The Southern African Power Pool (SAPP) steady state security assessment using contingency analysis

By

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ABSTRACT

The availability of electricity is an ongoing development of every sector of any economy. Studies have proved that many nations not only in Southern Africa but Africa as a whole are faced with power deficits and inconsistent supply and distribution of electrical power due to various reasons which include lack of sufficient generating sources, faulty equipment and unforeseen disturbances in the network. This negatively impacts both the quality of life and economic growth. A reliable power system, however, is one that is capable of withstanding a wide variety of disturbances and/or failures. This thesis assesses the severity of possible disturbances that can occur in the SAPP(Southern African Power Pool) network by carrying out a contingency ranking then verifying these results by performing a contingency analysis in DIgSILENT PowerFactory. By so doing, we are then able to affirm how reliable and secure the SAPP network is in accordance with the N-1 criteria. In this research, focus is given to two of the most critical and common failures to occur in a power system which are transmission line failure and generation unit failure. Both of which can cause alterations in the voltages of the transmission system and power flow thereby justifying why performing a contingency analysis allows one to determine which violations have been made after a disturbance occurs in the system. The result simulations reveal that the SAPP network is not secure in accordance with the N-1 criterion with the faults induced by the Harib-Kokerboom 1 transmission line and the Synchronous machine (2) generator contingencies being the most severe. Both contingencies led to voltage and thermal loading violations. This research is particularly important because it allows demonstrates some of the measures that can be put in place to mitigate the effects of unforeseen disturbances and failures that could occur in any given network.

DECLARATION

This research has not been previously accepted for any degree and is not being currently considered for any other degree at any other university.

I declare that this Dissertation contains my own work except where specifically acknowledged

Stacey Juliana Tombozi Mwale

214584027

Signed……………………………………….

Date………………………………

As the candidate's supervisor, I have approved this dissertation for submission.

Signed…………………..……... Date…………………………………..

Name: Dr. Innocent .E. Davidson

DEDICATION

I dedicate this thesis to my mother, Grace F.B. Mwale.

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LIST OF ABBREVIATIONS

BPC - Botswana Power Corporation

CA – Contingency Analysis

CEC - Copperbelt Energy Corporation

EDM - Electricidade de Mocambique

ENE - Empresa Nacional de Electricidade

ESCOM - Electricity Supply Corporation of Malawi

ESKOM - Electricity Supply Corporation

GDP – Gross domestic product

HCB - hidroelectrica de Cahora Bassa

HVDC – High voltage direct current

IEEE – Institute of Electrical and Electronic Engineers

KV – Kilovolts

LEC - Lesotho Electricity Corporation

LHPS - Lunsefwa Hydro Power Station

MATLAB – Matrix laboratory

MOTRACO - Mozambique Transmission Company

MVA – Megavolt Ampere

MW – MegaWatts

NAMPOWER - Namibia Power Corporation

NERC – Northern American Electric Reliability Corporation

PI – Performance index

PSCAD – Power system computer aided design

P.U – Per unit

RCI – Reactive compensation index

RTDS – Real time digital simulator

SADC – Southern African Development Community

SAPP – Southern African Power Pool

SCADA – Supervisory control and data acquisition

SEC - Swaziland Electricity Board

SNEL - Societe Nationale d'Electricite

SVC – Static VAR compensator

TANESCO - Tanzania Electricity Supply Commission

TCSC – Thyrister controlled series compensation

VAR – Volt ampere reactive

ZESA - Zimbabwe Electricity Supply Company Ltd

ZESCO - Zambia Electricity Supply Corporation Limited

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CHAPTER 1

INTRODUCTION

1.1 Overview

Southern African Development Community (SADC) is an organization that was formed in Lusaka, Zambia on 1 April 1980, following the adoption of the Lusaka Declaration [1]. The Declaration and Treaty establishing the Southern African Development Community (SADC) which has replaced the Co-ordination Conference was signed at the Summit of Heads of State or Government on 17 August 1992 in Windhoek, Namibia. SADC was established to build a regional community which would provide peace, security, cooperation in fields of shared interests, and ultimately an integrated economy [2]. The organization provides a forum where regional planning is carried out with the goal of encouraging self-sustaining development in Southern Africa, which is based on collective self-reliance and inter-dependence of Member States. It is built on the principle of achieving sustainable utilization of natural resources and effective protection of the environment.

Under the patronage of SADC is the Southern African Power Pool (SAPP), whose primary aim is to provide reliable and economical electricity to its customers. It is a cooperation of 12 national electricity companies in the Southern part of Africa and was the first formal international power pool to be created in Africa in 1995 [3]. The SAPP member countries include; Angola, Botswana, Democratic Republic of Congo, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe (see Fig.1). SAPP has facilitated broadband infrastructure in SADC in order to efficiently and effectively trade electricity among the countries utilizing cheap electricity generated by coal-fired thermal plants in South Africa and abundant hydropower potential in neighboring countries. The organization's other objectives include [4];

- To increase power accessibility in rural communities.
- Implement strategies in support of sustainable development priorities.
- Provide a forum for the development of a world class, robust, safe, efficient, reliable and stable interconnected electrical system in the Southern African region
- Harmonize relationships between member utilities.
- Co-ordinate and enforce common regional standards of Quality of supply (QoS); measurement and monitoring of system performance.
- Facilitate the development of regional expertise through training programs and research.

In order to effectively achieve its aims and objectives, the organization created a trading platform that enables the export and import of electrical power between the member states. This is carried out through three main trading platforms;

(i.) Bilateral trading - This involves the barter trade exclusively between two states without the use of hard currency for payment.

(ii.) Day ahead trading market (DAM) - Contracts are made between buyer and seller for the delivery of power and the following day the price is set and the trade is agreed upon.

(iii.) Post day ahead trading market (PDAM) - Unlike DAM, the price is set prior to deliver.

By 2013, SAPP comprised of a membership of 16 utility companies which also includes Independent Power Producers (IPP) and Independent Transmission Companies (ITC) from the 12 member countries shown in table 1-1. Whilst most of the utility companies are operational (OP), some are declared to be non-operational (NP), and others are merely observers (OB).

Table 1- 1: SAPP member state utilities

Utility	Status	Abbreviation	Country
Botswana power corporation	OP	BPC	Botswana
Electricidade de Mocazmbique	OP	EDM	Mozambique
Electricity Supply Corporation of Malawi	NP	ESCOM	Malawi
Empresa Nacional de Elecricidade	NP	ENE	Angola
Electricity Supply Corporation	OP	ESKOM	South Africa
Lesotho Electricity Corporation	OP	LEC	Lesotho
Namibia Power Corporation	OP	NAMPOWER	Namibia
Societe Nationale d'Electricite	OP	SNEL	DRC
Swaziland Electricity Board	OP	SEB	Swaziland
Tanzania Electricity Supply Commission	NP	TANESCO	Tanzania
Zambia Electricity Supply Corporation Limited	OP	ZESCO	Zambia
Zimbabwe Electricity Supply Company Ltd	OP	ZESA	Zimbabwe
Copperbelt Energy Corporation	ITC	CEC	Zambia
Lunsefwa Hydro Power Station	IPP	LHPS	Zambia
Hidroelectricia de Cahora Bassa	OB	HCB	Mozambique
Mozambique Transmission Company	OB	MOTRACO	Mozambique

Figure 1- 1: Member countries of SAPP

1.2 Problem Formulation

The number of power outages experienced in the Southern African region has escalated over the last decade due to a combination of factors, such as member countries' inadequate electrical power supply system; load growth in areas which were not adequately planned for; high population growth and rapid economic expansion [5]. Outages have also occurred as a result of technical and operational challenges. Power outages and poor quality of supply are often the result of insufficient generation capacity or unreliable power network grids. This research investigation seeks to evaluate the reliability of the SAPP region by assessing the grid's security taking mainly into consideration the voltage overload, voltage under load and thermal loading of the busbars and transmission lines. Security in this case refers to the degree of risk in the power networks ability to survive imminent disturbances or contingencies without interruption to customer service [6]. Determining the security of the power networks of the individual member states of the SAPP region would be inconsistent due to the electrical bilateral contracts they obligate allowing for the import and export of electricity amongst the countries [4], hence a much suited approached has been taken of analysing the region as a whole.

1.3 Aims and Objectives

The aim of this research study is to investigate the reliability of the SAPP regions power network by verifying a particular level of performance in accordance with SAPP standards. To adequately carry out the main aim the following areas will be explored;

- The determination of the region's generation plant portfolio and high voltage transmission system. This is done in preparation for model building and real-time digital simulation which will use the acquired information to build a precise model of the SAPP network.

- Modelling of the high voltage electric power network and interconnections of the SAPP using DIgSILENT PowerFactory.
- Performing a contingency analysis on the SAPP network model using DIgSILENT PowerFactory to determine the security status of the SAPP network.
- Optimizing power flow across the regional network and enhancing the performance of the existing SAPP power network by using strategic placement of new interconnections or enhancing the transmission capacity of existing interconnections.

1.4 Motivation

Every facet of human development is woven around a sound and stable energy supply regime [7]. This is why it is important to ensure that there is a constant supply of electricity throughout the SAPP region. The first step to achieving continuity of supply is by knowing the security status of the regions power grid. Having this information at hand is highly advantageous as it can allow for appropriate measures to be taken to improve not only the current situation but also make provision for future augmentation if necessary.

In order to determine the security status of the region, a contingency analysis will be carried out on the SAPP model; this will be carried out primarily using DIgSILENT PowerFactory. Contingency analysis will be advantageous as it can be used to analyze which contingencies will cause violations in the power network and allow appropriate modifications that will overcome such violations in order to improve the security of the network.

1.5 Hypothesis

The hypothesis that this research addresses is;

The overall reliability of the SAPP network can be enhanced by improving its security via methods such as strategic interconnections and placements of interconnection lines. The security of the power network is dependent on the severity of the violating limitations (thermal loading and bus voltage limits) resulting from contingencies.

1.6 Research questions

The questions that will be addressed whose answers will lead to the validation of the hypothesis are as follows;

1. How much power is transferred between the member states of the SAPP?

2. When any one generating unit/source has a fault in any one country, what thermal loading, bus voltage violations occur in the SAPP network?

3. When a disturbance occurs in the SAPP power network, what thermal loadings, bus voltage violations are induced?

1.7 Methodology

The preliminary network data used in this research was provided by SAPP through the support of ESKOM. This information was released under a strict confidentiality agreement that it was to be used for research purposes only. From the data received, the SAPP network used in this research was modeled and built using DIgSILENT PowerFactory whilst further simulations were run using MATLAB. The network was modelled such that focus was placed primarily on the interconnection lines between the member countries that are involved in the export and import of electricity in the region.

1.8 Contributions

The first contribution of this thesis is that it provides a simplified model of the SAPP network focusing only on the transmission network that are directly involved in the trading process. The second contribution is that a severity of the security analysis of the SAPP grid is given in detail with regards to voltage and thermal loading violations for the several operating scenarios that have been analysed. This was done using a MATLAB code that enables security selection and ranking. Furthermore, some solutions are suggested that would enhance the security of the SAPP network.

1.9 Publications in Journal and Conference proceedings

Some of the concepts presented in this thesis can be found in the papers published during my MSc studies;

[1] Mwale. S. J. T, Davidson. I. E, "A Steady-state Contingency Analysis of the SADC Regional Grid using the N-1 Criterion", Journal of Energy and Power Engineering, DOI: 10.17265/1934-8975, Vol. 9, May 2015

[2] Mwale. S. J. T, Davidson. I. E, "Security Analysis of the SADC Regional Electric Power Grid Using DigSilent Powerfactory Software Tool". In Proceedings of the 1st Eskom-EPPEI Students' Conference, Midrand, May 5-6, 2014.

[3] Mwale. S. J. T, Davidson. I. E, "SADC Power Grid Reliability - A Steady-state Contingency Analysis and Strategic HVDC Interconnections Using the N-1 Criterion", 2nd International Symposium on Energy Challenges and Mechanics, Scotland, United Kingdom, 19-21st August 2014

[4] Mwale. S. J. T, Davidson. I. E, "Power deficits and outage planning in South Africa", 2nd International Symposium on Energy Challenges and Mechanics, Scotland, United Kingdom, 19-21st August 2014

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In power system operations, it is desired to achieve a balance between power generation and load demand to maintain a constant frequency. The load demand of an electric power system varies throughout the day and also during different seasons, hence the available generation should be able to supply this load at any given time [8]. Electric power is becoming more imperative in the modern world and as most power utilizations are supplied by the power transmission and distribution system, the security of the power system is paid more and more heed to nowadays [9]. Security is one of the two counterparts that make up the reliability of a power system, the other is adequacy. Reliability can be referred to as the ability of a system to perform its required functions under stated conditions and for a specific period of time[10]. This, however, is highly dependent on both the security and adequacy; security is the ability of the power system to withstand disturbances without causing an impact on its load or quality of service thereof [6] and adequacy is the amount of capacity resources needed to meet peak demand [11]. According to Singoyi [12] for a power system to be considered secure, it must satisfy the N-1 criterion. This means, upon the tripping of any power component (overhead line, transformer and generator), no overload must appear on the remaining components. In addition, the thermal ratings of the equipment shouldn't exceed their maximum during the outage and the operational limits must be respected whatever the situation. According to IEEE 1453 – 2004 standard, under normal conditions the flows must be kept below the thermal rating of each network element. The voltage at each bus bar must be kept within a tolerance of ±5% of its nominal value. In emergency situations when an element outage occurs, the thermal rating of any equipment should not be exceeded and the voltage should be kept within 95% and 105% of its nominal value. A 15% over voltage is however acceptable for 5 seconds and a 20% over voltage for between 1 second and 2 second.

Gao [13] states that assurance of a secure state of generation is an essential task of the Power System Operator. Making accurate prediction during real time operation for the power system can help increase the security of the power system especially after the system has been affected by severe contingencies. Unreliability in a power system is usually caused by voltage collapse, frequency collapse and also overloading. Lu [14] found that as a result of the consequences of deregulation (economic imperatives and technical difficulties), the electric power system currently operates close to the security limits. And in order to protect the grid against severe contingencies and to increase the security margins, the transmission system operators have to take special measures that are based on security analysis. The authors proceeded to propose a cyclic security analysis methodology which checks the static, dynamic and transient behaviour of a given power system. The proposed methodology is able to establish if a certain operating point is secure by taking into account the possible contingencies.

According to Cutsem [15], a secure operating limit is the most stressed among a given set of operating points, such that the system can withstand specified contingencies. It is a general measure of security with respect to incidents, incorporating pre-contingency operator or controller actions and post contingency corrective controls. Their proposed approach deals with long term voltage stability limits that combine Dichotomic search with Quasi Steady State simulators to compute these limits with the efficiency required by real time applications. However, according to Bose [6], to secure the system against more severe disturbances requires more expensive designs, hence the design criteria are chosen to meet an appropriate level of security. In more developed countries, the customer is often willing to pay more for minimizing the interruption of power, whereas in less developed countries the scarcity of capital and other reasons keep the level of power system security lower. Therefore, it is cheaper to have neighbouring utilities provide backup electric power supply in case of generator outages and this leads to widespread interconnection of the transmission system as was the case in North America and Western Europe starting from the 1930's.

2.2 Power System Reliability and Security

Power system reliability is the measure of the capability of the electric power network to withstand sudden disturbances or unanticipated losses in the system components that can be caused by both natural and man-made events[16]. The functionality of power 'security' and 'reliability' makes them counterparts and it is because of this reason that the NERC replaced the term power system security by power systems operational reliability. An operationally secure network is one that has a low probability of experiencing power outage or faults in the equipment. As the availability of electricity is of paramount importance in every sector of growth in our communities, it is of vast importance that each power grid is of good reliability. A reliable power grid is characterized by the following [12];

(i.) The voltages must be within the limits.

(ii.) The grid must be able to withstand the loss of a generator.

(iii.) Must be able to withstand the loss of a transmission line.

(iv.) Must be able to retain stability during a short circuit.

(v.) The generating capacity must be greater than the load demand at any given time.

(vi.) The transmission lines must not be overloaded.

A noticeable sign of an unreliable power grid is frequent power outages or blackouts. Despite modern electrical power grids being monitored by trained system operators equipped with sophisticated monitors and control systems such as SCADA, large, frequent and uncontrolled blackouts are affecting millions of customers around the globe. This appears to be a problem that only seems to worsen. It was reported in 1995 that the frequent blackout in the USA was 7 days per year, this figure however escalated to 36 days per year by 2006[17]. In the last decade, Namibia, South Africa, Zambia and Zimbabwe have had to resort to load-shedding as a stop-gap measure in order to reduce demand. South Africa, has been particularly badly hit by energy shortages. South Africa's industrialists say the shortages are costing them billions of South African rand[5]. Mining accounts for about 15 per cent of South Africa's electricity demand. Other countries in the region such as Botswana, Namibia and Swaziland, which rely on South Africa for their energy supplies, have had to turn to other neighbouring countries for electricity. Increased blackout in any region is an indication that there is need for a tool that can inevitably predict and prevent blackouts in real time and hence, one possible tool that can be used to determine the reliability of a power grid is to perform what is known as a contingency analysis [18] explained further in section 2.3.

With the constant increasingly growth rate of our economies a huge strain is often placed on the electrical power networks pushing them closer to their limits. Several electrical equipment are constantly being developed and improved so as to help meet the reliability and efficiency of such growing networks. Some of the equipment produced for the purpose of such include;

i. Circuit breakers that are designed to be able on command to interrupt currents up to full short-circuit rating within milliseconds and without failure.
ii. Surge arrestors that must limit over voltages within microseconds.
iii. Voltage and Current transformers, which must continually provide accurate measurement data on the load and status of the power system.
iv. FACTS (Flexible alternating current transmission system) that can be used to enhance controllability and increases power transfer capability of the network. Transmission quality and efficiency is improved by supplying either inductive or capacitive power to the grid.

