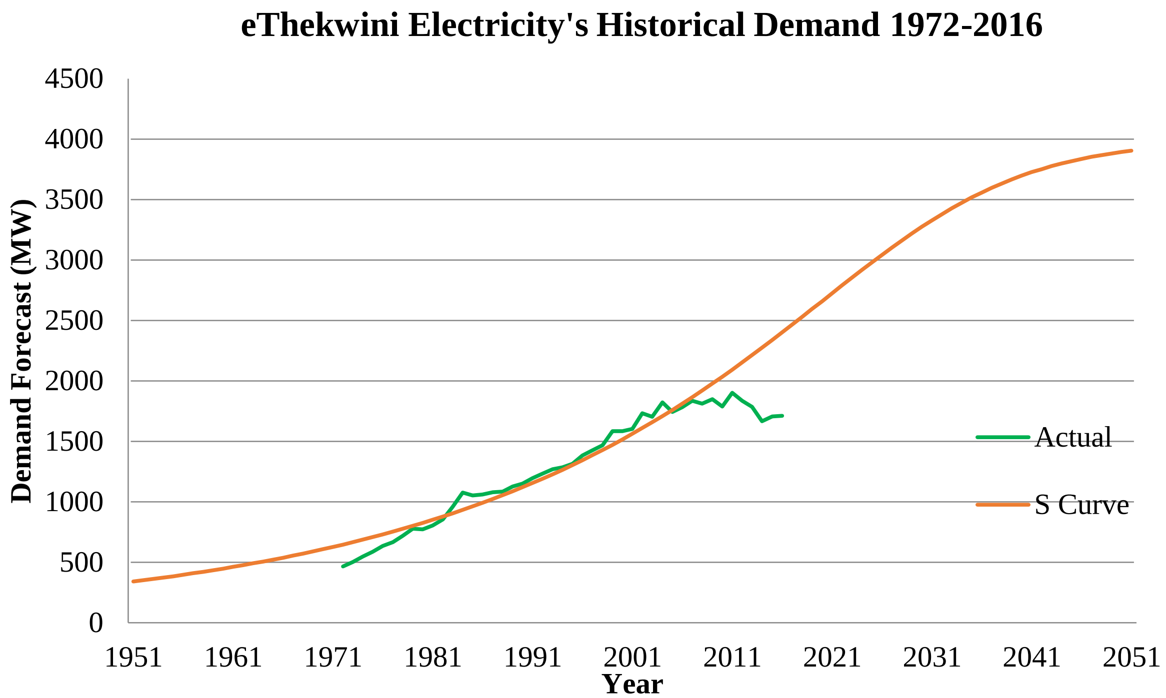

Figure 11: eThekwini Electricity's historical demand from 1972 to 2016 [34]

This is then followed by an increase that surpassed the s-curve and then another dip towards the curve towards the nineties. From there on it followed the curve until 2000, when there was a nationwide property boom that lasted until the 2007/8. Thereafter the global recession and the power crisis that lead to load shedding in 2008 has an effect on the demand which then dropped. The peak reached in 2007 was 1835MW, with a subsequent peak in 2009 at 1848MW with the major construction activity taking place prior to the 2010 FIFA World Cup being hosting in South Africa.

EM is a very popular tourist, sporting and events destination and hosted group and knockout matches, including the quarter and semi-finals of the World Cup. Annual events held in the city include the Durban July handicap horse race, Comrades Marathon and key soccer and rugby matches. The Durban International Convention Centre is host to international conventions such as the World Aids conference and the Conference of the Parties (COP17). In 2011 EE reached its highest maximum demand of 1903MW. The peak demand for the year is generally seen in the summer months due to the hot summers experienced and an increase in cooling that is required. Between 2012 and 2015, due to constraints in generating capacity, more frequent load shedding was experienced and this reduced the demand to 1667MW in 2014, a maximum demand that was last experienced in 2001/2.

Furthermore there were large increase in electricity tariffs that caused consumers to use less power. EE and ES also embarked on Demand Side Management (DSM) projects to reduce the demand on the national grid. There were free installation of CFLs, LED lighting and energy saving shower heads to households in the EM. Consumers could have solar geysers installed at a subsidised cost. To reduce the peak consumption geyser timers were installed in households at no cost to the customer in 2012-13.

3.2.2 Future demand

3.2.2.1 Load forecasting

As part of their Masterplan Project, EE has embarked on geographic load forecasting (GLF) to determine the size and location of growth within the EM. This model currently caters for a 20-year period and is planned to extend to 30 years. As part of the GLF, an Economic Develop Study forecast has been carried to provide an indication of future size, spatial distribution and characteristics of the population for the period [18]. The sources of the data used in this investigation are:

- Spatial Development Plan [35]
- Integrated Development Plan: Annual review [35]
- Inanda, Ntuzuma, KwaMashu (INK) Nodal Economic Development Profile [35]
- Economic Spatial Plan [36]
- Industrial Spatial Strategy [37]
- Integrated Housing Plan [38]
- Integrated Transport Plan [39]
- Developments – Regional Offices [40]
- Tongaat-Hulett Developments [41]
- Stats SA 2011 [42]

The major triggers for development in EM were identified to be the King Shaka Airport and Dube Tradeport, the Port of Durban Harbour Expansion, the Cato Ridge Cargo Hub and the Durban Dig-Out Port to be constructed on the old airport site, south of the city centre. These can be seen in figure 13. The data from these development were used as inputs to the GLF and produced the 20 year load forecast for the EM, shown in figure 12.