In order to accurately model, simulate and test such equipment before they are installed in the actual power system, several hardware equipment and software tools and programs have been developed. Some of which include the Real Time Digital Simulator (RTDS), DIgSILENT PowerFactory, Powerworld simulator, PSCAD™/EMTDC™ and RSCAD. In order to test, simulate and design models of power systems, scaled down models of power system components had to be used. The introduction of hardware and software tools have not only increased accuracy and flexibility but have also reduced purchase and operating costs. Industries, utility companies and research institutions alike have all highly benefited from this development [19].

The Monte Carlo simulation has for a long period of time been used to assess reliability of power systems. This is a technique that is used to understand the risk of impact in which multiple trial runs called simulations are run in the hopes of approximating the probability of a certain outcome. The Monte Carlo simulation works by method of selecting a random value based on a range of estimates made by experts on the area or past experience. A forecasting model (one which plans ahead for the future) is made to which the estimated values will be implemented and simulated. The ranges of values were obtained to help the programmer understand the risk and uncertainty in the model. The aim of the Monte Carlo simulation was to give a clearer picture based on how one creates the estimates, how likely the resulting outcomes are. The disadvantage however of this method is that the simulation is only good as your estimation. The simulation only represents probabilities and not certainties.[20], [21], [22].

Power system simulation has long been recognized as an important and necessary step not only in network development, but also in the design and testing of power generation and transmission systems. Recent advances in both computer hardware and sophisticated power system component modelling techniques have significantly increased the application of digital simulation in the power system industry. Simulation of a power system in the steady state condition is used primarily during either the planning phase or in control centers to optimize the steady state system operation. Whilst simulation under dynamic and transient conditions are required for complex systems where the performance is determined by the power plant control and the control of electronic equipment [23]. The study of power system transients deals with events which occur due to disturbance on the power system (line faults, breaker switching). Transient simulations are performed in order to examine these stresses and to evaluate what effects they will have on the system being studied. The results are then used to ensure component ratings are sufficient and that appropriate protection devices are in place to prevent damage to components when faults occur.

Advances in digital signal processing together with improvement in accuracy and efficiency of power system component models have had a significant effect on digital simulation technology. For relatively simple systems, real time operation can be achieved for only short periods of time using high end, high speed computer work stations [24], [25] Although real time simulation of large scale power systems has long been desired, the application of real time simulators was traditionally reserved for small to medium scale powers systems (i.e less than 70 buses). Analogue hybrid simulators were physically too large and expensive for these systems and fully digital simulations of this size were yet to be realized. As a result, large scale simulators were left mainly to non-real transient stability programs. The benefits provided by large scale real time simulation of power systems was later realized and it was discovered real time electromagnetic transient simulations add the following capabilities [26];

- Faster results through real time performance
- Physical protection and control equipment testing
- More detailed time domain simulation

- Detailed analysis of power electronic controllers (e.g HVDC, SVC, TCSC)
- Real time response for training and education of power system personnel

2.3 Contingency Analysis

Power system steady state security is an instantaneous condition as it is a function of time and of the robustness of the system with respect to the imminent disturbances[27]. The last century has demonstrated that every facet of human development is woven around a sound and stable energy supply regime. Some of the factors that threaten the reliability of the network include aging infrastructure of both the transmission and distribution networks[28]. One method of ensuring a reliable and secure power network is by careful monitoring, automation and information management. Such a tool that can be used to carry out a power system analysis in this regard is a contingency analysis. CA is the study of the outage of elements such as transmission lines, transformers and generators, and investigation of the resulting effects on line power flows in the remaining parts of the system network. This tool is especially effective during the operation and planning stages to study the effect of contingencies. Contingencies referring to disturbances, including transmission element outages or generator outages that may cause sudden and large changes in both the configuration and state of the system. They often result in severe violations of the operating constraints and in many cases lead to power outages [29]. Steady state contingency analysis aims at the assessment of the risk that certain contingencies may pose to an electrical network in real time. For any system to be considered secure it should conform to what is known as the N-1 criterion (section 2.5). CA is used also as a study tool for the offline analysis of contingency events and as an online tool to show operators what would be the effects of future outages. This allows operators to be better prepared to react to outages by using pre planed recovery scenarios. During contingency analysis it should be noted that [30];

- Security is determined by the system's ability to withstand equipment failure
- Weak elements are those that present overloads in the contingency conditions (congestion)
- Standard approach is to perform a single (N-1) contingency analysis simulation

Contingencies put the whole or part of the power system under stress and this occurs due to[10];

- Sudden opening of the transmission line
- Generator tripping
- Sudden change in the generation
- Sudden change in the load

The contingency flow chart used in this research to assess the security of the SAPP model has been adapted from Ahmad et al [31] shown in fig. 2-1.

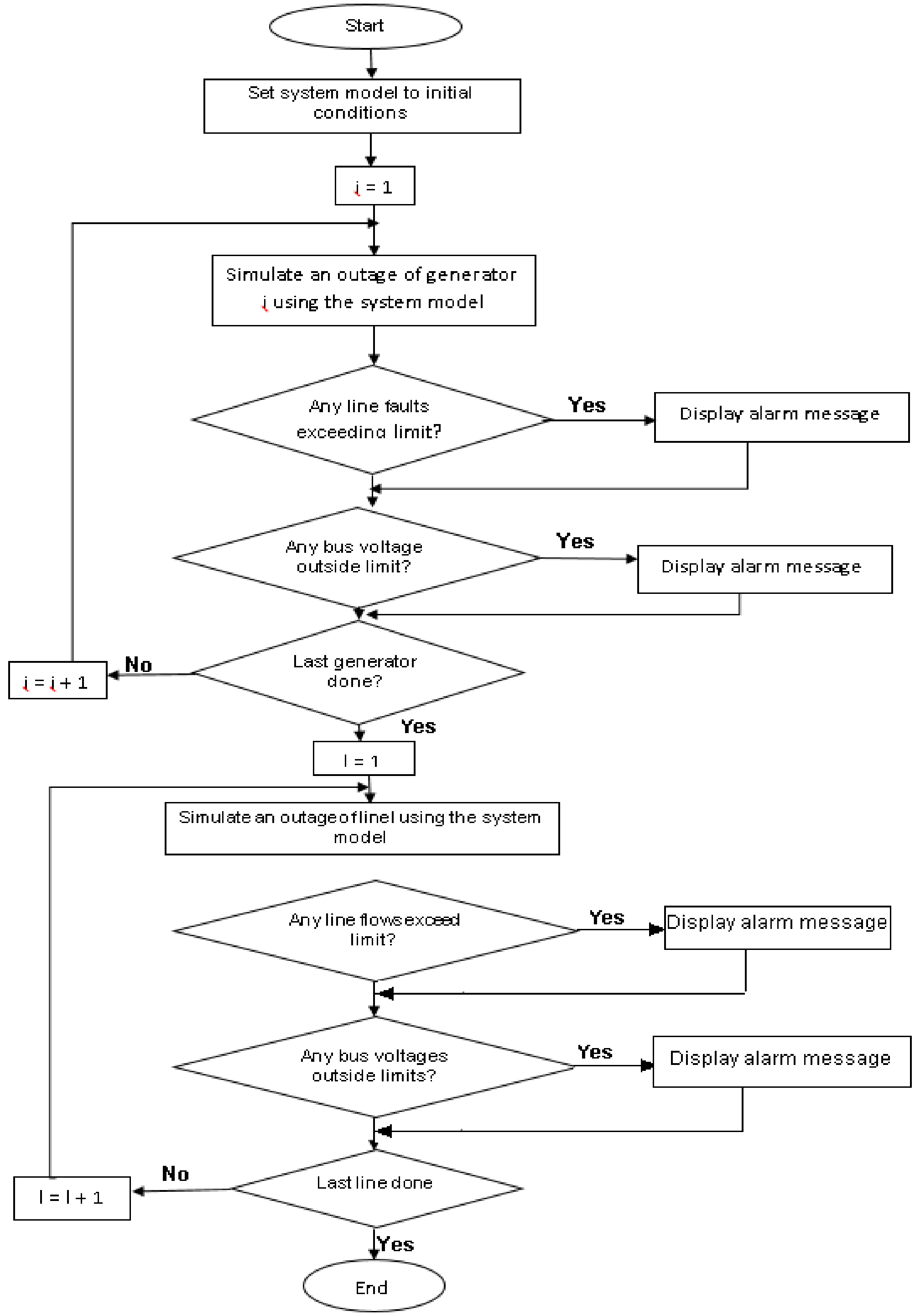


Figure 2 - 1: Contingency analysis flow chart [31]

Ahmad et al [31] carried out a contingency analysis on the Bangladesh power system in order to identify the ranking which will aid in knowing the amount of losses for any fault in the generator, bus, transformer and the transmission line. It should be noted however, that over the years there has been an evolution of contingency analysis methods that have been used dating as early as the 1950's. There are several methods that can be used to analyse the occurrence of a contingency in a network that are separate from the N-1 criterion, some of which include; the concentric relaxation method [32], the bounding method [33], the DC power flow method [34], the ward equivalent method [35].

2.4 Contingency Ranking and Selection

In practice, it is often not feasible to carry out a line outage on each independent transmission line in an exceptionally larger power system in an effort to study the overloading that will occur in the system. As is the case, a contingency ranking is applied to identify which lines have a higher probability of causing system overload. There are several methods that have been used previously in an effort to assess the extent of the security status of a network. Abdallah et.al rendered the development of a contingency ranking algorithm which would rank algorithms based on their relative severity as desirable. The main objective of this method is to find all the critical cases which are then ranked based on their effects on line loading or bus voltages [36]. Albuyeh and Nara used what is known as the performance index (PI) which entails a wide system scalar PI so as to compute the severity of each case by calculating their PI value ranking them accordingly [37], [38]. Another contingency ranking algorithm is the screening method used by Mori et al and Hao et al. This particular method is based on approximate power flow solutions to eliminate those non-critical contingencies. [39], [40].

According to Kirschen [41] the N-1 security criterion provides just an impartial perspective on the severity of a power system as compared to the risk based approach to security assessment which provides significantly more information on which to base operating decision. The authors believed that the risk should be measured in terms of expected outage costs to the consumers. The risk calculation should not be limited to the reflection of the predefined set of contingencies but rather should factor in the actual probabilities of the outages leading to load disconnections. They went on to carry out a case study based on the IEEE-Reliability Test System showing how different operating points on the systems deterministic security boundary vary risk levels. The risk level changes for given operating points, considerably ranging between fair, average and bad. The paper also demonstrates how the use of adaptive deterministic security boundaries make it possible to compare the cost and benefit of relaxing operating limits. The reactive compensation index (RCI) is one method that has been used extensively by BC Hydro in Canada for assessing voltage stability. In this methodology, the π (pi) section model is used to evaluate the RCI for active power flow and compensation injection theorem using only the base case load flow under each line outage condition. The method estimates the distance between the pre-contingency and line outage case nose by using the total reactive injection required at the load buses to establish similar voltage levels for both cases. The RCI is formulated as [42];

$$\text{RCI} = \sum_{n=1}^{NB} Q^{c}nj \tag{2-1}$$

Where;

NB - number of load buses

$Q^c nj$ - reactive power supplied by the artificial shunt compensator at the n^{th} load bus for the outage of j^{th} line to maintain the voltage profile as in perfect condition.

Another methodology is the performance index (PI) given by the equation (2-2) [43];

$$PI = \sum_{l=1}^{L} \alpha l w l \left(\frac{pl}{pl*}\right)^2 \qquad (2\text{-}2)$$

Where;

pl - active power of line l

$pl*$ - transmission capacity of branch l

αl - number of parallel lines for branch l

wl - weighting factor of the line which reflects the influence of a fault

L - Number of branches in the network

When there is no overloading present, $\frac{Pl}{Pl*} < 1$ and when there is overloading $\frac{Pl}{Pl*} > 1$ and the positive exponential element makes the PI relatively large. This index is used to generally reflect the power systems security.

Jagadish et al [44] carried out an experiment in India and used the Remedial Action Schemes (RAS) for Contingency Analysis. As the name suggests they are necessary actions which need to be taken to solve the violations caused by a contingency. They are also defined as Special Protection Schemes (SPS) or System Integration Schemes (SIS). The RAS is designed to mitigate specific critical contingencies that initiate the actual system problems. There may be a single critical outage or there may be several critical single outages for which remedial actions are needed. In order to investigate how far the system is from insecure conditions and how a transaction of active power can affect the loading of the transmission system, it is necessary to analyse the sensitivities of line flows with respect to bus injections. These sensitivities are termed as Power Transfer Distribution Factors of i-j elements and for the transaction between m-n is given by the formula;

$$PTDF_{ij(mn)} = \frac{\Delta Pij}{\Delta Tmn} \qquad (2\text{-}3)$$

Where,

$PTDF_{ij(mn)}$ - Power Transfer Distribution Factors for line i-j for transaction between m - n

ΔTmn - Change in transaction between m and n

ΔPij - Change in the real power flow of line i-j for transaction between m-n

The results obtained from this approach proved to be quite accurate and thus providing new tools for developing remedial control actions for higher order contingencies.

System performance indices are not unique and obtain different forms depending on the parameters that are of importance to the engineer. However, in selecting a PI, physical properties of the system should be taken into consideration. The most common form of system PI give a measure of the deviation from rated values of system variables such as line flows, bus voltage and bus power injections. The PI that will be used in this thesis is one that will list the contingencies in ranking of severity of line over loads (PI_p) and the 'out of limit' voltages (PI_V) given by the equations (2-4) to (2-6) [45]. And in order to get a reflection of the reactive power capacity constraints due to generator outages we will apply equation (2-7) [46].

$$PI_P = \sum_{i=0}^{Nl} \left(\frac{W}{2n}\right) \left(\frac{Pi}{(pi^{max}}\right)^{2n} \qquad (2\text{-}4)$$

Where;

PI_P – Active power index

Pi - power flow in MW

pi^{max} - MW capacity of the line

Nl - Number of lines in the system

W - Rean-non negative weighing factor = 1

n – Penalty function = 1

$$pi^{max} = \frac{Vi.Vj}{X} \qquad (2\text{-}5)$$

Where;

Vi - voltage at bus i after load flow

Vj - voltage at bus j after load flow

X - Reactance of the line connecting bus

$$PI_V = \sum_{i=1}^{NB} \left(\frac{W}{2n}\right) ((| \; Vi| \; - | \; Vi^{sp}| \;) \; / \; \Delta Vi^{lim}))^{2n} \qquad (2\text{-}6)$$

Where;

PI_V – Reactive power index

Vi - voltage magnitude corresponding to bus i

Vi^{sp} – specified voltage magnitude corresponding to bus i

ΔVi^{lim} – Voltage deviation limit

n – Penalty function = 1

NB – Number of buses in the system

W – Real non-negative weighting factor = 1

$$PI_V = \sum_{i=1}^{NB} \left(\frac{W}{2n}\right) ((|\ Vi| \ - |\ Vi^{sp}|\ ) \ / \ \Delta Vi^{lim}))^{2n} + \sum_{i=0}^{NG} \left(\frac{W}{2n}\right) (\frac{Qi}{(Qi^{max}})^{2n} \qquad (2\text{-}7)$$

Where:

PI_V – Reactive power index

Vi - voltage magnitude corresponding to bus I

Vi^{sp} – specified voltage magnitude corresponding to bus i

ΔVi^{lim} – Voltage deviation limit

n – Penalty function = 1

NG – Number of generating units

W – Real non-negative weighting factor = 1

Qi^{max}- Reactive power limit at bus i

Qi – Reactive power at bus i

2.5 N-1 Criterion

The N-1 criterion is one which is used to determine the security status of a power system following unpredicted faults and is an abstraction representing a single contingency or the outage of any one element following an incident. An ‘N-m’ contingency refers to the loss of m components in the power system where m ≥1. As such, a first level contingency where only one component is lost during a fault is represented as N-1, a second level fault is represented as N-2 and so forth. Therefore, the total number of m contingencies that can occur in a power system is represented by the expression C_{Nm}, where; m = 0, 1, 2, 3,…, N and N = number of elements. The total number of all possible contingencies that can occur in a power system is given by the equation;

$$TC_{Nm} = \sum_{m=1}^{N} CNm \qquad (2\text{-}8)$$

Where;

$$C_{Nm} = \frac{N!}{m!(N-m)!} \quad (2\text{-}9)$$

An example given for a small network contingency with N = 10 elements, applying eq (2-8), the network has the possibility of having ten N-1 contingencies, forty five N-2 contingencies, one hundred and twenty N-3 contingencies and so on. This is a simple illustration of the combinational probabilities of contingencies that can occur in any one system. The bigger the network, the more the probabilities, making systematic computation of all possible failures requiring an exceptional amount of time to compute. In this research, multiple contingencies (N-2 and higher) are disregarded due to the magnitude of the case study model and focuses only on first level contingency.

Two of the most critical and common failures to occur in a power system are the transmission line failure and generation unit failure. Both of which can cause alterations in the voltages of the transmission system and power flow. This is why performing a contingency analysis allows one to determine which violations have been made after a disturbance occurs in the system. Even whilst the loss of a generation unit can cause additional dynamic problems usually affecting the frequency and operation output, this research is limited to the voltage and thermal violations that are reached during and after each contingency.

2.5.1 Voltage Violations

Voltage violations occur at the buses. A violation of the voltage at the bus bar indicates that the voltage post contingency at the bus bar has exceeded its acceptable limit of 0.95 – 1.05pu (per unit) of the nominal voltage. This standard is according to the IEEE which is a professional association to which all global standards succumb for a range of industries. When a voltage drop occurs post contingency, meaning the voltage at the bus bar is below 0.95pu of the nominal voltage, there will be a spike in the reactive power as more of it will be injected into the bus in an effort to increase the voltage profile at the bus bar. Similarly, when a voltage rise occurs post contingency, exceeding the permissible 1.05pu of the nominal voltage, a drop in the reactive power will be experienced as more of it will be absorbed at the buses to maintain the nominal voltage.