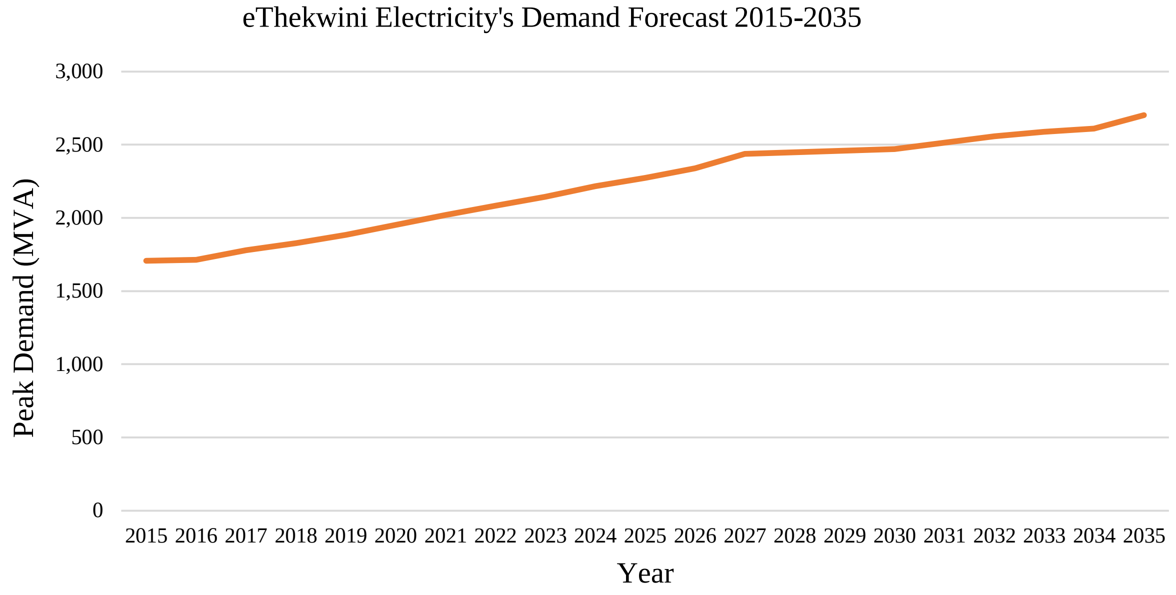

Figure 12: EThekwini Electricity 20 year Demand Forecast

The graph shows a steady increase in demand at an average increase of 2.9% per year. The 2035 peak is forecasted to be 2 789 MW. This is approximately an increase of 1 000 MW over the 20 year period.

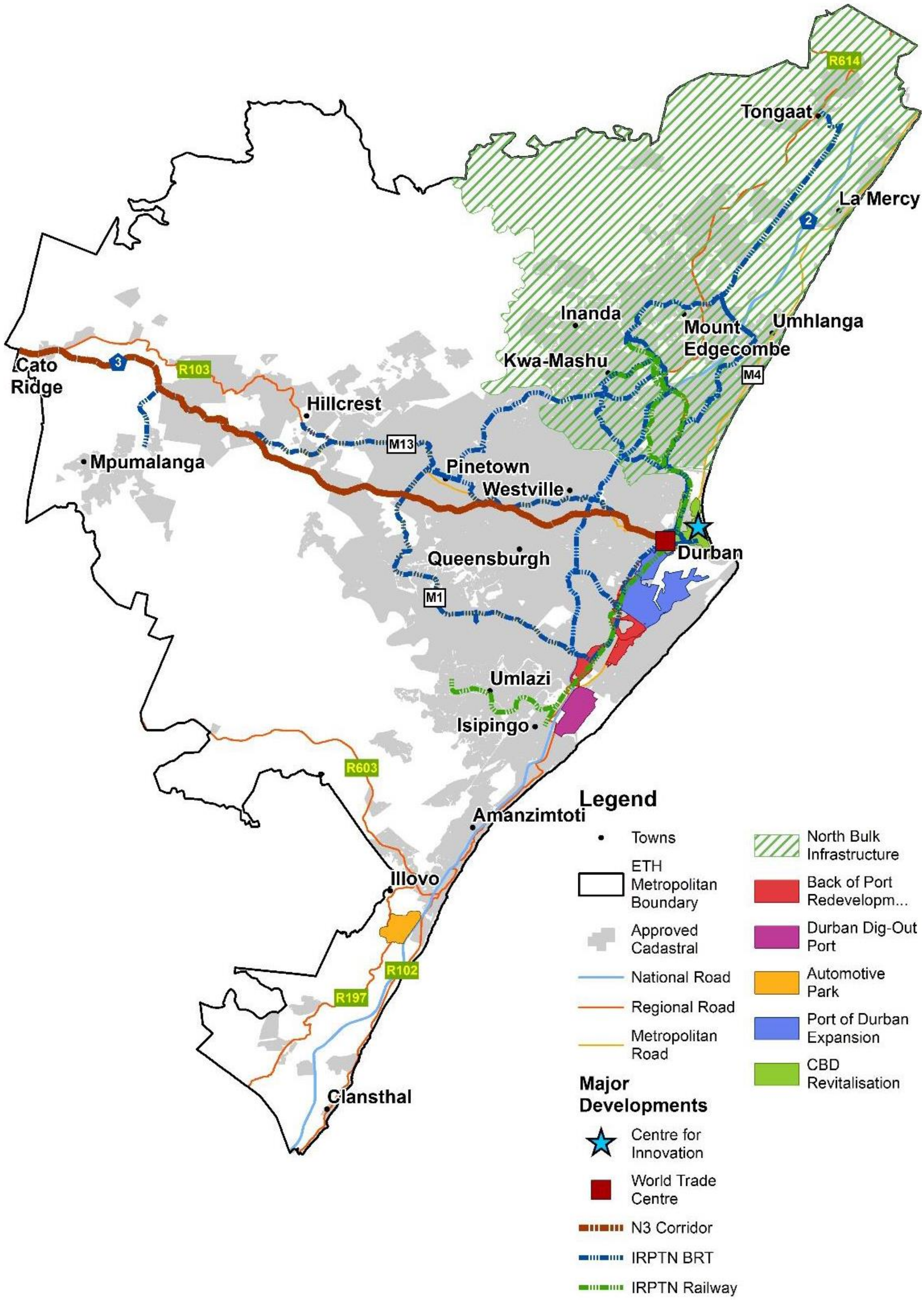

Figure 13: The major developments expected within EM in the next 20 years [37]

Most of this load is expected in the north of EM as shown in figure 13 by the green hashed area, called North Bulk Infrastructure. This is agricultural land, sugar cane farms, that is being rezoned for development by Tongaat-Hullet Developments.

3.3 132 kV Network Operation

The 132 kV network has been designed and constructed fully interconnected at this voltage level. This provides better voltage regulation, more reliability and more robustness. A more inter-connected network is expected to have higher fault current levels. It has been noticed that the network fault levels have been gradually, but steadily increasing. This has been evident in network studies that have been conducted over the last few years.

3.3.1 Supply Standards

3.3.1.1 Firm supply

EE conforms to the NERSA grid code of providing a firm (n-1) supply to its customers. N-1, or a firm supply means that should the load be X at a point in the network, the line and substation will be rated to supply 2X, and should a single component be out of service due to general maintenance or a fault in the network, then the supply to the customer will not be affected due to redundancy in the network. There are cases where customers prefer unfirm supply due to the higher costs of a firm supply.

3.3.1.2 Switched firm supply

The switched firm supply is when the network has to be reconfigured in order to restore supply to the customer. Reconfiguration of the network is carried out by switching in or out components of the network. There will be a temporary loss of supply to the customer, while this takes place and supply is fully restored.

3.3.2 Fault level standards

The 132 kV equipment was initially rated at 25 kA. This rated then increased to 31.5 kA and the current equipment being purchased has rating of 40 kA. Manufacturers follow the trends of the industry and standardise on the rating of equipment. Should the required rating vary, it is considered non-standard and a premium would have to be paid for the equipment. Furthermore, the maintenance of non-standard equipment is a challenge. At the 11 kV voltage level, fault levels have been increasing as well, and the equipment ratings have increased from 20 kA to 25 kA.

A few years ago, the idea of splitting the 132kV network was analysed and found to reduce the fault current levels to acceptable values. This would require pre-defined points at a strategic location. For electricity, these points were chosen to be at switching stations. The result of this means that the network would be split into a central, northern and southern region. Each region would have its own source of 132 kV supply that would be provided by a different 275/132kV substations. Should there be a fault on the 275kV network and the particular 275/132 kV the SS is unable to supply its entire 132kV load, then the network would then be required to close points of the 132kV network to prevent a loss of supply.

3.4 Chapter Summary

The EE covers a large area, most of which is developed. Significant growth is expected over the next 20 years, even though there has been dip in the demand in recent years. The forecasting allows for the utility to carry out adequate forward planning. Growth will bring the challenge of meeting the power demands. The equipment used by EE are in keeping with industry standards.

CHAPTER 4 - NETWORK STUDIES

4.1 Study Methodology

The EE network was assessed together with the fault current migration measures. The criteria used to determine which of the measures would be studied are:

- Impact on the fault level reduction
- Ease of operation
- Time to implement
- Maintenance and repairs
- Proven technologies at the 132 kV voltage level
- Efficiency and losses
- Capital Cost

Based on the listed criteria, the flowing methods were analysed:

- Splitting the 132 kV network: The network was split by creating open points in the 132 kV network. These open points have been strategically located so as to separate the grid into sub-grids, and thus create central, northern and southern grids. The list of open points used for the grid are shown in Appendix 1.
- Introducing a higher voltage network: A 275 kV network was simulated as backbone to the 132 kV network that will remain non-interconnected. This network has been simulated as the backbone to the mini-grids that were simulated in (a). Furthermore opportunities to extend the 275 kV network have been simulated by creating 275 kV substations at Umgeni and Bellair SSs. These replace the 132 kV interconnection by 275 kV.
- Fault current limiting reactors at bus-sections: The optimal position to minimise the losses in the network are for them to be used at bus-sections. Fault current limiting reactors were simulated at the 132 kV bus-section at Klaarwater SS (KLA SS).
- Effects of generation on the network: Nearby generators were switched off in the model and fault levels were simulated.
- Reduction in 275 kV transformation: A transformer was switched off in the model and fault levels were simulated.
- High impendence transformers: High impedance transformers reduces high 132 kV fault currents. It is important to assess the losses that will be incurred and therefore calculations have been carried out to determine the losses and estimate costs of implementing such a solution.
- Equipment replacement: A cost analysis has been carried out for this option.

4.2 Power System Study Simulations

A detailed model has been used for the networks studies that was carried out using the Power System Simulation package (PSS®E), version 33.5. The Eskom and EE models were merged to obtain a true representation of the network. Figure 14 shows the EE model being simulated in PSS®E.

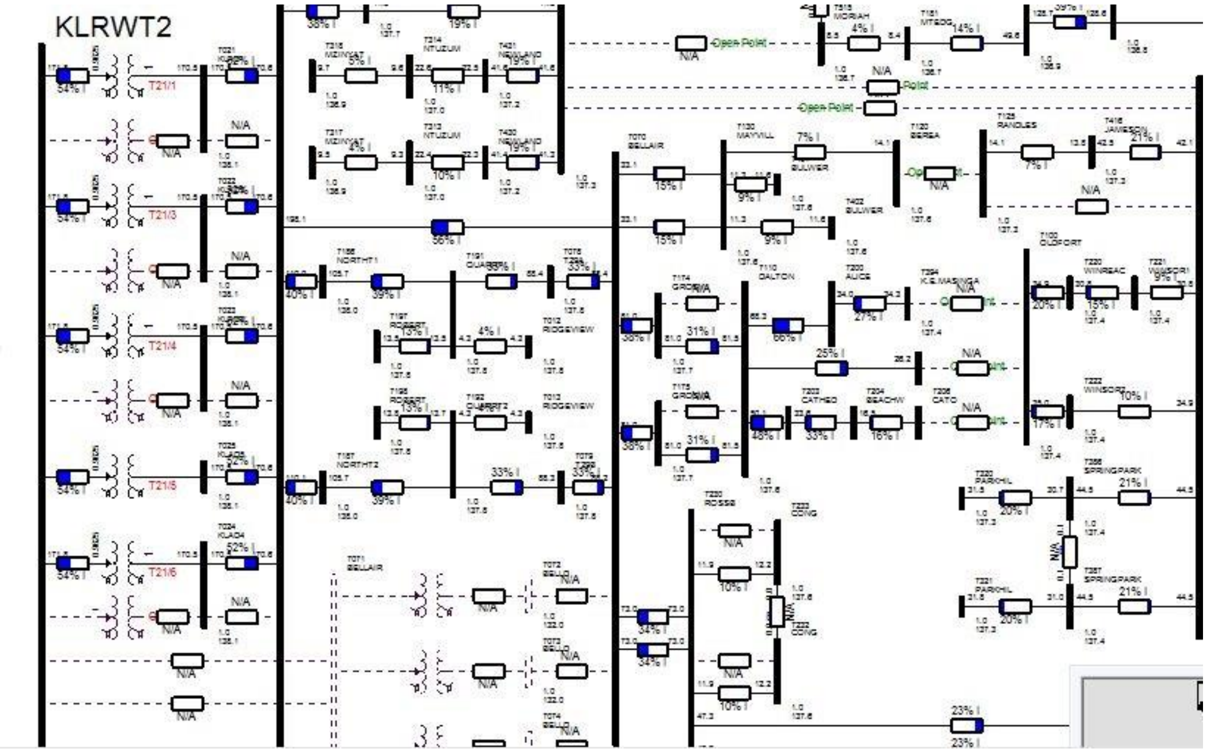

Figure 14: EE Network model single line drawing in PSS®E

Fault Level Assumptions:

- IEC short-circuit assumptions with a voltage of 1.1 pu was used.
- Calculated fault levels were the expected root-mean-square values of the alternating component of fault level in a bolted fault at a substation.
- Fault level contributions from EE's customers were excluded as the information were not available.