2.5.2 Line MVA Limit / Thermal Overload Violation

When the MVA rating of the transmission line exceeds its given rating (which varies for each kind of transmission line) the line MVA is violated. Transmission lines are known to have some level of resistance which results in heat losses causing the transmission line to become hotter as more current flows through it. The maximum amount of current that can be transferred through a conductor whilst keeping the conductor's temperature below its limit is what is specified as the maximum power in MVA, commonly referred to as the thermal rating of the line. Even while most lines are designed to withstand 125% of the thermal limit, some utilities declare a thermal limit ranging between 80% - 90% an alarm situation. For purposes of this research however, any line that exceeds 80% of its thermal limit will be considered an alarm situation whilst those surpassing 100% their thermal limit will be referred to as being overloaded.

Some of the factors that define the thermal rating of a line include;

- Current through a conductor
- Conductor characteristics
- Location – latitude, elevation, line direction, etc.
- Weather – wind speed/direction, air temperature, sun light.

CHAPTER 3

SAPP OVERVIEW

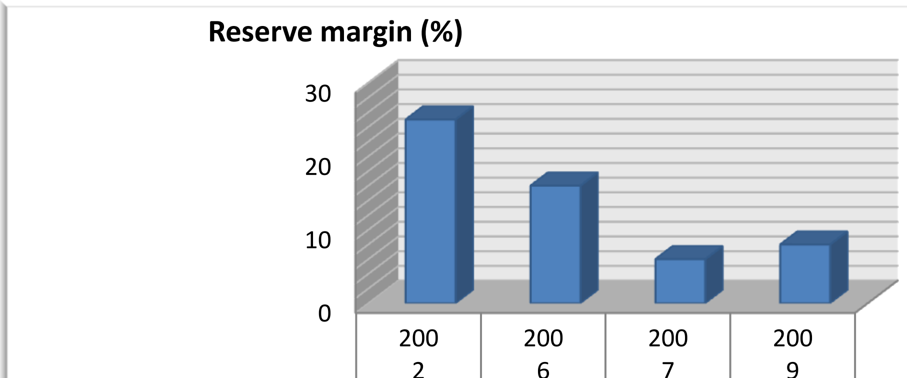
3.1 SAPP Overview

The 12 member countries of SAPP have a combined population of approximately 260 million people dated 2014 and covers a surface area of 9296102 km² and a combined GDP of US$655 billion. This is slightly over 1000000 km² of Europe's 10180000 km² and 2000000 km² more than Australia [47]. The region has a peak demand of 54000MW against a generating capacity of 52000MW which is an improvement considering a deficit of recorded 7000MW in 2009[48]. Table 3-1 shows the various energy resources that the member countries of SAPP use in the generation of power ranging from hydro, oil and also nuclear [49].

Table 3- 1: SAPP member generation sources in MW

Country	Oil	Coal	Gas	Nuclear	Hydro	Total
Angola	89		174		474	737
Botswana		132				132
DRC					2333	2333
Lesotho					73	73
Malawi	36				278	314
Mozambique	64				2122	2186
Namibia	29	115			240	384
South Africa	2424	36360		1 616	665	41065
Swaziland					62	62
Tanzania	79		640		561	1280
Zambia	10				1752	1762
Zimbabwe		1026			750	1776
Total	**2731**	**37633**	**814**	**1616**	**9310**	**52104**

Like its SAPP member counterparts, South Africa is no exception when it comes to major power outages brought about due to rapid economic growth and expansion which have contributed to a diminishing generation reserve capacity against an increasing growth in demand. The increased electricity demand over the years has been brought about due to a vastly increased customer base, economic growth and a late start to the construction of new Power plants. Musidza [50] indicates that a joint effort was essential to meet the countries estimated 4% GDP growth and the targeted 6% GDP growth and the socioeconomic imperatives in 2007. Eskom was required to have produced 70% (in MW) with the remaining investment balance (30%) attained through private sector participation with direct independent power producers (IPPs) and distribution generation (DG) in the power generation [51]. This is particularly significant as the country is the largest exporter of electrical Power (2000 MW) in Southern Africa and is interconnected to five neighboring countries; Botswana at 400kV, Swaziland at 400kV, Namibia at 220kV and 400kV, Mozambique at 275kV and 400kV, and Lesotho at 132kV [52]. Eskom generates at least 75 percent of the SAPP regions electricity with other smaller economies such as Zimbabwe generating 4%, DRC 3.4% and Zambia 2.9%. South Africa is historically known to have had one of the highest electricity reserve margins worldwide [5]. Reserve margin is the excess available capacity above the normal peak demand levels. The South African electric power reserve margin has decreased over the years as shown in Figure 1.



	2002	2006	2007	2009
Reserve margin (%)	25	16	6	8

Figure 3- 1: South African reserve margin (2002 - 2009)

This has negatively affected the region as a whole. Fig. 3-2 shows a clear increase in the consumption of electricity in the SADC region (to which all SAPP members belong) in a space period of 4 years (2008 – 2011) despite the failure to increase the electrical power generation capacity.

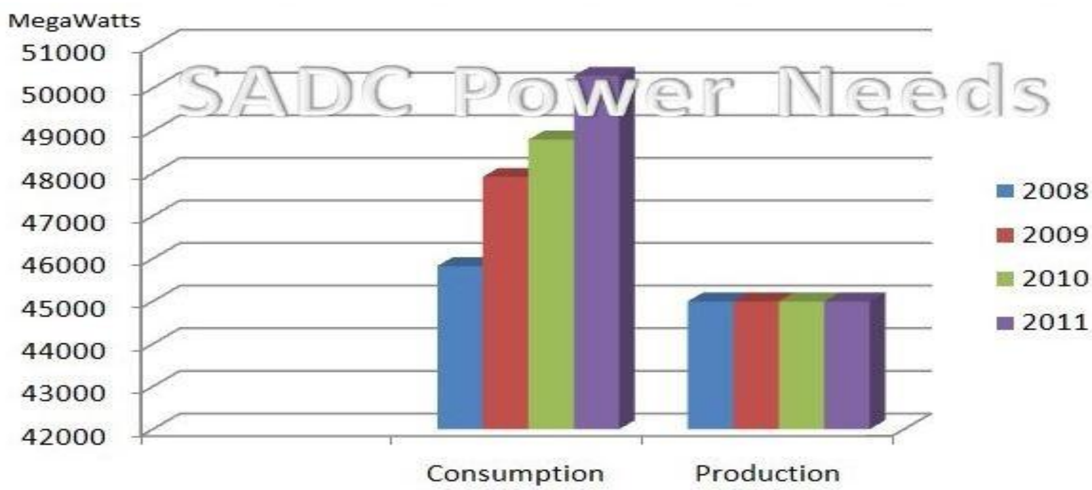


Figure 3- 2: SADC consumption against product (2008 - 2011)[16]

3.2 SAPP Interconnections

The SAPP interconnection for 2012 has been developed and shown in figure 3-3. Three of the member states are non-operational (not yet connected to the SAPP market) which include Angola, Malawi and Tanzania. However, plans have been ongoing in an effort to connect the above mentioned states to the SAPP grid as depicted in many SAPP reports. Padambo [53] reports on a proposal in which Malawi is to be connected to the SAPP market through the Mozambican grid to which Zimbabwe and South Africa are also connected. Similar plans are being made for Tanzania and Angola.

This research focuses on the SAPP grid security status which entails the regions ability to maintain a continuous and sufficient supply of electrical power to its consumers even after a fault has occurred in the networks power grid. Security is one of the variables that make reliability in conjunction with adequacy. To assess the networks security, a contingency analysis will be carried out on the regions electric grid using the real time simulators known as DIgSILENT Powerfactory. In real time simulation, the computer model is executed at the same rate as the actual physical system, meaning if it takes a period of one minute for an actual physical system to shut down, it will also take one minute for the computer model of that same system to shut down. Dynamic contingency analysis is referred to as real-time. Real time simulation is becoming an essential simulation environment for engineering design, especially in power systems [54]. For the reason being that it allows the controls to be subjected to everything from steady state to rare emergency operating conditions and is ideal for closed loop interaction between the power system and the control hardware.

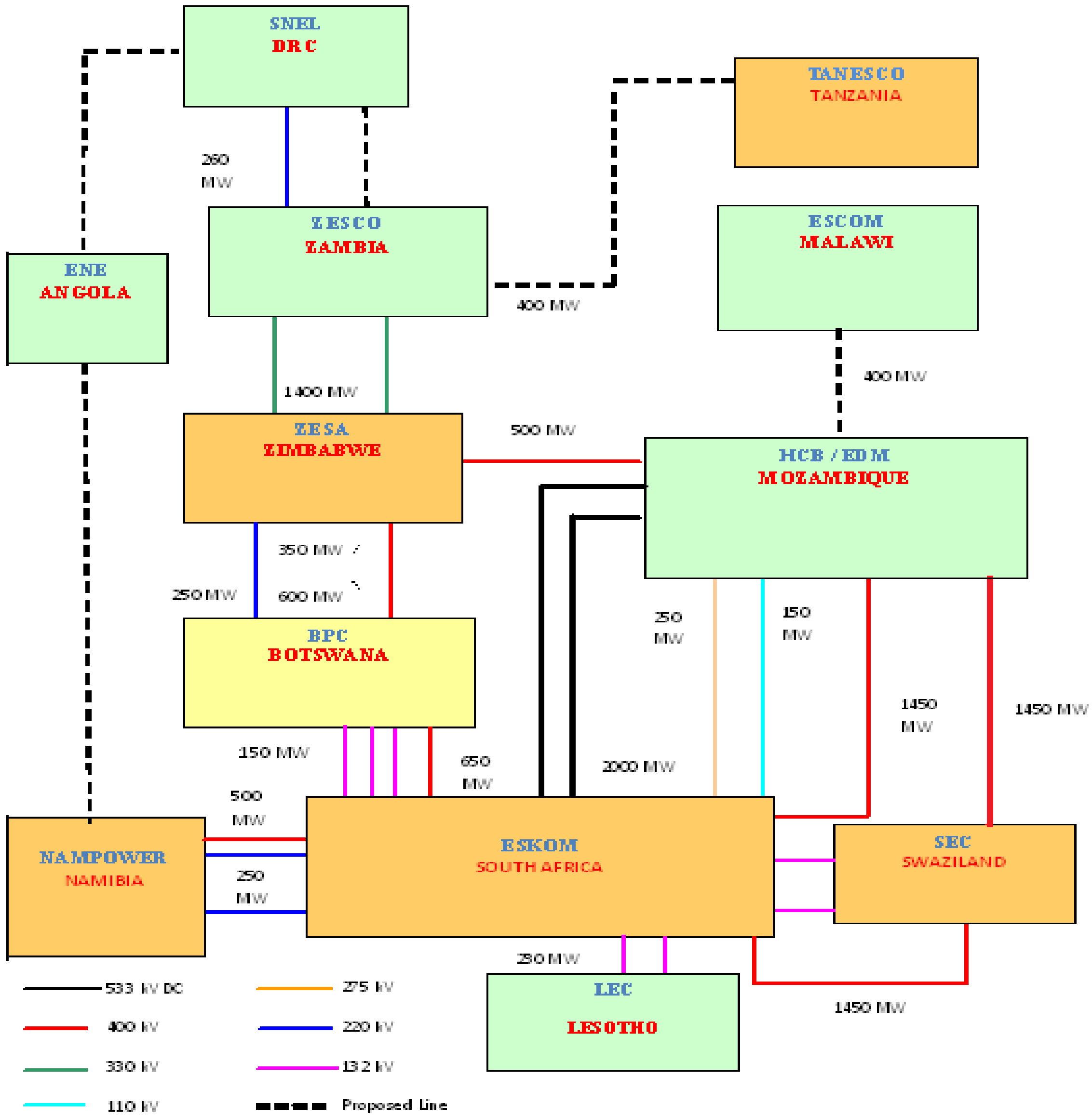


Figure 3- 3: SAPP interconnection as of 2012

3.3 SAPP Planning Criteria

SAPP has put in place a system planning criteria that is to be adhered to during the inter-utility planning process and is also the same criteria to which this model building and simulation of this project will adhere. This system planning has been set to meet the minimum requirements of SAPP and ensures that the transmission of electrical power from the generators to the load centres is reliable, efficient and economical. In any case the development of the transmission system may occur for a number of reasons which include but are not limited to;

- Reconfiguration, decommissioning and optimization of existing network
- Changes to customer requirements or networks
- The introduction of new transmission substations or modification of an existing connection between transmission systems
- The cumulative effect of a number of developments as referred to above

3.3.1 The Planning Process

SAPP's planning process follows the phases listed below which is all in accordance with the SAPP transmission planning criteria[55];

- Identification of the problem
- Formulation of alternative options to meet the need
- Study of these options to ensure compliance with agreed technical limits and justifiable reliability and quality of supply standards
- Costing of these options on the basis of approved procedures
- Determination of the preferred option
- Building of a business case for the preferred option using the agreed justification criteria
- Request for approval of the preferred option and initiation of execution

3.3.2 Transmission Planning Criteria

The transmission planning criteria sets out the standards that are applied in the short, medium and long term planning period. The primary aim of transmission planning is to maintain stable operation of the bulk transmission system for most probable system contingencies. The transmission network shall maintain continuity of power supply to customers under any single contingency of N-1 contingency.

3.3.3 Transmission Planning Concepts

The interconnected transmission system should be capable of performing reliably under a wide variety of expected system conditions while continuing to operate within equipment and electric system thermal, voltage and stability limits as specified in the SAPP criteria. Electric power systems must be planned to withstand contingencies and maintenance outages. Extreme event contingencies which measure the robustness of the electric system should be evaluated for risks and consequences.

3.3.4 Planning Criteria

Individual members may develop planning criteria that shall, as a minimum, conform to this Transmission planning criteria. Individual criteria shall consider the following;

a) Overload power above nominal being carried in any single transmission circuit, multi-circuit transmission line, way leave, as well as through any single transmission station shall be avoided.
b) Inter utility power flows shall not result in risk to the electric system under normal and contingency conditions as outlined in this criteria.
c) Sufficient reactive capacity shall be planned within the SAPP system at appropriate places to maintain transmission system voltages within voltage limits or as determined by the member under contingency conditions.

3.3.5 Power Transfer Capability

Transfer capability is the measure of the ability of the interconnected systems to reliably move power from one area to another area over all transmission circuits between those areas under specific system conditions. Transfer capability is also directional in nature.

Some major points concerning transfer capability analysis are outlined below;

a) System Conditions – Base system conditions are identified and modeled for the period being analyzed, including projected customer demand generation dispatch, system configuration and scheduled power transfers.
b) Critical Contingencies – During transfer capability studies, both generation and transmission system contingencies are evaluated to determine which facility outages are most restrictive to the transfer being analysed.
c) System Limits – The transfer capability of the transmission network can be limited by thermal, voltage, stability or contractual considerations.

3.3.6 Contingency Criteria for Long Term Planning Purposes

- With one line or transformer or reactive compensation device out of service (N-1), it shall be possible to supply the entire load under all credible system operating conditions.
- A system meeting the N-1 contingency criterion must comply with all relevant voltage limits and the applicable current limits, under all system conditions.

3.4 Integration of Power Stations

When the integration of power stations is planned, the following network redundancy criteria must apply;

3.4.1 Power Stations of Less Than 1000MW

- With all connecting lines in service, it shall be possible to transmit the total output of the power station to the system for any system load condition. If the local area depends on the power station for voltage support, the connection shall be made with a minimum of two lines.
- Transient stability shall be maintained following a successfully cleared single phase fault.
- If only a single line is used, it shall have the capability of being switched to alternative busbars and be able to go onto bypass at each end of the line.

3.4.2 Power stations of More Than 1000 MW

- With one connecting line out of service (N-1), it shall be possible to transmit the total output of the power station to the system for any system load condition.
- With the two most onerous line outages (N-2), it shall be possible to transmit the total output of the power station less its smallest unit to the system.
- Smallest unit installed at the power station shall only include units that are directly connected to the transmission system and are centrally dispatched.

i. Transient stability shall be retained for the following conditions;

- A three phase line or busbar fault, cleared in normal protection times, with the system healthy and the most onerous power station loading condition; or
- A single-phase fault cleared in “bus strips” times, with the system healthy and the most onerous power station loading condition; or
- A single-phase fault, cleared in normal protection times, with any one line out of service and the power station loaded to average availability.

ii. The cost of ensuring transient stability shall be carried by the generator if the optimum solution, as determined by the system operator, results in unit or power station equipment being installed.

iii. Busbar layouts shall allow for selection to alternative busbars. In addition, feeders must have the ability to go onto bypass.

iv. The busbar layout shall ensure that no more than 1000MW of generation is lost as a result of a single contingency.

v. To enable the system operator to successfully integrate new power stations, detailed information is required per unit and power station.

vi. When the integration of a nuclear facility or off-site power supple to a nuclear facility is planned, the levels of redundancy and/or reliability of the transmission system and off0site power supple requirements specifies in its nuclear operating license or by the national nuclear regulator within the country shall apple.

3.5 Voltage Limits and Targets

The busbar voltages should remain within the following bands under system healthy conditions;

Table 3- 2: SAPP voltage limits

Network Condition	**Voltage Limit**
System healthy	0.95 --1.05 p.u.
After N-1 contingency before corrective actions	0.90 – 1.05 p.u.
After N-1 contingency after corrective actions	0.95 – 1.05 p.u.

The minimum voltage limit under different contingency conditions for system planning studies (after N-1 contingency) should be 0.95 pu unless otherwise specified by the customer.

3.6 Equipment Loading Limits

3.6.1 Transmission Lines

Utilities shall determine thermal ratings of standard transmission lines and update these from time to time. The thermal ratings shall be used as an initial check of line overloading. No transmission line should be loaded more than its normal thermal limit under normal operating conditions or more than its contingency rating under N-1.

Table 3- 3: SAPP transmission line thermal rating limit

Network Condition	**Thermal rating limit**
System healthy	Rated A (Normal rating)
Under N-1 contingency	Rate B (Contingency rating)

3.6.2 Transformers

No transformer should be loaded more that 100% of its thermal limit under any operating conditions

Table 3- 4: SAPP transformer thermal rating

Network Condition	Thermal rating limit
System healthy	Thermal rating of transformers (i.e the 100% rating)
Under N-1 contingency	Thermal rating of transformers (i.e the 100% rating)

3.6.3 Series Capacitors

The maximum steady state current should not exceed the rated current of the series capacitor and under normal conditions. Use the International Electrotechnical Commission standards (IEC 60143) for cyclic overload capability.

3.6.4 Shunt Reactive Compensation

Shunt capacitors shall be able to operate at 30% above their nominal rated current to allow for harmonics and voltage up to U_M (Maximum continuous voltage on any bus for which equipment is designed).

Reactive compensation, whether new or modified, may cause harmonic resonance problems and harmonic resonance studies must be conducted.

3.7 Shunt Reactive Device Switching

The size of shunt capacitor and reactor banks is limited by the voltage change caused by switching a bank. As a first approximation the per unit voltage change can be determined by dividing the capacitor bank size (MVAr) by the three phase fault level in MVA.

This voltage change when switching shunt devices should not exceed:

- Three percent (3%) with the system healthy or
- Five percent (5%) under contingency conditions

3.8 Circuit Breakers

Rapturing capacity of circuit breakers should meet the maximum system fault levels and other conditions considered for the safe and secure operation of the system.

CHAPTER 4

SAPP NETWORK BUILDING AND LOAD FLOW SIMULATION

4.1 Network Building and Design

Step 1: The SAPP network model was built using the DIgSILENT PowerFactor. The preliminary data that was used to construct the model was provided by SAPP and ESKOM (under a strict confiditiality agreement). A reduced equivalent model for each country was developed and represented as substations. This was done to eliminate computing constraints that were being experienced when the national grids of each country were inhtergrated to form the SAPP network model. The models were reduced from a network consisting of transmission voltages of 11kV, 33kV, 88kV, 110kV,132kV, 220kV, 275kV, 330kV and 400kV to a HV model consisiting of transmission voltages of 132kV, 220kV, 330Kv and 400kV. Appendix 1 shows a summary of the grid information that was collected prior to the building of the SAPP model showing a combined total of 1407 busbars for the entire region. As shown in appendix 2, the models were built such that only the transmssion networks that are directly connected to the SAPP network were included. This resulted into the reduced 58 busbar network model on which simultion were run. The following procedure was adopted in developing the reduced order equivalent model of the SAPP model;

Step 2: The single line diagrams of the member states of SAPP where built using DIgSILENT PowerFactory as shown in the fig.4-2 to 4-10.

Step 3: Data specifications of each component, namely: power transformers, transmission lines, generators, loads, reactors, are inserted using the raw data collected.

Step 4: The separate models are then interconnected to build one network, each country being represented as a substation in the SAPP megastation (fig.4-11).

Step 5: The thermal ratings of the components and the voltage ratings of the busbars are set in DIgSILENT PowerFactory according to the SAPP requirements specified in sections 3-3 to 3-5.

Step 6: The models are checked for connectivity to make sure that there will be a constant flow of power through each substation. The connectivity of the models are represented in seven different colours, each of which represent a split according to how many nodes are connected to that particular grid and alson non connectivety according to the the legend in fig 4-1.

Station Connectivity	
Split 1	
Split 2	
Split 3	
Split 4	
Split 5	
Split >= 6	
Not connected	

Figure 4- 1: Split sections of station connectivity

Figure 4-2 shows the HV power network of SEB, Swaziland's electric power utility company.

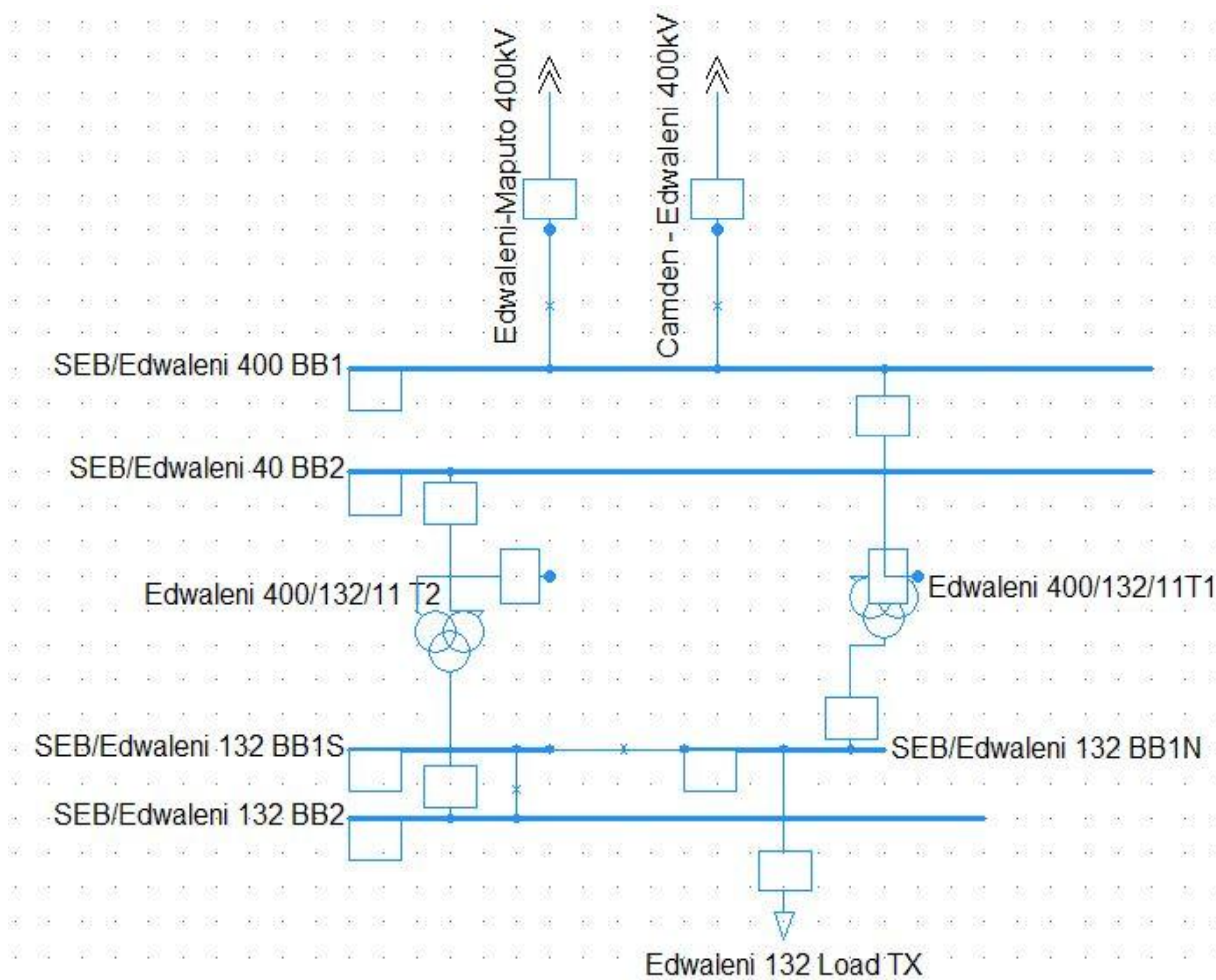


Figure 4- 2: SEB network model

Figure 4-3 shows the HV power network of NAMPOWER, Namibia's electric power utility company.

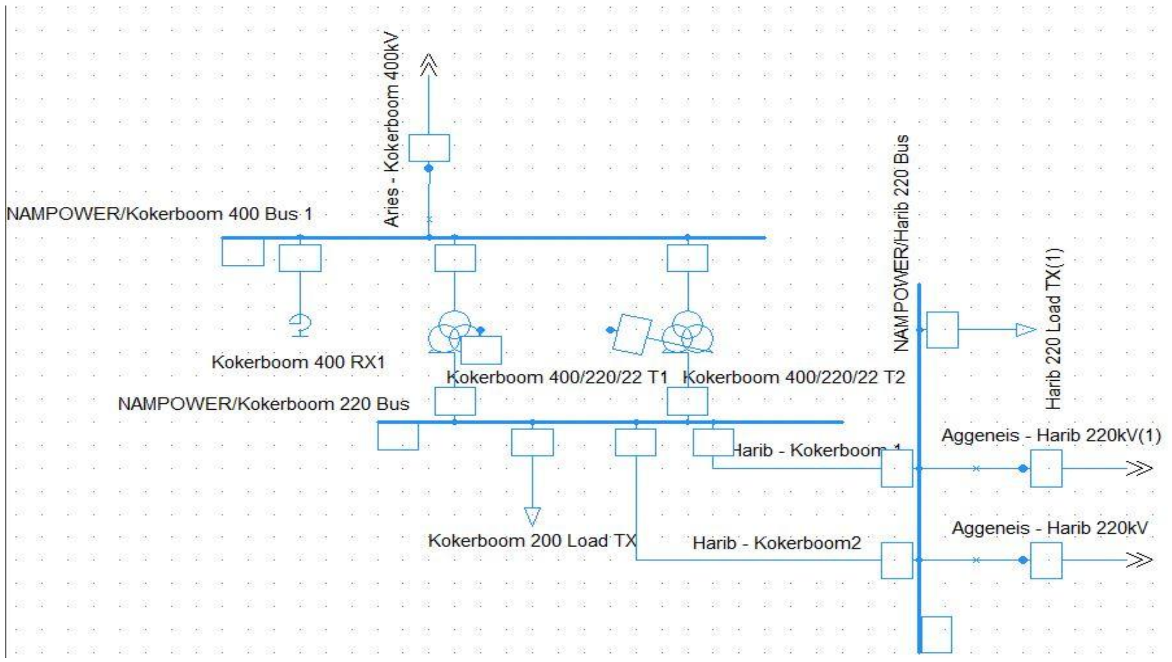


Figure 4- 3: NAMPOWER network model

Figure 4-4 shows the HV power network of EDM, Mozambique's electric power utility company.

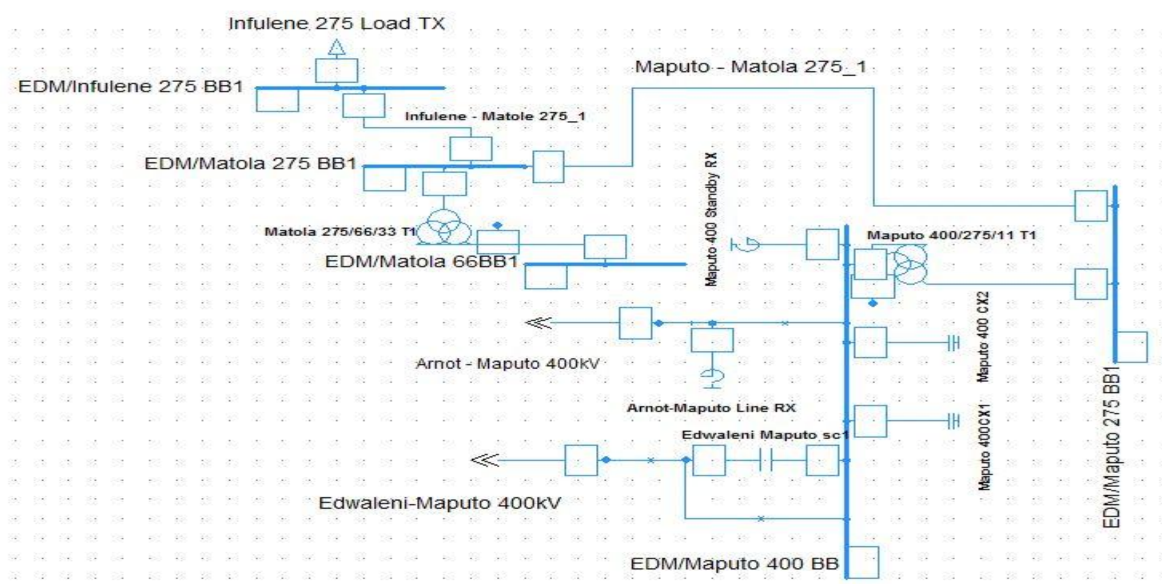


Figure 4- 4: EDM network model

Figure 4-5 shows the HV power network of BPC, Botswana's electric power utility company.

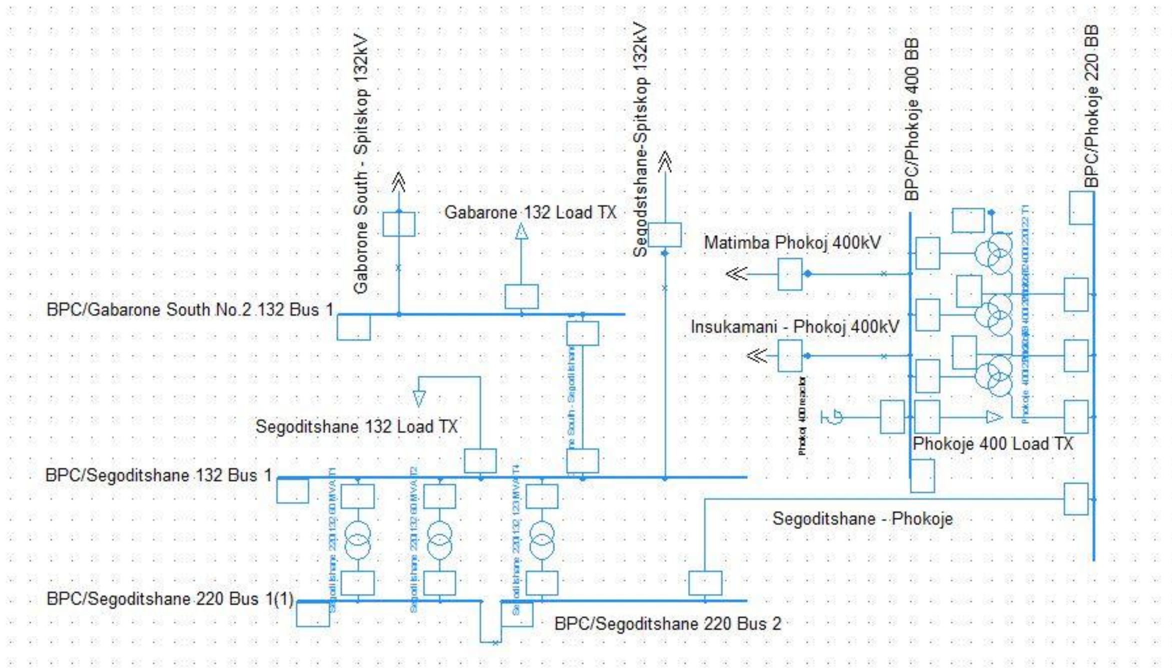


Figure 4- 5: BPC network model

Figure 4-6 shows the HV power network of ZESCO, Zambia's electric power utility company.

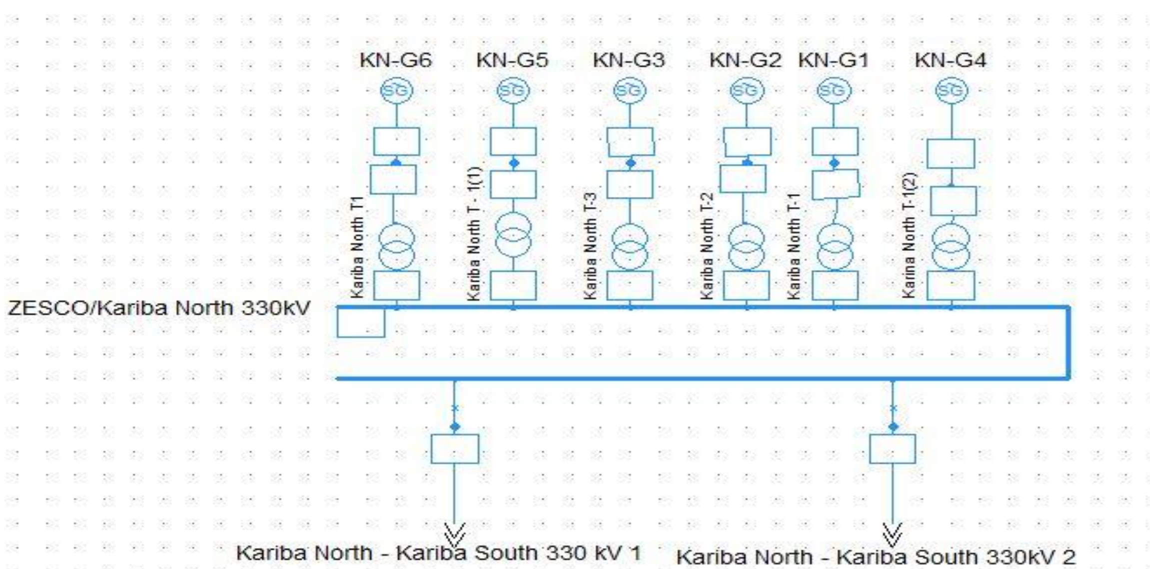


Figure 4- 6: ZESCO network model

Figure 4-7 shows the HV power network of ZESA, Zimbabwe's electric power utility company.