In order to get a long term view of the fault levels and be in a position to plan accordingly, the network models used to conduct the study were those that looked furthest into the future at the time of the study. EE's 2020 model was used together with Eskom's 2025 model.

The study was carried out at EE's most strategic intake from ES, the 275/132 KLA SS, which supplies approximately 40% of EM, more load than any of the other intakes within the EM. The KLA SS's details have been summarised in the table 7.

Table 8: 275/132 kV Klaarwater substation details

Rating (MVA)	275 kV Feeder Bays	132 kV Feeder Bays	275/132 kV Transformers	Peak Loading (MVA)
1575	**4**	**11**	**5**	**916**

It was originally designed for a firm of 750 MVA. The transformers are currently being upgraded to 315 MVA. In order for the upgrade to take place, a 5th transformer has been installed to maintain supply and simulations. It has capacity to supply out 275 kV should the need arise. Figure 14 shows the SS together with the interconnections between the intakes at 275 kV (shown in red) and a simplified version of the 132 kV network (shown in blue). The SS is supplied from Hector SS by 2 single circuit overhead lines (OHTL) and a single OHTL from Georgedale SS, both of which are owned and operated by ES and situated in the west of the EM. There is 275 kV interconnection between the KLA SS and EE's 275/132 kV Durban South SS (DS SS).

4.3 Study Procedure

4.3.1 PSS®E simulation

For each of the options studied the following procedure was carried out:

- A load flow was simulated using the full Newton Rapson method in PSS®E [45]. It was essential for the model to reach convergence.
- Checks were carried out to ensure there were no violations in the network.
- A fault current simulation was done using the IEC16909 method.
- The fault level reading were then exported to Exel spreadsheets.

4.3.2 Base Model and study models

- A base model was used to simulate a base case for of fault levels. This is shown in figure 14, and is a fully inter-connected model, all 132 kV busbars, bus-sections are closed.
- The base model was then changed to represent the study case model.
- A fault level simulation was then done on this model.

4.4 Problems with the study

The study is based on the information in the models which is a snapshot of the network in time. The operation of the network due to outages might not be a reflection of how the network is operated. As a result the assumptions would have to cater for the worst case scenario, thus the maximum loads for SSs, ohtls and cables were in the simulations. Network parameters such as generator outputs and tap change positions of transformers are not possible to predict or determine accurately, more especially for the ES network.

4.5 Chapter Summary

The criteria in section 4.1 were used to determine the methods to be studied. The network studies simulate the options and produce expected FCLs. The results of the base case indicate the FCLs, should no mitigation measures be put in place and has been used to determine the effectiveness of the solution. The most feasible option for the utility would reduce or maintain FCLs to below equipment rating, provide the utility with robustness and flexibility, be practical to implement and be financially viable.

CHAPTER 5 – RESULTS AND DISCUSSIONS

The results of the study on this network were a reflection of the theory. The utility would have to analyse the benefits versus the capital costs of the options. A long term view would have to be taken that has to consider life-cycle costing, operational benefits, future growth and network expansion.

5.1 Base Model

The model was simulated as per figure with all ohtls and cables in service. The results are shown in Appendix 2.

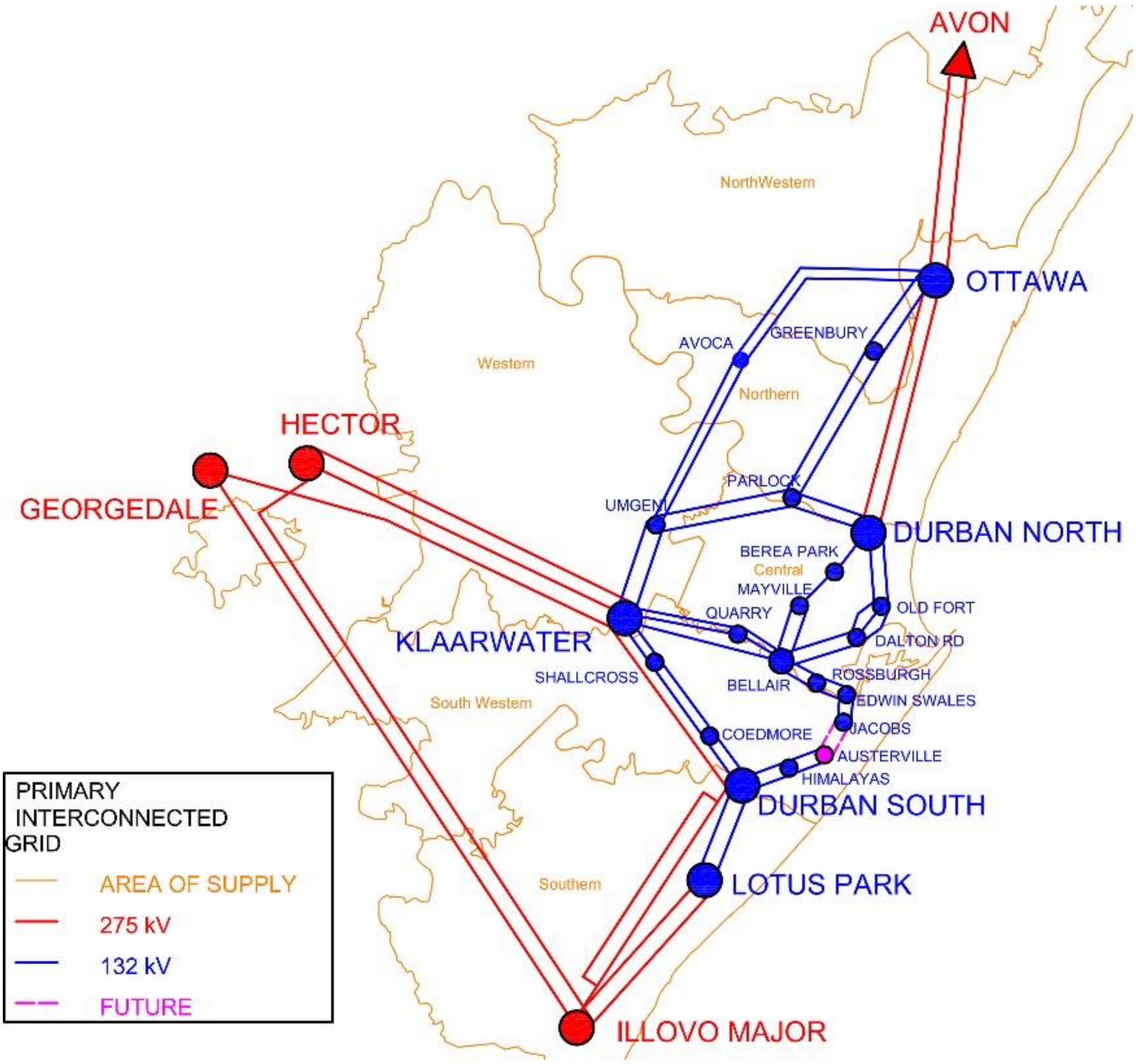

Figure 15: The HV Base 132 kV Model

The single phase fault levels were generally higher than the 3 phase fault levels at most SS's. The highest fault levels were experienced at KLA SS and D.S SS with both surpassing the 40 kA for single phase faults. A large no of SS's would exceed the 31.5 kA that was the old specification equipment. None of the 3 phase fault levels exceeded 40 kA. 17 SSs were over 31.5 kA, 2 SSs exceeded 40 kA. The results indicate that the fully interconnected network exceeds equipment rating and some form of FCL mitigation is required.

5.2 Splitting the 132 kV Network

The reduction in the 132 kV interconnection increases the system impedance and will reduce the FCL in the network. A simplification the split network is shown in figure 15. The network open points are contained in Appendix 2.

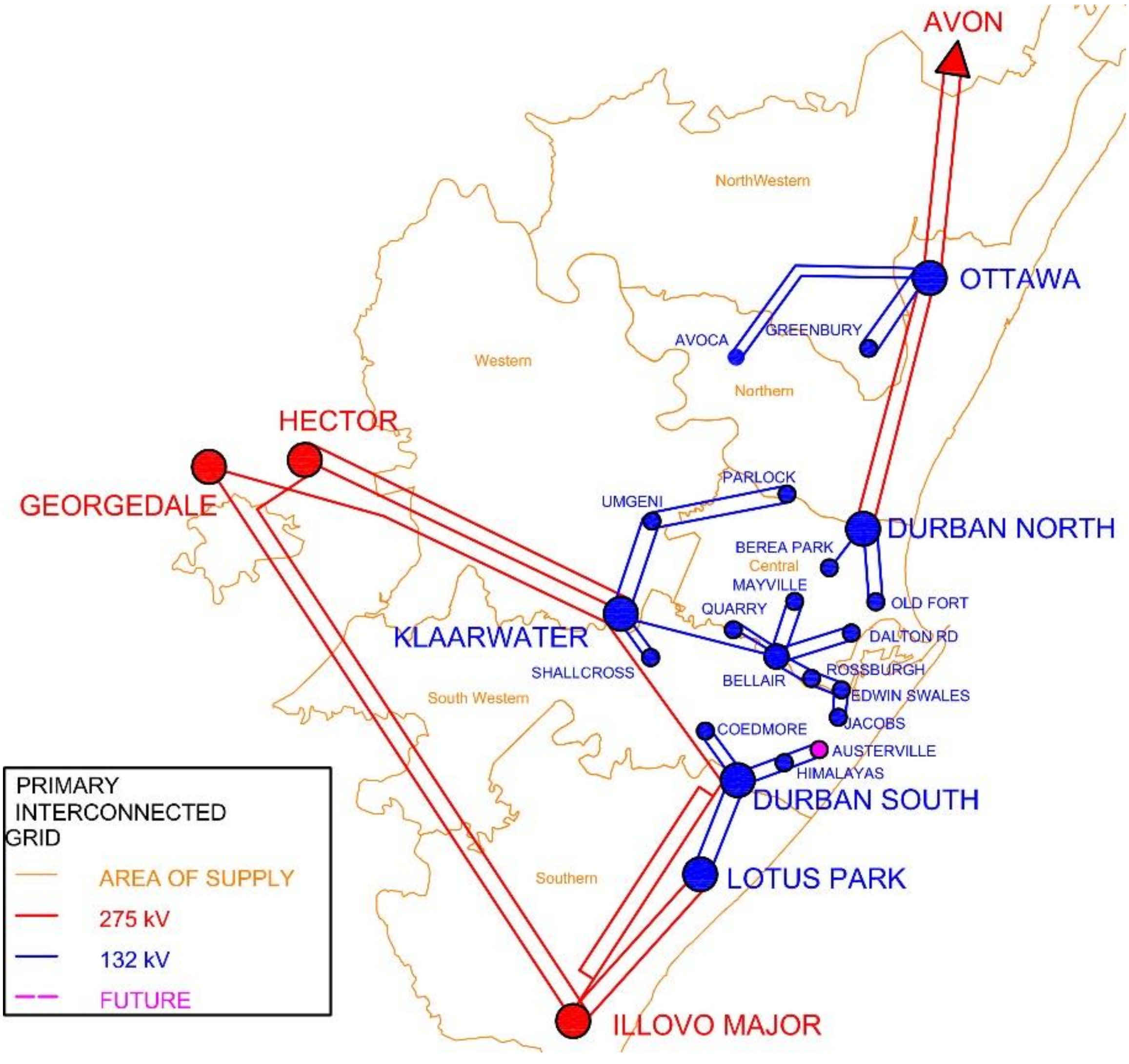

Figure 16: Splitting of the 132 kV Network

The effect is a reduction of between 2-4 kA in the fault levels. None of the SS's exceeded the 40 kA standard. KLA SS has fault levels of 35 kA for 3ph and 38.5 kA for 1ph. 5 SSs were over 31.5kA.

The system would have to still maintain its level of security and remain healthy should portions of the network loose supply due to faults in the network. This solution allows for the replacement of under-rated CB's can be cost-effective if there is equipment that would have to be replaced due to age or condition. Network studies would have to be carried out for the current and future configurations. The future fault levels would have to be catered for by the higher rated breakers should system fault levels increase further. The plan must cater for outages for the replacement to be carried out.