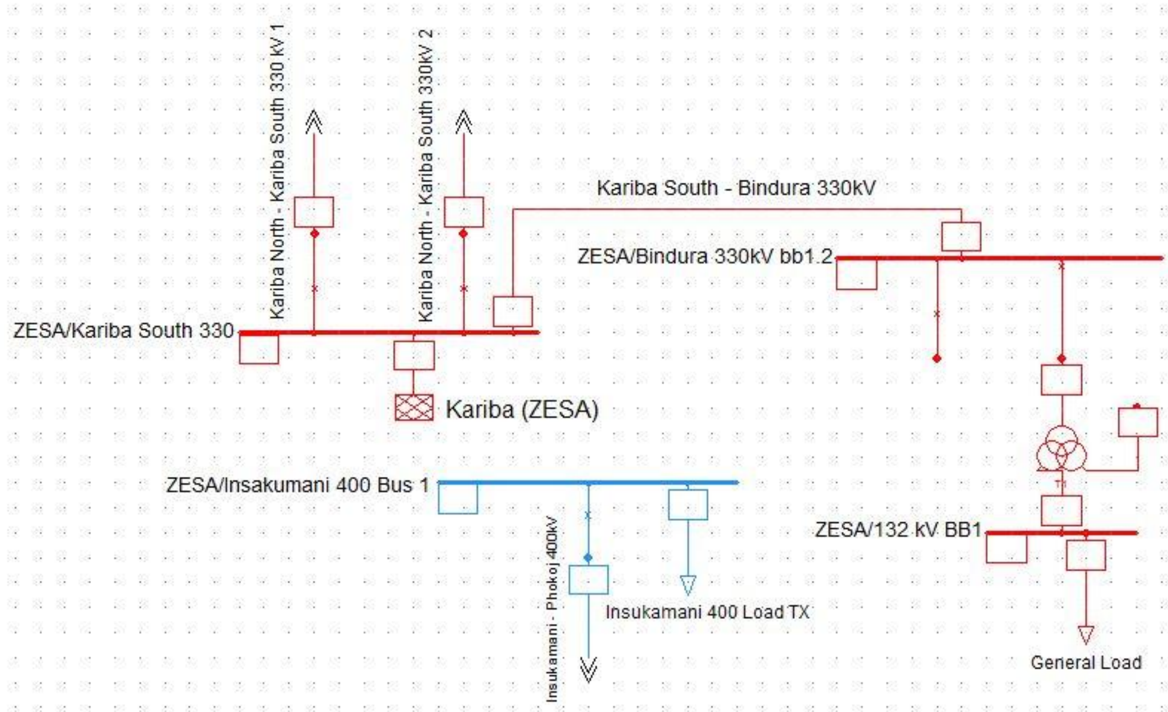


Figure 4- 7: ZESA network model

Figure 4-8 shows South Africa's ESKOM power utility sectioned into three; ESKOM A, ESKOM B and ESKOM C. ESKOM A comprises of the Aries and Aggeneis power station, ESKOM B is comprised of the Spitskop power station and ESKOM C the Matimba, Arnot, Camden and Normandie power stations. The sections were made simply to enhance visibility during presentation taking into consideration the vast size of the ESKOM network and by no means reflect any actual fragmantation or division by ESKOM.

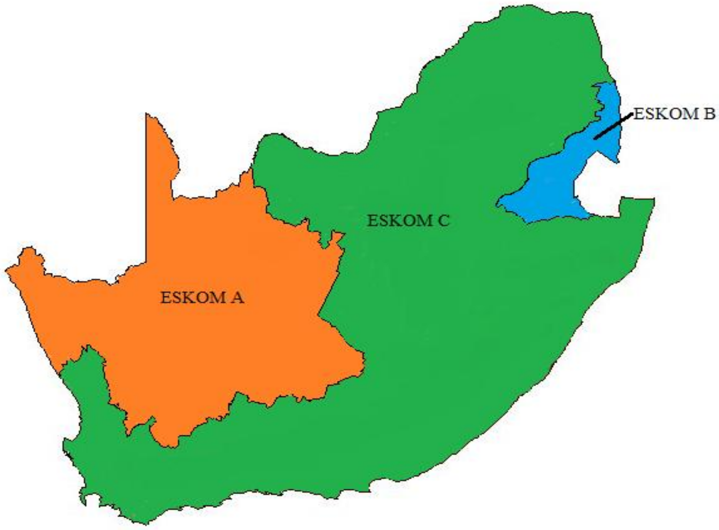


Figure 4- 8: The three sections of the ESKOM utility as referred to in this research

Figure 4-9 shows the HV power network of ESKOM A, South Africa's electric power utility company.

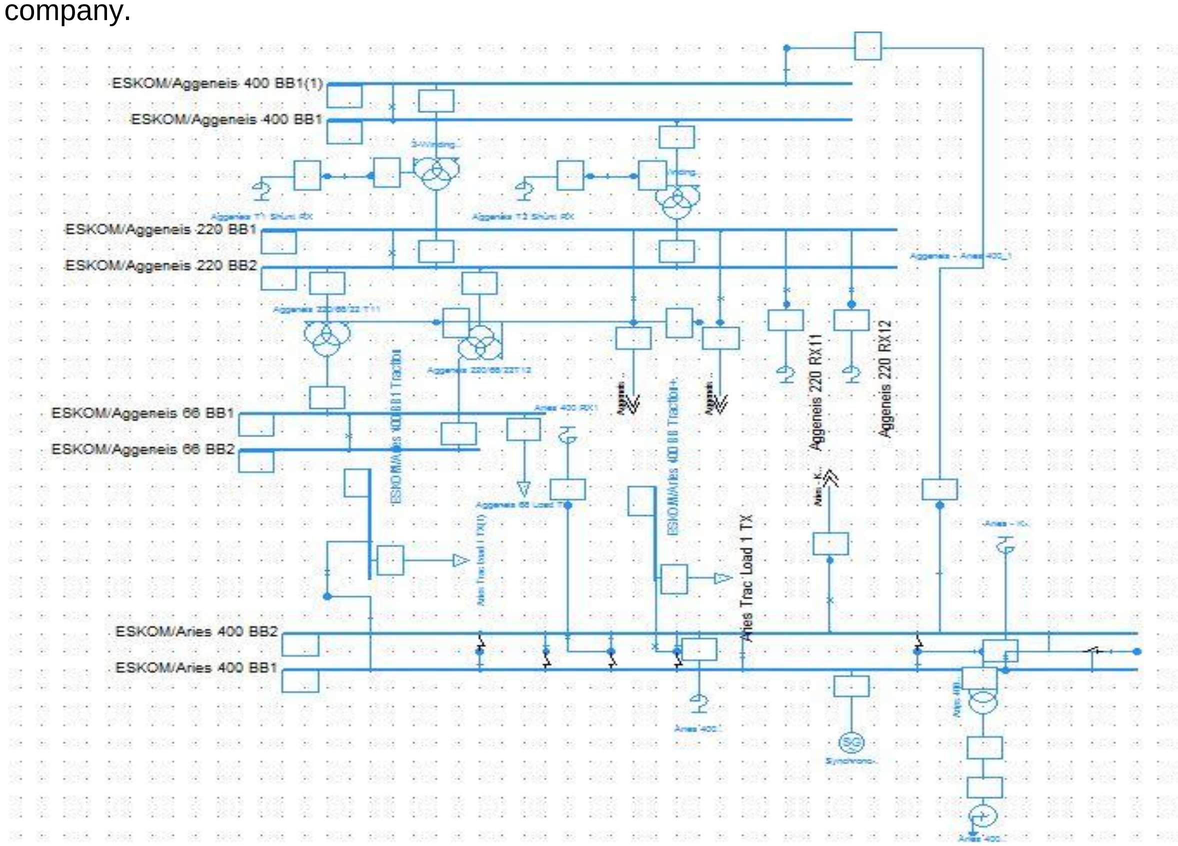


Figure 4- 9: ESKOM A network model

Figure 4-10 shows the HV power network of ESKOM B, South Africa's's electric power utility company.

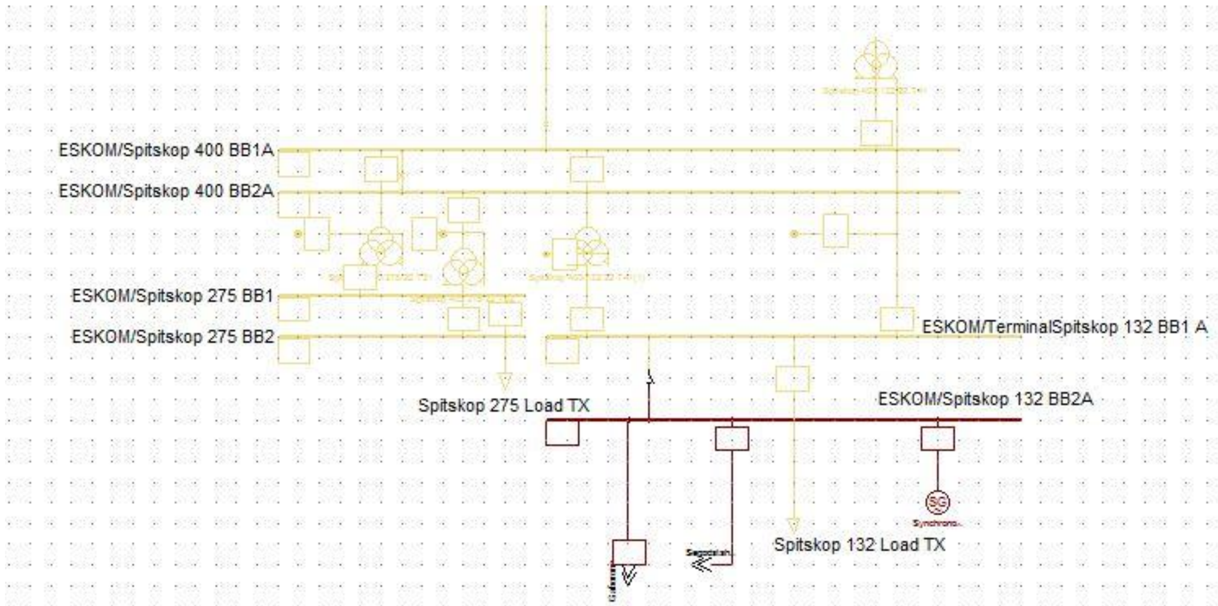


Figure 4- 10: ESKOM B network model

Figure 4-11 shows the HV power network of ESKOM C, South Africa's's electric power utility company.

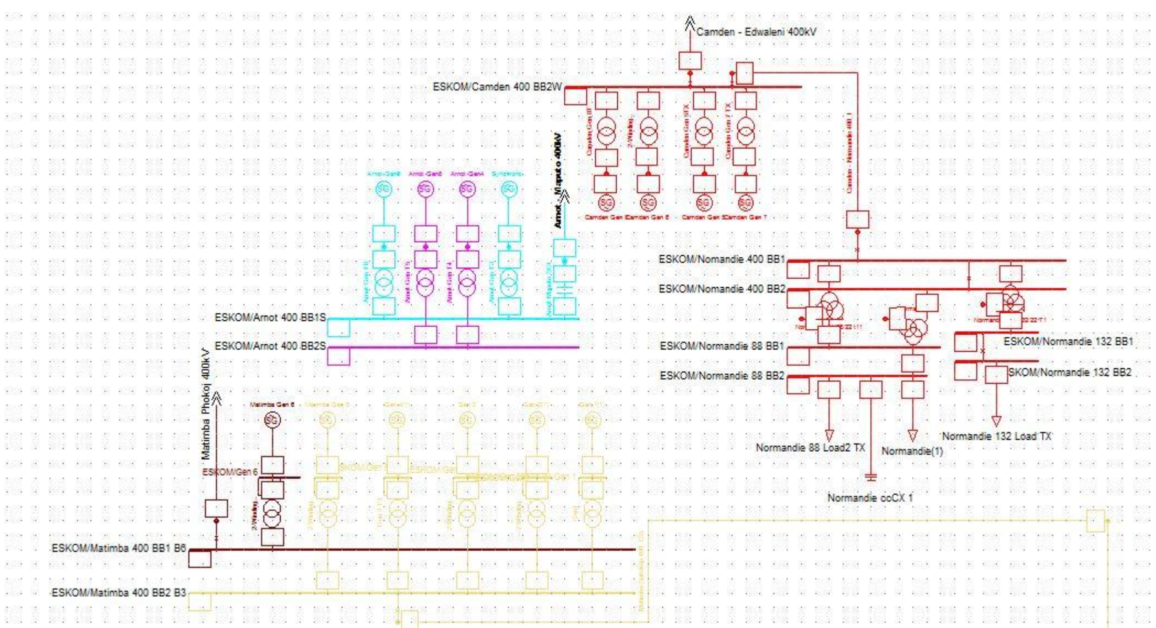


Figure 4- 11: ESKOM C network model

Figure 4-12 displays the SAPP network after interconnecting all the substation in the region to create one mega station. The variation in the colour indicates connectivity in the station.

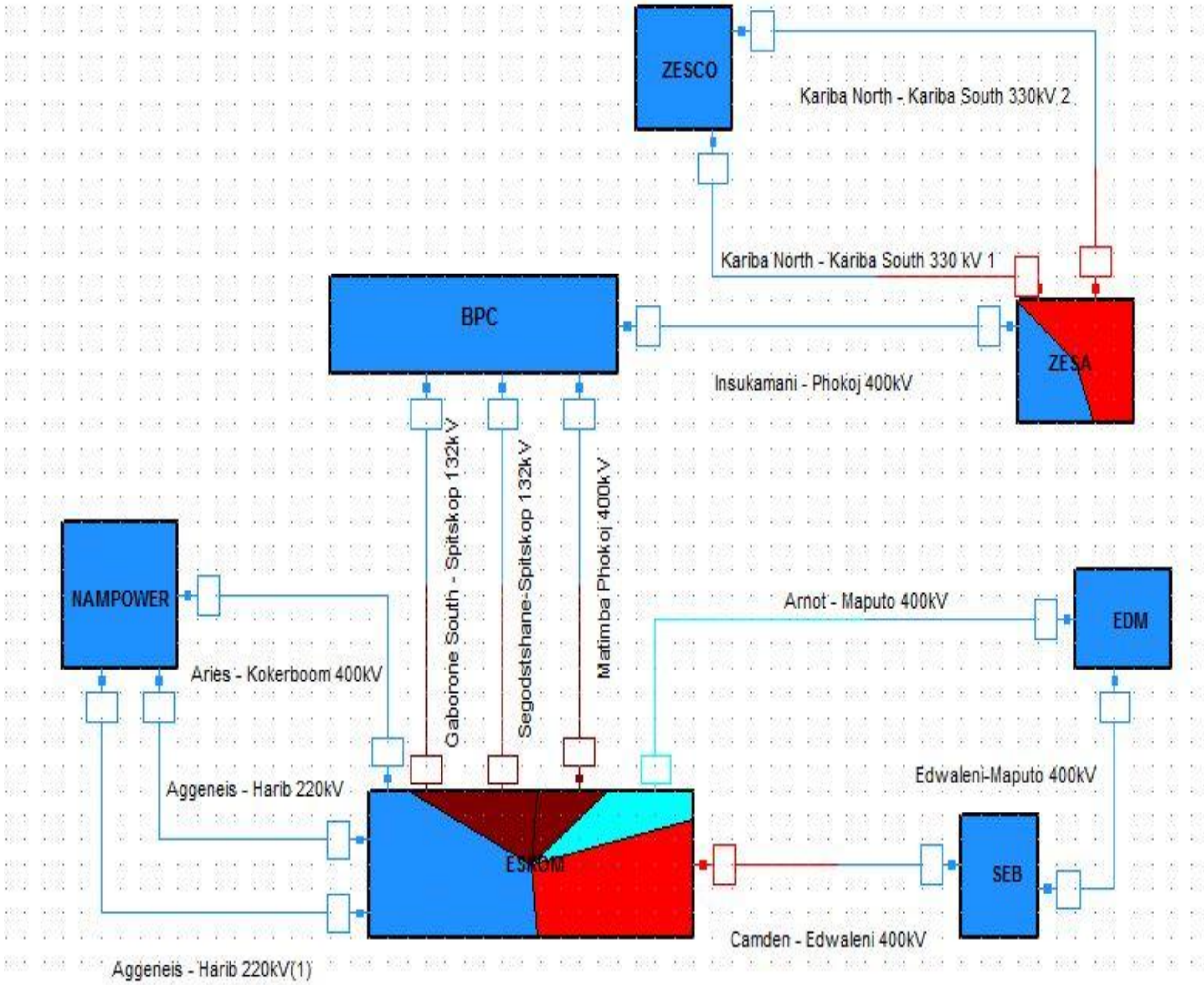


Figure 4- 12: SAPP network model

4.2 Base Case Load Flow Analysis

A load flow analysis was performed on the SAPP network model in order to obtain the base case results comprising of the generator outputs, bus voltage profiles and the line flow profiles. The base case is the network model in its normal steady-state with all elements operating as they are expected to, this stage is carried out to obtain a better understanding of the changes that the network undergoes from the pre-contingency state to post-contingency states. The load flow is carried out in DIgSILENT PowerFactory and the results are colour coded in which the lower voltage limits, the upper voltage limits and the loading range are represented.

Fig.4-13 shows the specification of different ranges of the voltage and thermal limits and confirms that after the load flow was run on the SAPP model (fig.4-14), most of its network lies within the acceptable voltage limits of 1.05 - 0.95pu of the nominal voltage

Voltage limit		
Range	**Colour**	**Status**
>= 1.1		Excessively high voltage
>= 1.05		Upper voltage limit exceeded
		Within secure range
<=0.95		Lower voltage limit exceed
<= 0.9		Excessively low voltage

Thermal loading legend		
Range	**Colour**	**Status**
<= 80%		Normal
>= 80%		Activates warning alarm
>= 100%		Beyond secure thermal loading limit

Figure 4- 13: Upper, lower voltage limits and thermal loading legend

Figure 4-14 displays the SAPP network after a load flow is performed. This is the pre contingency state of the model before any fault or disturbance has been applied to any one of the components.