5.3 Higher System Voltage

The introduction of higher system voltages can be very cost effective as a long to medium term strategy together with the splitting of the network, it offers interconnection at 275 kV. Introducing 275k at 132 kV Switching Stations that a large number of SSs is simulated.

5.3.1 275/132 kV at Bellair SS

Bellair SS has 9 circuits at 132 kV and in shown figure 14. The introduction of 275/132 kV transformation reduces the fault levels by 3-4 kA at KLA SS to 34 kA, when compared to the split network model. The effect on DS SS was less with a reduction of 1kA was 31.4kA.

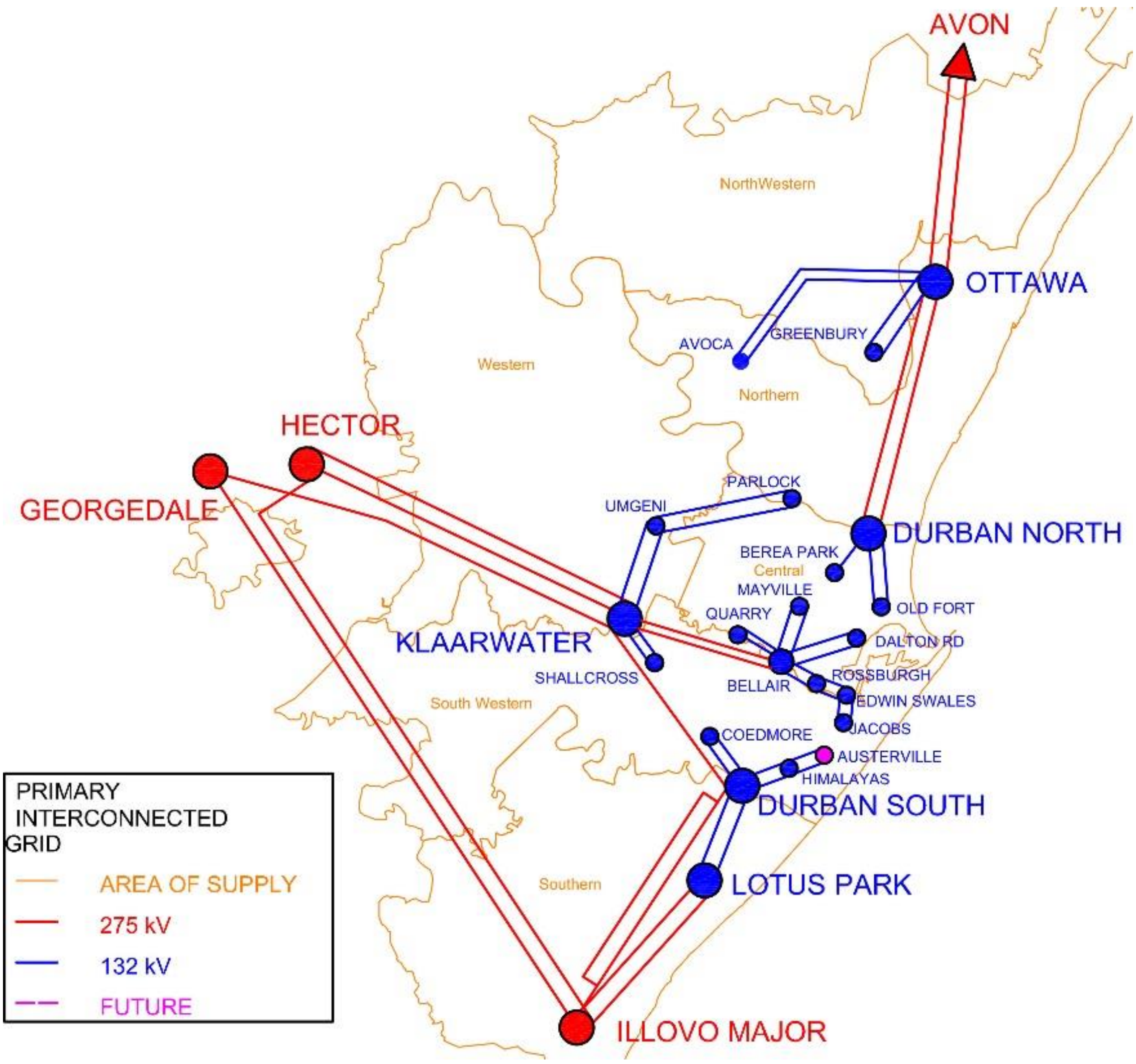

Figure 17: 275/132 kV at Bellair SS

5.3.2 275V/132 kV at Umgeni SS

The option of 275V/132 kV at Umgeni SS has a more significant impact on the fault levels on KLA SS by ensuring that levels remained below 30 kA, shown in figure 15.

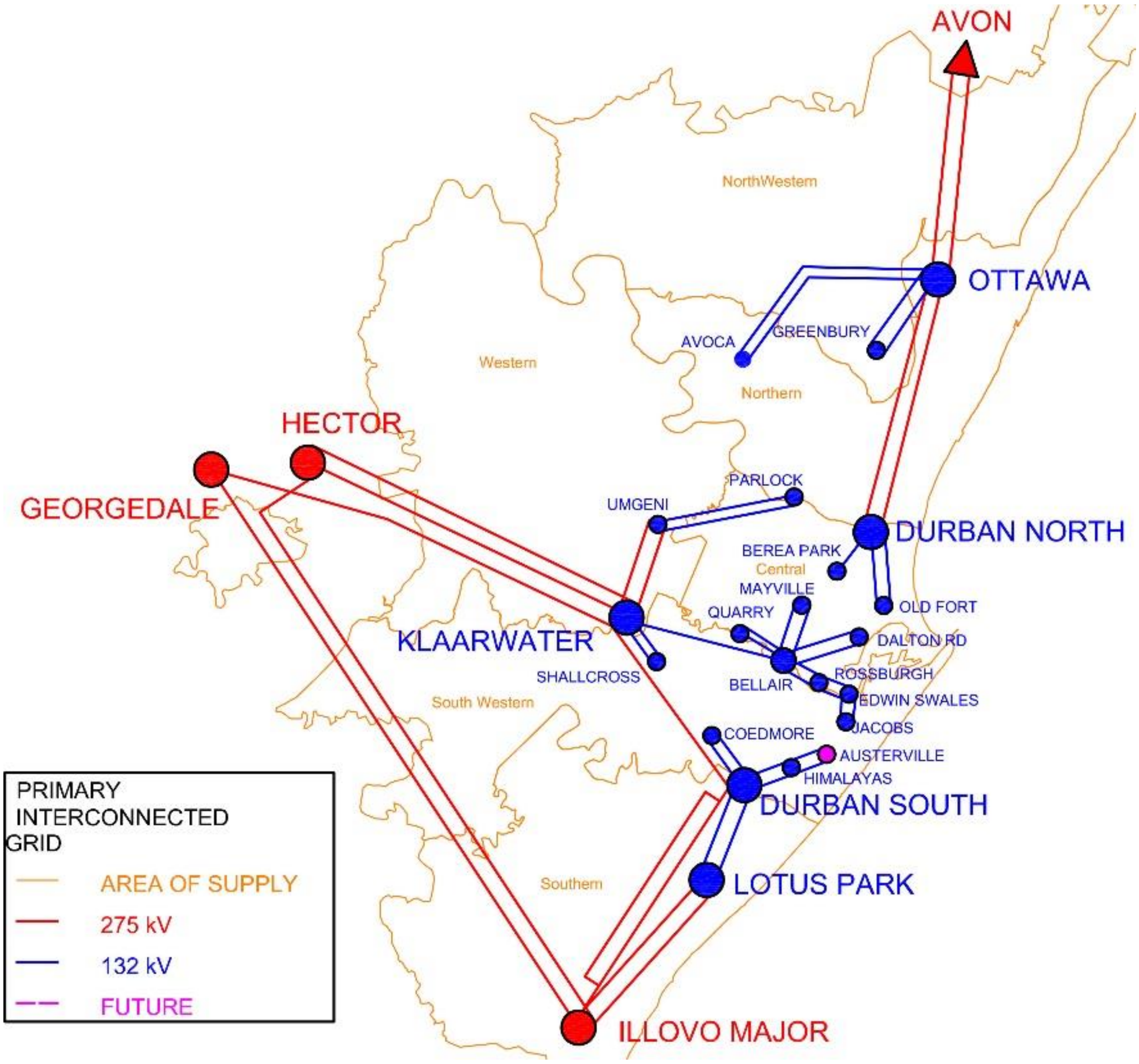

Figure 18: 275V/132 kV at Umgeni SS

There is a 9 kA reduction at KLA SS. Security of supply is provided by the higher voltage level. As a longer term option a higher voltage network would be constructed. This method is effective in making the network more secure and to improve the reliability of the network after the 132 kV network has been reduced by creating open points.

5.4 Interconnection at 275 kV between Klaarwater, Umgeni and Durban North

Expansion of the 275 kV network to connect the Umgeni SS to Durban North's has the effect of providing an alternate supply to Durban North and Ottawa SS and is shown in figure 18. A slight reduction of approximately 0.5 kA was seen in the FCLs in most SSs.

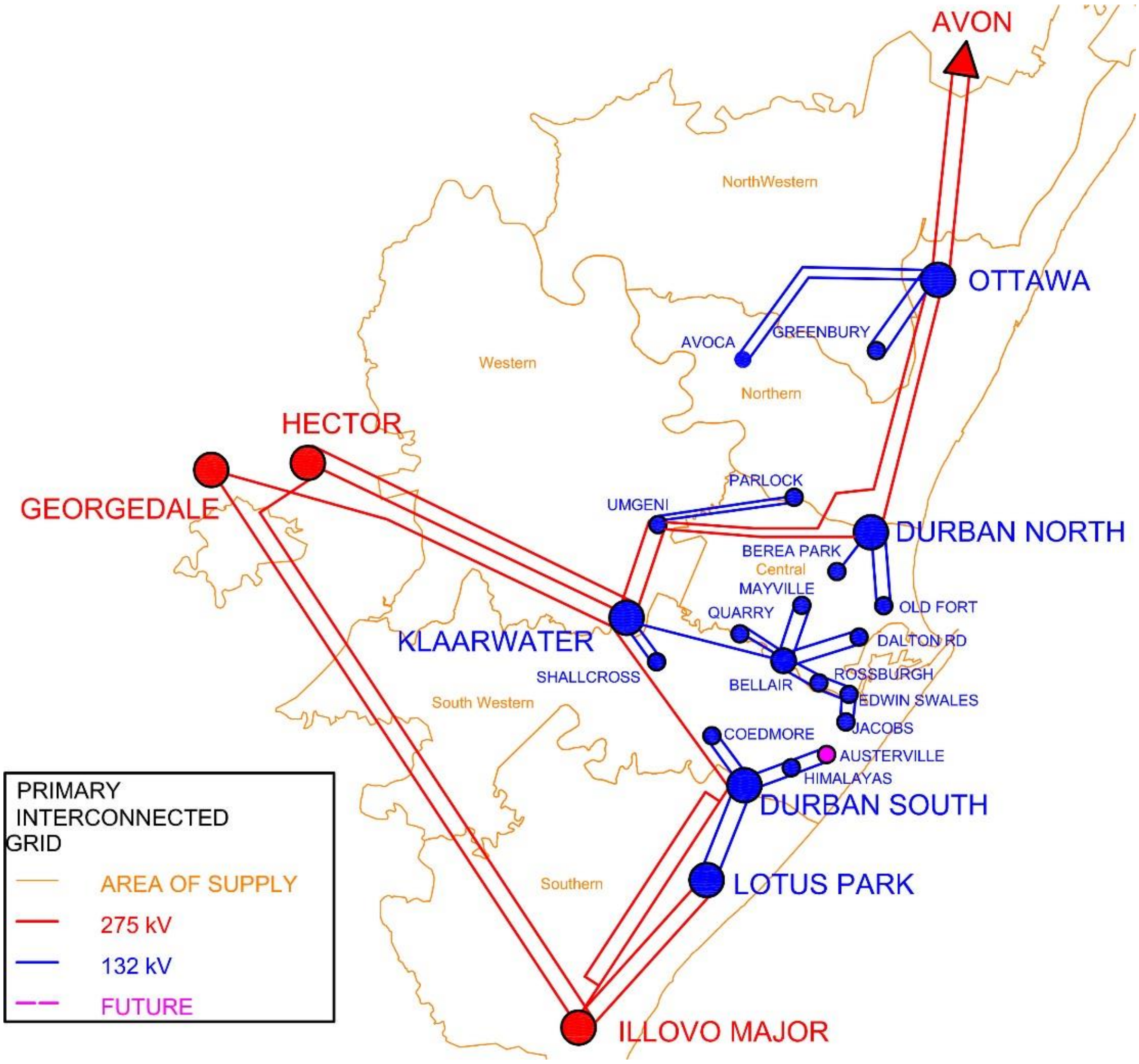

Figure 18: Interconnection at 275kV between Klaarwater, Umgeni and Durban North

Expanding the 275 kV network creates a 275 kV ring and provide support to the SSs in the north of the EM.