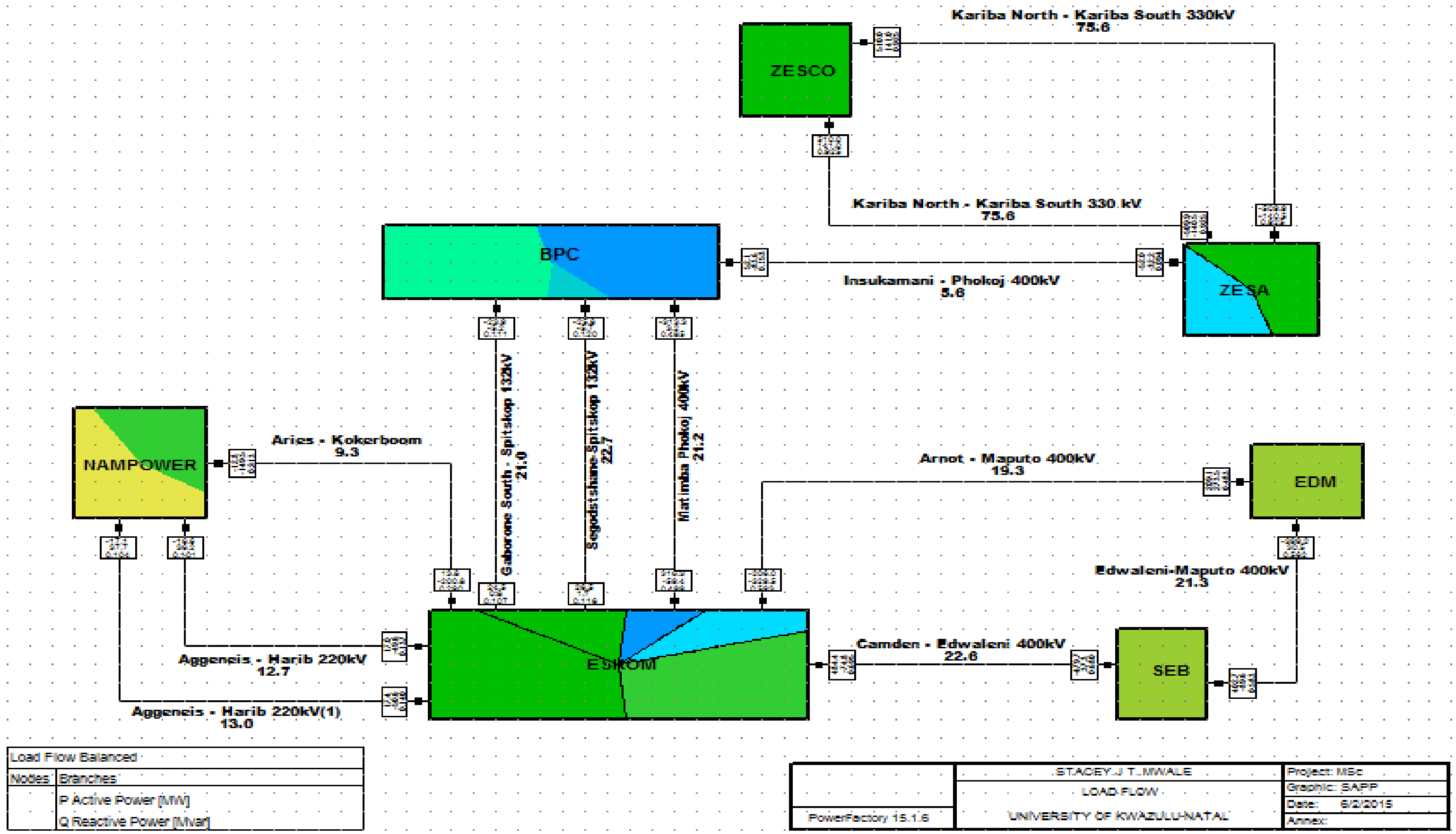


Figure 4- 14: SAPP network model pre-contingency

Figure 4-15 shows the SEB substation post contingency with the network operating within the acceptable security limits.

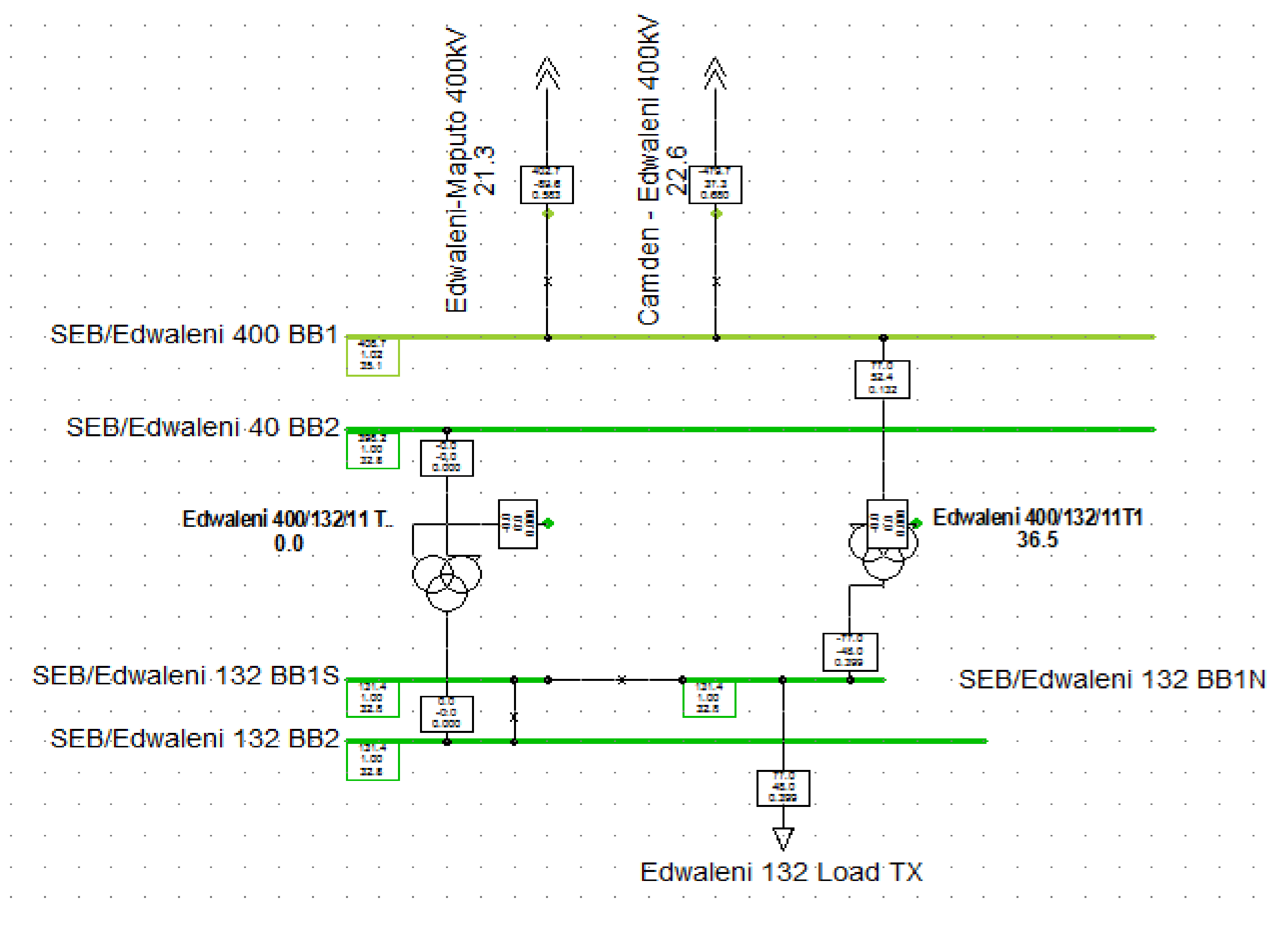


Figure 4- 15: SEB substation pre-contingency

Figure 4-16 shows the EDM network pre contingency. The busbars are all operating within the required secure limit, with the Matola 66BB1 busbar operating close to the minimum required limit, as the color indicates.

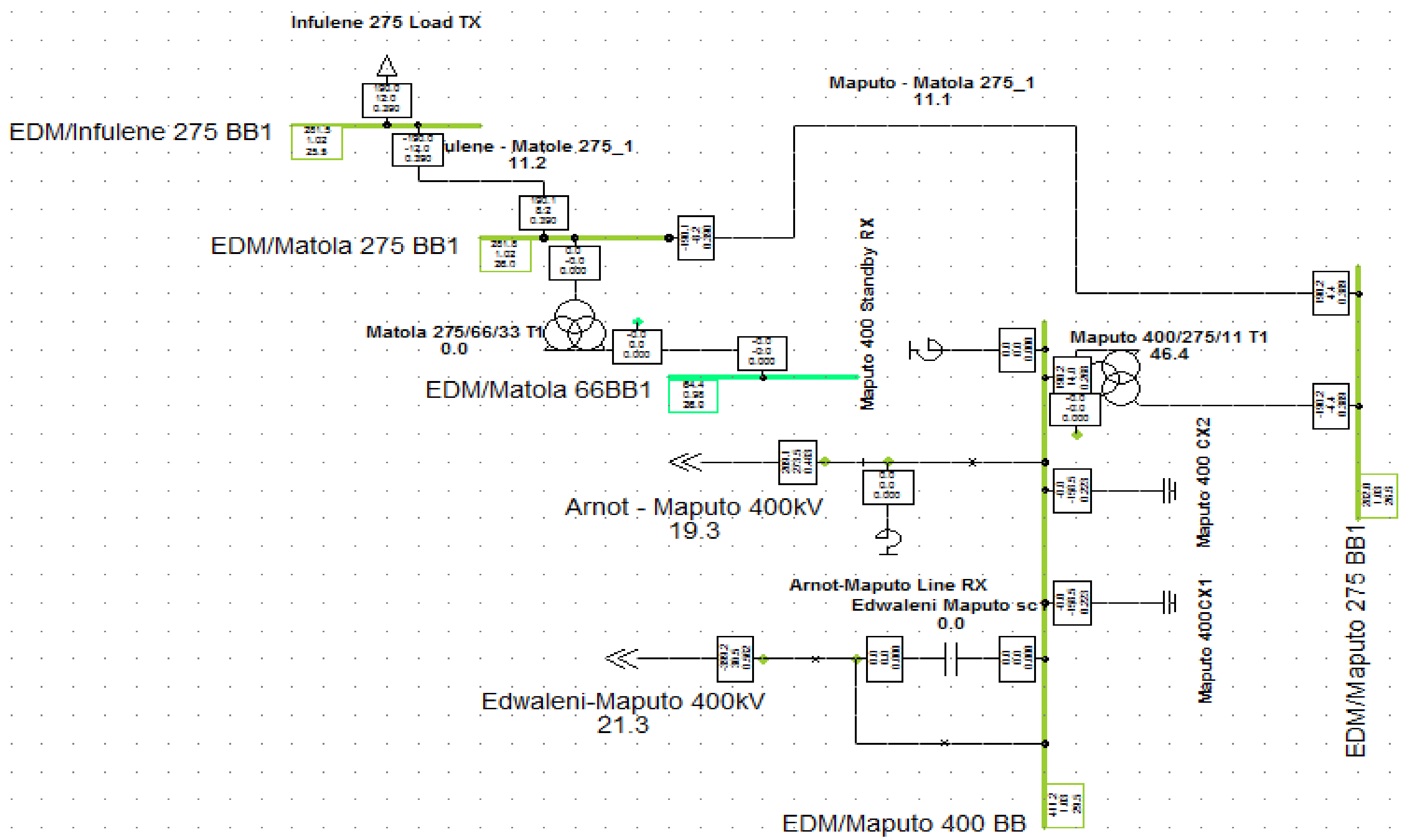


Figure 4- 16: EDM substation pre-contingency

Figure 4-17 shows the BPC network pre contingency. Most of the busbars drop below the required minimu nominal volatge of 0.95 p.u.

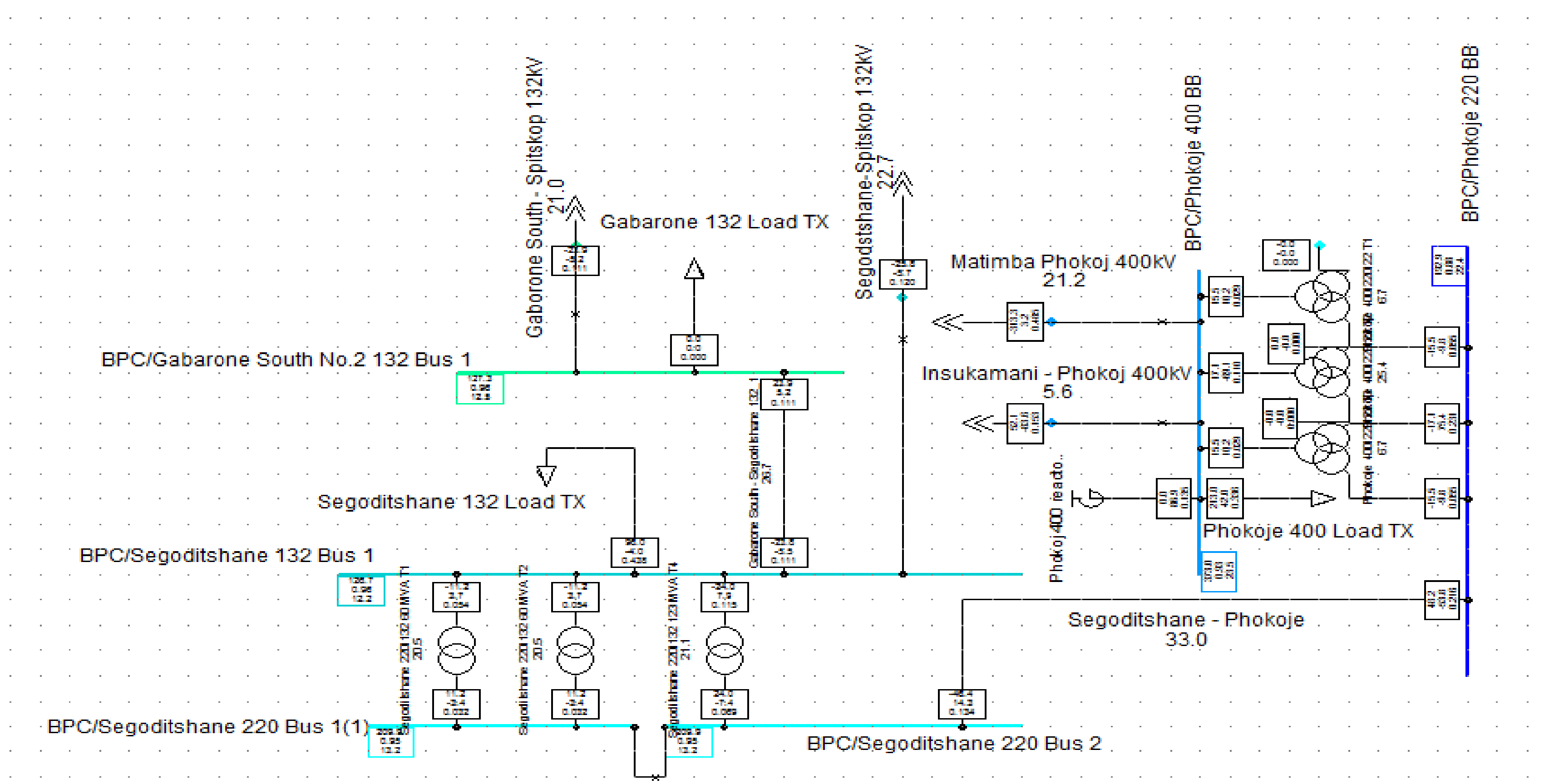


Figure 4- 17: BPC substation pre-contingency

Figure 4-18 shows that the busbar of the ZESCO network pre contingency stays within the acceptable limit. The generators and transformers however, are all loaded over 80%. Even whilst this condition is still acceptable, an alarm has been raised for necessary action to be taken to prevent any damage if the thermal loading limit is exceeded.

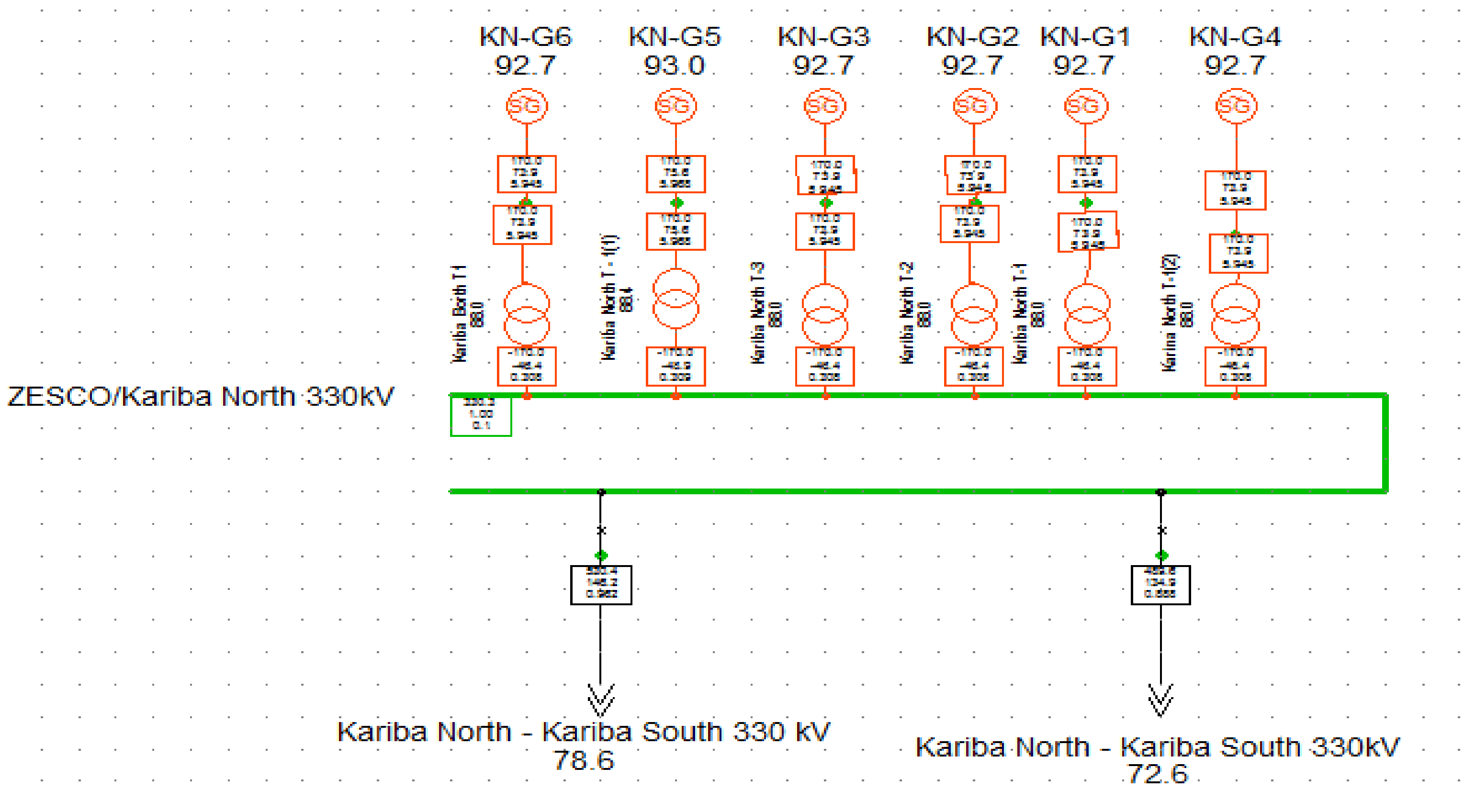


Figure 4- 18: ZESCO substation pre-contingency

Figure 4-19 shows the ZESA network pre contingency with all but one busbar within the acceptable security limits. The Insakumani 400 bus 1 busbar drops below the accptable 0.95 p.u of its nominal volatge after the load flow is performed.