5.5 The Effect of Generation

The switching out the Ingula generation scheme, a 1300 MW pumped storage scheme, had a reduction of 1 kA or less on the general fault levels. A reason for low decrease is that the generators are approximately 250 km from the EM and that it would have a greater effect on the surrounding loads.

5.6 Reduced 275/132 kV Transformation

A reduction in transformation at KLA SS, by switching out the 5th transformer, reduced the FCL by 2-3 kV across most of the SS's. This has increased the network impedance at the 132 kV busbars at the SS and this seen by lower down in the network.

5.7 Splitting of the 132k busbar at KLA SS and a reactor testing

The KLA SS busbars were split to test the FCLs. It was noticed that the fault levels at KLA bar no.1 decreased by 5 kA on the 3 phase and 3 kA on single phase FCLs. The 3 phase FCLs were higher at 40 kA. At KLA bar no.2, the FCLs were much lower at 23 kA on single phase and 22 kA on 3 phase. It was not possible to balance the load so that the power that flowed through the bus-section was reduced, which would reduce losses should a reactor be used. The reactor in this case would not be feasible since the FCLs are above 40 kV on one of the bars.

5.8 High impedance transformers of fault current limiting reactors

The installation of high impedance transformers or FCLRs would reduce faults currents to a pre-determined value. In the case of the KLA SS, an FCL of 31.5 kA would have to be maintained as opposed to the expected 40 kA.

$$Zsystem = \frac{Vsystem}{\sqrt{3} * Ifc}$$

where: Zsystem = System impedance in ohms (Ω)

Vsystem = System Voltage in volts (V)

Ifc = Fault current in amperes (A)

For 31.5 kA: $Zsystem = \frac{132\ kV}{\sqrt{3}*31.5\ kA}$= 2.4Ω

For 40 kA: $Zsystem = \frac{132\ kV}{\sqrt{3}*40\ kA}$= 1.9Ω

Thus if the impedance is to be restricted to 31.5 kA, it has to be maintained at 2.4Ω.

The additional impedance required to restrict FCL to 31.5kA is thus = 2.4-1.9 = 0.5Ω.

As a percentage, the source impedance has to increase by approximately 25%. The system losses would increase by the same percentage should high impedance transformers or FCLRs be implemented in the network.

5.8 Chapter Summary

The studies produced varied levels of FCL mitigation. The most significant decreases in FCLs were seen by splitting the network and creating a Northern, Central and Southern grid. This is cost-effective and can be carried out with no additional equipment. A network contingency plan must be put in place for losses of supply to the any of the mini-grids. The 275 kV interconnection of the mini-grids will mitigate against increasing FCLs and provide and a strong backbone to the 132 kV mini-grids. This ensures that acceptable FCLs are maintained over a longer period of time, while the capital investment has to be quantified.

The high electrical losses experienced by high impedance transformers and FCLRs make this an option, if the other options prove to be more costly. The energy losses incurred are substantial and could amount to more than the cost of replacing under-rated switchgear.

CHAPTER 6 – CONCLUSION

The power supply industry has undergone significant changes over the last two to three decades. There have been increases and decreases in demand, but the trend is a steady increase. This has been seen in eThekwini Electricity where an average 2.9% per year is expected for the next 20 years. Geographic load forecasting enables the utility determine the size, type and location of loads. There will be combination of new loads and increases in existing load. This is due to new development and expansion of the urban area and densification within the city.

Summary and Recommendations

The growth of the power network with more 132 kV lines and cables required to supply new and existing upgraded substations will result in a steady increase in the FCLs across the network. A number of options have been researched and tested on the eThekwini Electricity network.

In the short to medium term, operating the network with open points offer, the utility reduced FCLs at minimal cost. This allows for CB upgrades to be carried until further increases in FCLs occur as result of increases in generation capacity, upgrades in the transmission network and more new distribution substations being commissioned.

In the medium term opportunities exist to expand the 275 kV network. Where operational flexibility might be lost by creating open points, having a strong 275 kV backbone will make the network more robust and secure. The 275 kV can be expanded to existing 132 kV switching stations, where there are multiple 132 kV circuits, by adding transformation and thus reducing the number of parallel 132 kV circuits. This expansion has options to offer an alternate supply to the substations that are being supplied from the North of the EM.

The use of active fault current limiters is in its infancy stage at 132 kV. Breakthroughs in superconducting technology could reduce the cost and lead to a solution that is cost effective and limits losses. Apart from the losses, air core reactors require a fair amount of space in SSs which is a challenge in existing SSs within EE. Similarly, high impedance transformers are an option if the initial higher capital costs and losses can assessed against the replacement of CBs. The age profile and rating of the CBs must be quantified and strategies put in place to replace the CBs, if required.

As part of the planning process, sub-transmission customers need to be involved in the medium to long term planning of the transmission network. This will enable the future FCL to be calculated early and incorporated in the utilities capital and maintenance plans.

Recommendations for further study

Due the restrictions placed on networks by high FCLs, network operation is limited, these limitations have an effect on the reliability that can be researched to quantify the financial costs. These costs can then be compared to the mitigation measures as opposed to equipment replacement. High FCLs reduce the options for Optimal Power Flow, these implications on a network can be researched.

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APPENDIX 1: NETWORK OPEN POINTS

2020	**Open Points Region**
Coedmore SS and Shallcross SS	Open points between Central grid and Southern grid
Umlazi Tee ohtl and Durban South SS	
Austerville SS and Himalayas Road SS	
Berea Park SS and Randles SS	Open points between Central grid and Northern grid
Parlock SS and Durban North SS	
Parlock SS and Moriah SS (future)	
Old Fort SS and Addington SS	
Old Fort/Cato Street SS	
Old Fort/K.E. Masinga Road SS	
Phoenix Industrial Park Tee ohtl and Phoenix North SS	

APPENDIX 2: NETWORK SIMULATION RESULTS