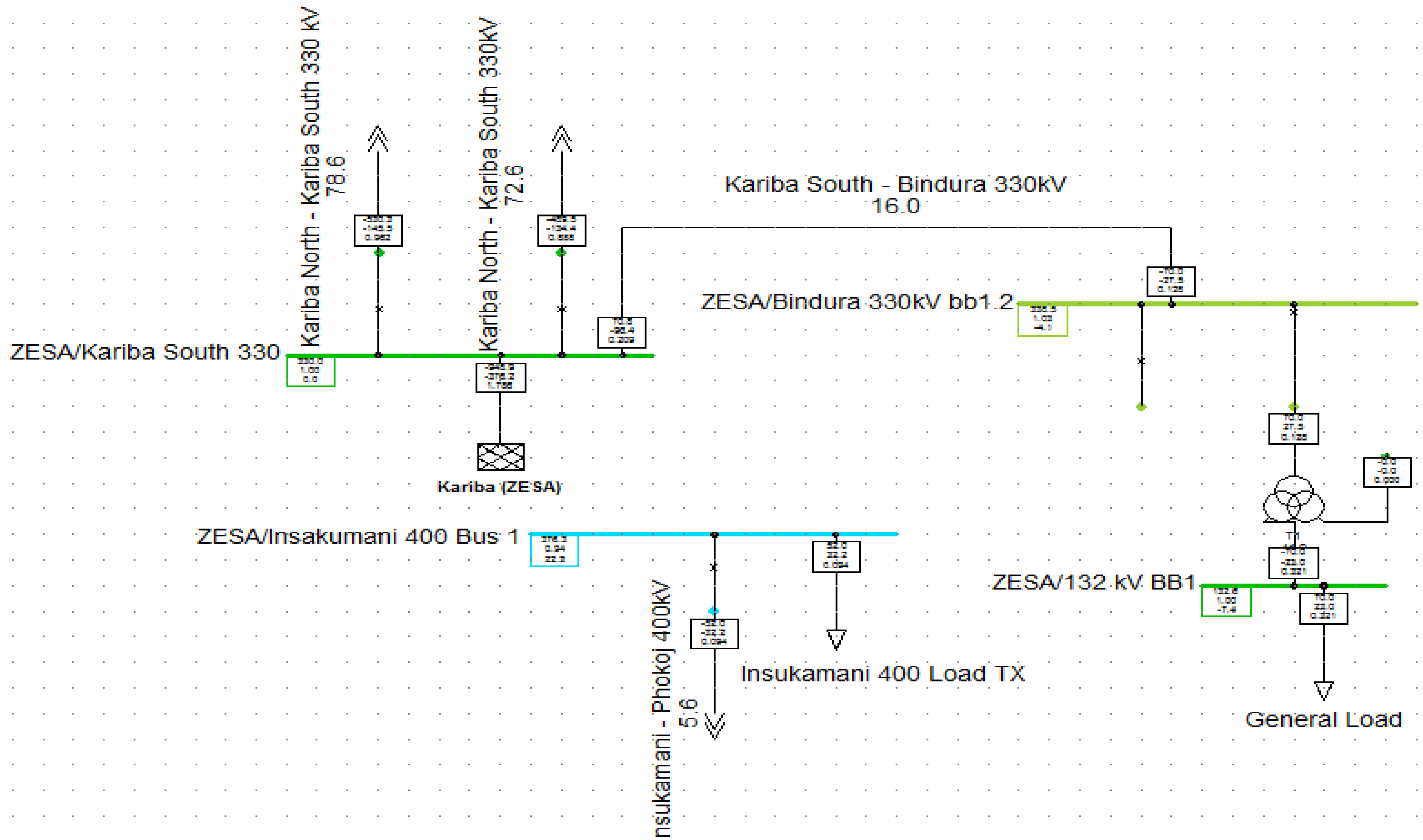


Figure 4- 19: ZESA substation pre-contingency

The ESKOM A network in figure 4-20 shows that all the busbars fall within the required limits pre contingency. One element however, the synchronous machine 2 indicates that it undergoes a thermal loading of over 100%.

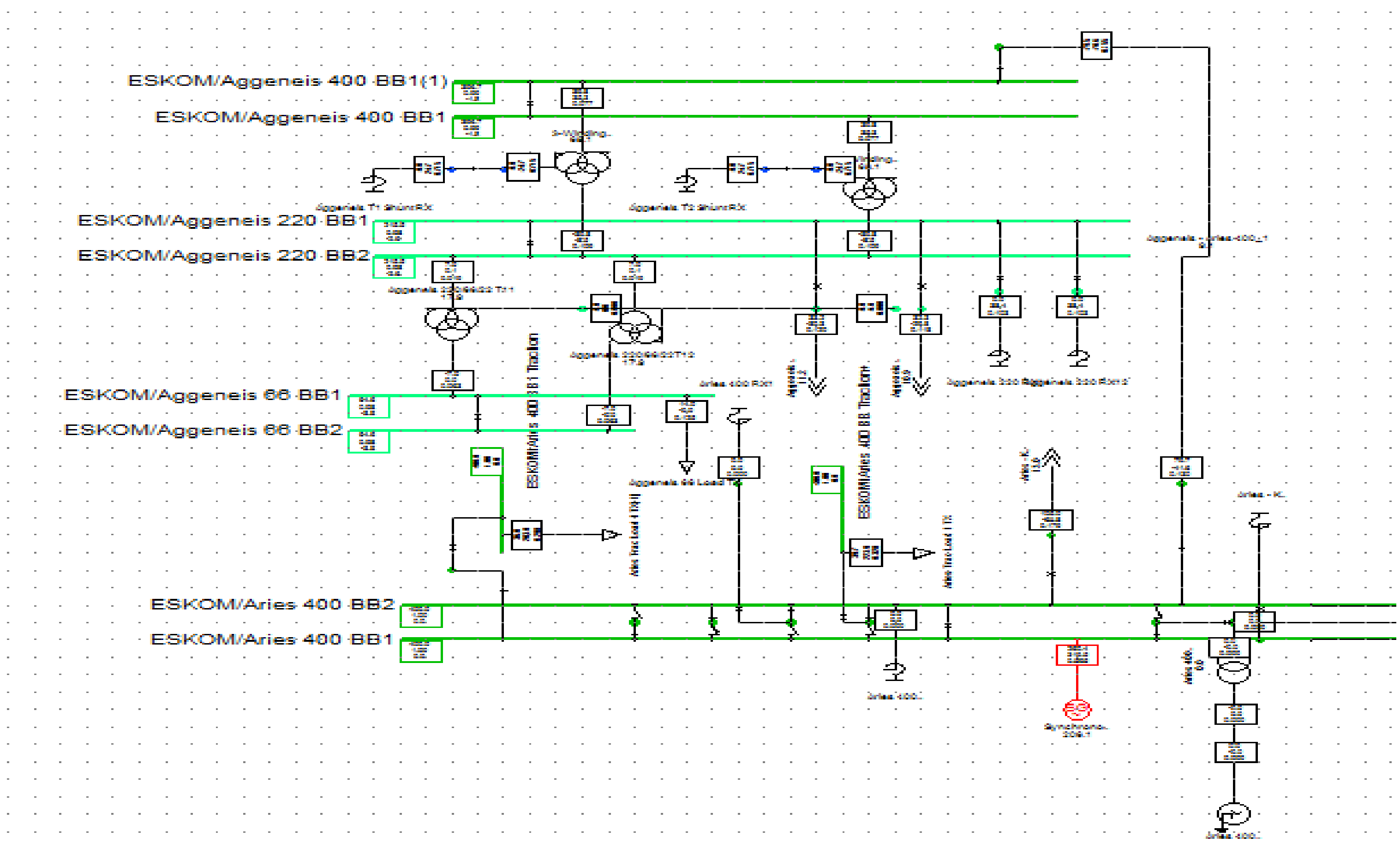


Figure 4- 20: ESKOM A substation pre-contingency

The ESKOM B network in figure 4-21 shows a variation in the busbars, some of which are within the acceptable limits and some that have dropped beyond the minimum secure limit.

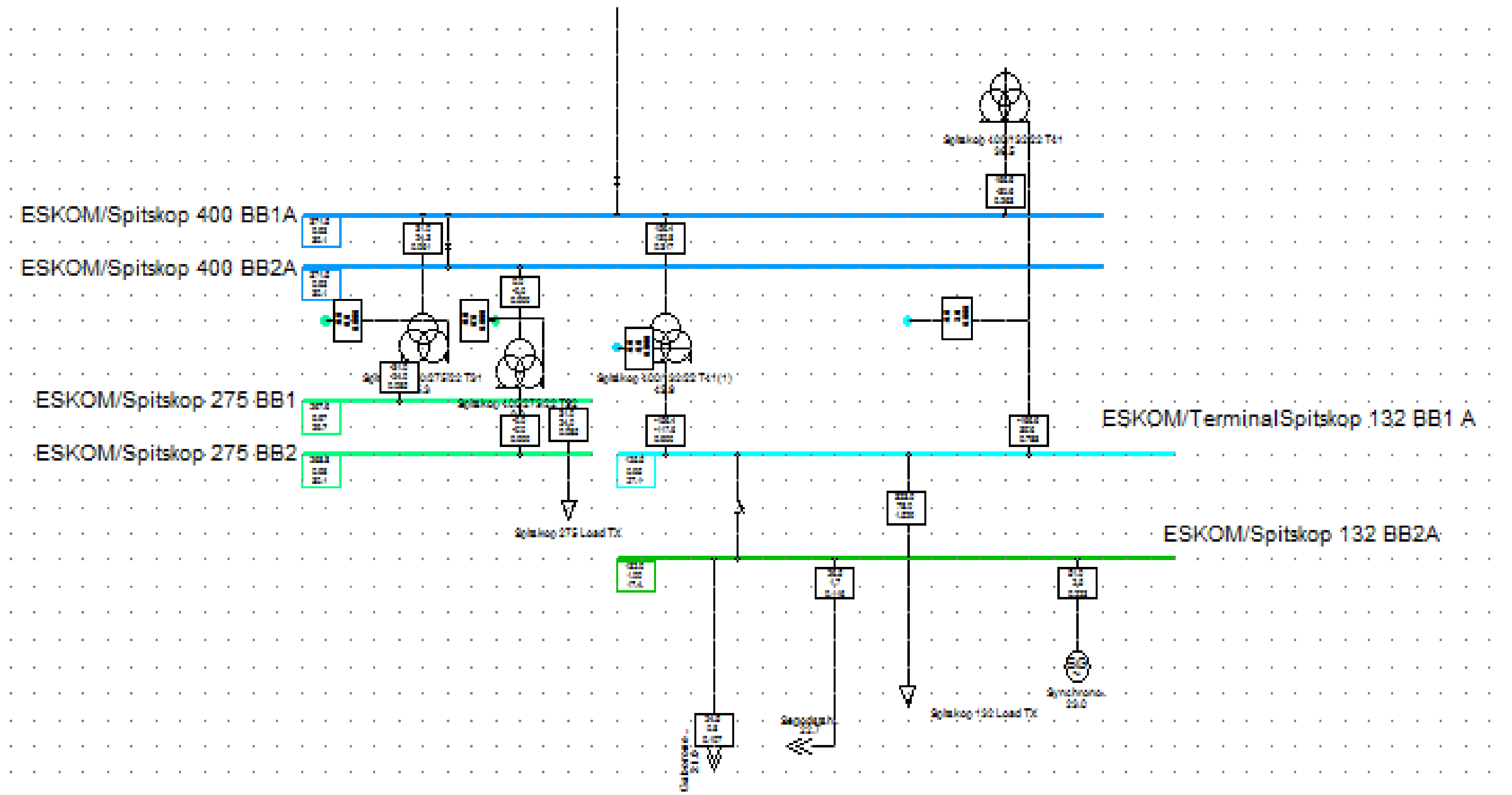


Figure 4- 21: ESKOM B substation pre-contingency

The ESKOM C network in figure 4-22 shows a combination of results including overloaded generators and transformers, busbars with voltages dropped beyond the secure limits, and also some with voltage rises above the acceptable limit.

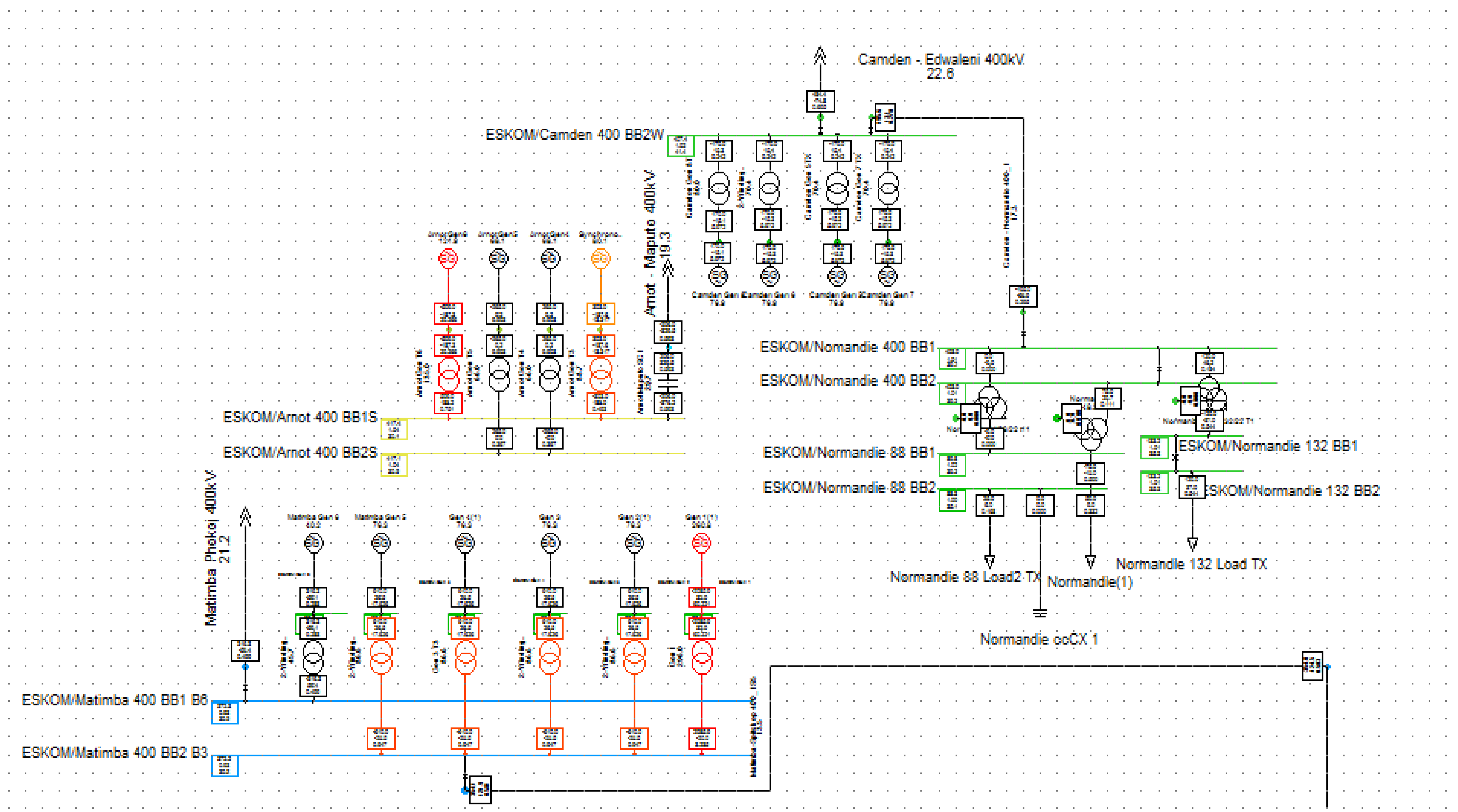


Figure 4- 22: ESKOM C substation pre-contingency

The NAMPOWER network in figure 4-23 shows two busbars that drop beyond the secure limit; the Kokerboom 220 Bus and Kokerboom 400 Bus1. The remaining Harib 220 Bus remains in the acceptable secure range.

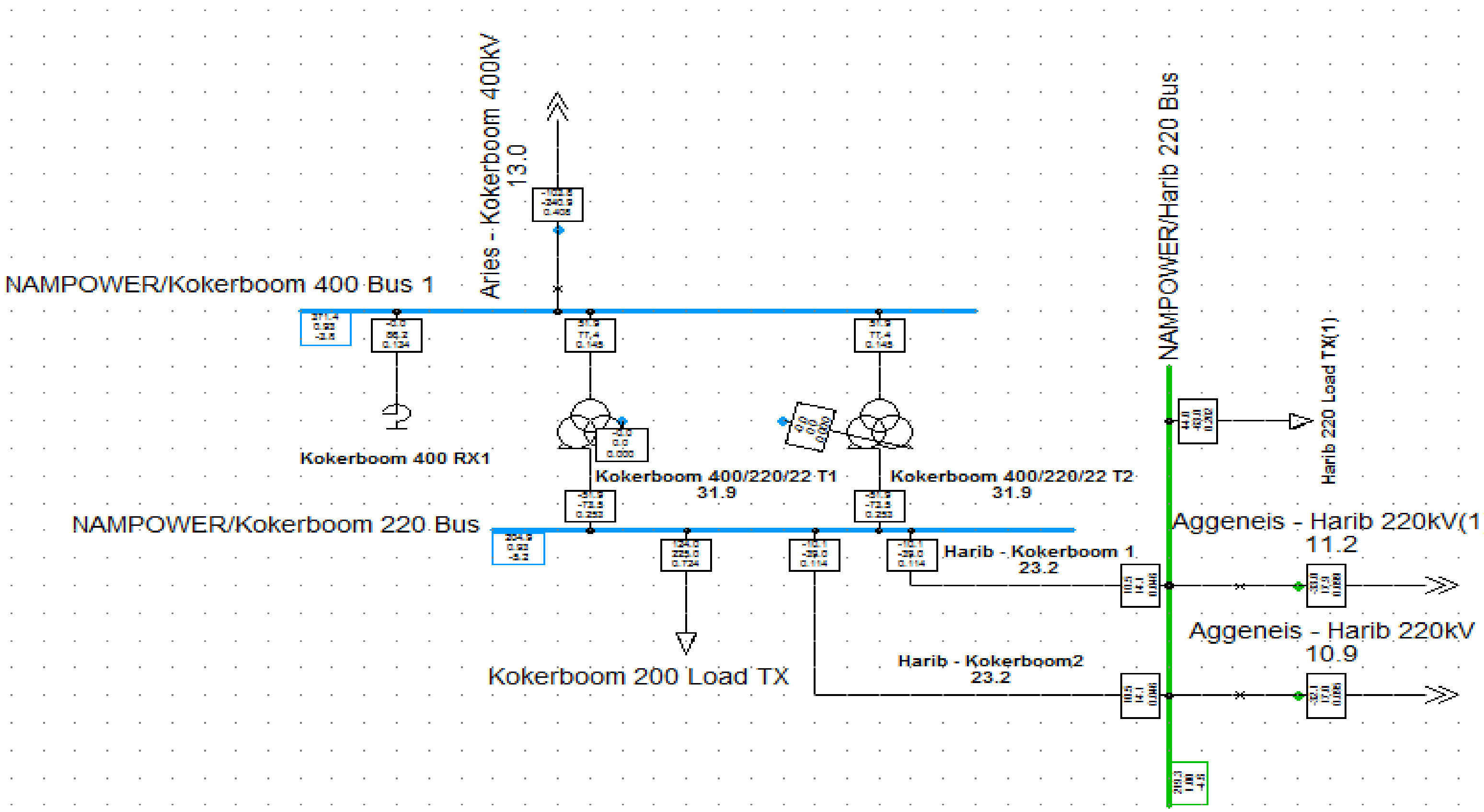


Figure 4- 23: NAMPOWER substation pre-contingency

The bus voltage profiles, generator output profile and the line flow profiles of the SAPP model base case are presented in tables 4-1, 4-2 and 4-3 below respectively . The tables contain several indices such as voltage deviation, power factor, voltage magnitudes, reactive power and line loadings that are vital in the calculation stage and are all derived using the Newton-Raphson solution method in DIgSILENT PowerFactory.

Table 4- 1: SAPP model base case bus voltage profile

Busbar Name	**Utility**	**Nom.L-L Volt. kV**	**u, Magnitude p.u**	**U, Angle deg**	**du, Voltage deviation %**
Segoditshane 220 Bus 1(1)	BPC	220	0.95	13.25	-4.58
Segoditshane 220 Bus 2	BPC	220	0.95	13.25	-4.58
Phokoje 220 BB	BPC	220	0.88	22.41	-12.32
Phokoje 400 BB	BPC	400	0.93	23.53	-6.76
Gabarone South No.2 132 Bus 1	BPC	132	0.96	12.53	-3.59
S. Phikiwe 22 BB	BPC	220	0.88	22.41	-12.31
Segoditshane 132 Bus 1	BPC	132	0.96	12.17	-4.01
Kokerboom 220 Bus	NAMPOWER	220	0.93	-5.20	-6.86
Harib 220 Bus	NAMPOWER	220	1.00	-4.65	-0.30
Kokerboom 400 Bus 1	NAMPOWER	400	0.93	-3.82	-7.16
Edwaleni 132 BB2	SEB	132	1.00	32.80	-0.44
Edwaleni 132 BB1S	SEB	132	1.00	32.80	-0.44
Edwaleni 132 BB1N	SEB	132	1.00	32.80	-0.44
Edwaleni 40 BB2	SEB	400	1.00	32.80	-0.44
Edwaleni 400 BB1	SEB	400	1.02	35.08	2.18
Infulene 275 BB1	EDM	275	1.02	25.50	2.37
Matola 275 BB1	EDM	275	1.02	26.03	2.47
Matola 66BB1	EDM	66	0.98	26.03	-2.41
Maputo 275 BB1	EDM	275	1.03	26.57	2.54
Maputo 400 BB	EDM	400	1.03	29.46	2.79
Kariba North 330kV	ZESCO	330	1.00	0.11	0.08
Kariba South 330	ZESA	330	1.00	0.00	0.00
Insakumani 400 Bus 1	ZESA	400	0.94	22.25	-5.93
Bindura 330kV bb1.2	ZESA	330	1.03	-4.12	2.57
132 kV BB1	ZESA	132	1.00	-7.39	0.45
Aries 400 BB2	ESKOM	400	1.00	0.00	0.00
Aries 400 BB1	ESKOM	400	1.00	0.00	0.00

Busbar Name	Utility	Nom.L-L Volt. kV	u, Magnitude p.u	U, Angle deg	du, Voltage deviation %
Aries 400 BB Traction+	ESKOM	400	1.00	0.00	0.00
Aggeneis 66 BB2	ESKOM	66	0.98	-3.79	-2.05
Aggeneis 66 BB1	ESKOM	66	0.98	-3.79	-2.05
Aggeneis 220 BB2	ESKOM	220	0.98	-2.64	-2.03
Aggeneis 220 BB1	ESKOM	220	0.98	-2.64	-2.03
Matimba 400 BB1 B6	ESKOM	400	0.93	29.95	-6.92
Matimba 400 BB2 B3	ESKOM	400	0.93	30.33	-6.94
Spitskop 400 BB2A	ESKOM	400	0.93	30.06	-7.12
Spitskop 400 BB1A	ESKOM	400	0.93	30.06	-7.12
Spitskop 275 BB1	ESKOM	275	0.97	29.73	-2.68
Spitskop 275 BB2	ESKOM	275	0.98	30.06	-2.24
TerminalSpitskop 132 BB1 A	ESKOM	132	0.95	27.09	-4.92
Spitskop 132 BB2A	ESKOM	132	1.00	17.44	0.00
Aggeneis 400 BB1(1)	ESKOM	400	0.99	-1.76	-0.82
Aggeneis 400 BB1	ESKOM	400	0.99	-1.76	-0.82
Gen 5	ESKOM	20	1.00	0.00	0.00
Gen 4	ESKOM	20	1.00	0.43	0.00
Gen3	ESKOM	20	1.00	0.43	0.00
Gen 2	ESKOM	20	1.00	0.43	0.00
Gen 1	ESKOM	20	1.00	0.43	0.00
Gen 6	ESKOM	20	1.00	0.00	0.00
Arnot 400 BB1S	ESKOM	400	1.04	30.09	4.35
Arnot 400 BB2S	ESKOM	400	1.04	30.05	4.29
Camden 400 BB2W	ESKOM	400	1.02	41.39	1.86
Normandie 88 BB2	ESKOM	88	1.00	35.06	0.29
Normandie 88 BB1	ESKOM	88	1.02	39.21	2.03
Nomandie 400 BB2	ESKOM	400	1.01	39.21	0.76
Nomandie 400 BB1	ESKOM	400	1.01	39.21	0.76
Normandie 132 BB1	ESKOM	132	1.01	35.29	0.92
Normandie 132 BB2	ESKOM	132	1.01	35.29	0.92
Aries 400 BB1 Traction	ESKOM	400	1.00	0.00	0.00

Table 4- 2: SAPP model base case generator output profile

Name	Short Form	Active Power MW	Reactive Power Mvar	Apparent Power MVA	Power Factor	Loading %
Arnot Gen4	G.1	265.0	0.2	265.0	1.0	68.1
Arnot Gen5	G.2	-265.00	0.22	265.00	-1.00	68.12
Arnot Gen6	G.3	-508.95	-187.33	542.33	-0.94	121.87
Synchronous Machine	G.4	303.00	-187.59	356.37	0.85	80.08
Synchronous Machine(2)	G.5	51.00	2.51	51.06	1.00	23.00
Camden Gen 5	G.6	170.00	-15.26	170.68	1.00	76.88
Camden Gen 6	G.7	170.00	-15.26	170.68	1.00	76.88
Camden Gen 7	G.8	170.00	-15.26	170.68	1.00	76.88
Camden Gen 8	G.9	170.00	-15.13	170.67	1.00	76.88
Gen 1(1)	G.10	610.00	26.51	610.58	1.00	76.32
Gen 2(1)	G.11	610.00	26.51	610.58	1.00	76.32
Gen 3	G.12	610.00	26.51	610.58	1.00	76.32
Gen 4(1)	G.13	610.00	26.51	610.58	1.00	76.32
KN-G1	G.14	170.00	73.89	185.36	0.92	92.68
KN-G2	G.15	170.00	73.89	185.36	0.92	92.68
KN-G3	G.16	170.00	73.89	185.36	0.92	92.68
KN-G4	G.17	170.00	73.89	185.36	0.92	92.68
KN-G6	G.18	170.00	73.89	185.36	0.92	92.68
Matimba Gen 5	G.19	-2085.87	31.99	2086.12	-1.00	260.76
Matimba Gen 6	G.20	316.29	-59.10	321.76	0.98	40.22
Synchronous Machine(4)	G.21	260.42	319.46	412.15	0.63	206.08
KN-G5	G.22	170.00	75.63	186.07	0.91	93.03

Table 4- 3: SAPP model base case transmission line profile

Name	Short form	From Terminal i Busbar	To Terminal j Busbar	Voltage Magnitude Terminal i in p.u.	Voltage Magnitude Terminal j in p.u.	Line Loading %	Active power Terminal i in MW
Aggeneis - Aries 400_1	L.1	Aggeneis 400 BB1(1)	Aries 400 BB2	0.992	1.000	9.084	79.54538
Aggeneis - Harib 220kV	L.2	Harib 220 Bus	Aggeneis 220 BB1	0.997	0.980	10.909	65.02118
Aggeneis - Harib 220kV(1)	L.3	Harib 220 Bus	Aggeneis 220 BB1	0.997	0.980	11.151	65.02118
Aries - Kokerboom 400kV	L.4	Kokerboom 400 Bus 1	Aries 400 BB2	0.928	1.000	13.006	103.8494
Arnot - Maputo 400kV	L.5	Terminal(36)	Maputo 400 BB	0.945	1.028	19.332	205.9504
Camden - Edwaleni 400kV	L.6	Camden 400 BB2W	Edwaleni 400 BB1	1.019	1.022	22.631	680
Camden - Normandie 400_1	L.7	Nomandie 400 BB1	Camden 400 BB2W	1.008	1.019	17.333	195
Edwaleni-Maputo 400kV	L.8	Edwaleni 400 BB1	Maputo 400 BB	1.022	1.028	21.325	479.7498
Gabarone South - Segoditshane 132_1	L.9	Segoditshane 132 Bus 1	Gabarone South No.2 132 Bus 1	0.960	0.964	26.723	96
Gaborone South - Spitskop 132kV	L.10	Gabarone South No.2 132 Bus 1	Spitskop 132 BB2A	0.964	1.000	20.973	23.8921
Harib - Kokerboom 1	L.11	Kokerboom 220 Bus	Harib 220 Bus	0.931	0.997	23.179	124
Harib - Kokerboom2	L.12	Kokerboom 220 Bus	Harib 220 Bus	0.931	0.997	23.179	124
Infulene - Matole 275_1	L.13	Infulene 275 BB1	Matola 275 BB1	1.024	1.025	11.155	190
Insukamani-Phokoj 400kV	L.14	Phokoje 400 BB	Insakumani 400 Bus 1	0.932	0.941	5.580	313.2951
Kariba North-Kariba South 330 kV	L.15	Kariba North 330kV	Kariba South 330	1.001	1.000	78.598	1020
Kariba North-Kariba South 330kV	L.16	Kariba North 330kV	Kariba South 330	1.001	1.000	72.553	1020
Kariba South-Bindura 330kV	L.17	Kariba South 330	Bindura 330kV bb1.2	1.000	1.026	16.021	1019.755
Maputo - Matola 275_1	L.18	Matola 275 BB1	Maputo 275 BB1	1.025	1.025	11.138	190.0823
Matimba Phokoj 400kV	L.19	Phokoje 400 BB	Matimba 400 BB1 B6	0.932	0.931	21.217	313.2951
Matimba-Spitskop 400_1S5	L.20	Matimba 400 BB2 B3	Spitskop 400 BB1A	0.931	0.929	13.500	2440
Phokoje-S Phikwe 220_2	L.21	Phokoje 220 BB	S. Phikiwe 22 BB	0.877	0.877	0.437	48.17146
Phokoje-S. Phikwe 220_1	L.22	Phokoje 220 BB	S. Phikiwe 22 BB	0.877	0.877	0.437	48.17146
Segoditshane - Phokoje	L.23	Segoditshane 220 Bus 2	Phokoje 220 BB	0.954	0.877	32.958	46.40919
Segodstshane-Spitskop 132kV	L.24	Segoditshane 132 Bus 1	Spitskop 132 BB2A	0.960	1.000	22.732	96

4.3 Contingency Ranking

4.3.1 Line Outage Contingency Ranking

The contingency ranking was computed using the MATLAB coding (Appendix 3 and Appendix 4) which depicts several line and busbar violations as formulated in Equation (2-4 – 2-7). Contingency ranking algorithms can be classified into two groups; performance index and screening method. The performance index method uses scalar performance index to quantify the severity of contingency cases. The screening method is based on determining the margin between the voltage collapse point and the current operating in what is referred to as the voltage stability criteria [37], [39], [38]. The algorithm adapted in this research is the performance index method and the procedure used for the contingency ranking is as follows:

Step 1: Load flow is carried out in the networks pre-contingency state using the Newton Raphson iterative method under DIgSILENT PowerFactory.

Step 2: Generate a fault in any one of the transmission lines (L.1) in the network resulting in the outage of that line and run a load flow analysis.

Step 3: Using the generator, busbar and line profiles obtained from the post contingency analysis, apply necessary values to the MATLAB coding (Appendix 4) in order to get the PI_P and PI_V for the first line contingency C.L.1.

Step 4: Generate another line contingency (C.L.2) in a different transmission line and run a load flow analysis.

Step 5: Repeat steps 2 to 4 to acquire the PI_P and PI_V of the all the line contingencies in the network.

Step 6: Arrange the several indices to identify which contingencies are more critical.

The above steps are repeated in order to acquire the performance indices for the outage of the several generators in the network using the MATLAB coding in Appendix 5 and are labelled according to which generator is faulted example C.G.1 to indicate generator G1 has a fault.

The results obtained from the line contingency ranking are shown in and fig.4-24 with C.L.12 being the most critical and C.L.1 being the least severe. Picking only the six highest ranked performance indices (fig.4-25), a contingency analysis will then be run for each contingency case using DigSilent PowerFactory.

Table 4- 4: Line outage performance index

Contingency	PI_V	PI_p	Total
C.L.1	0.0215	0.1063	0.1278
C.L.2	0.173	0.0839	0.2569
C.L.3	0.1733	0.084	0.2573
C.L.4	0.1642	0.0812	0.2454
C.L.5	0.1368	0.1116	0.2484
C.L.6	0.2007	0.0512	0.2519
C.L.7	0.1406	0.1303	0.2709
C.L.8	0.1846	0.0466	0.2312
C.L.9	0.1235	0.0836	0.2071
C.L.10	0.2154	0.0836	0.299
C.L.11	0.211	0.0837	0.2947
C.L.12	0.2227	0.0837	0.3064
C.L.13	0.1718	0.0949	0.2667
C.L.14	0.1586	0.0766	0.2352
C.L.15	0.1718	0.0827	0.2545
C.L.16	0.1718	0.0827	0.2545
C.L.17	0.1795	0.0791	0.2586
C.L.18	0.1694	0.0948	0.2642
C.L.19	0.1675	0.0897	0.2572
C.L.20	0.1744	0.0826	0.257
C.L.21	0.1718	0.0827	0.2545
C.L.22	0.1718	0.0827	0.2545
C.L.23	0.1432	0.0753	0.2185
C.L.24	0.1384	0.0837	0.2221

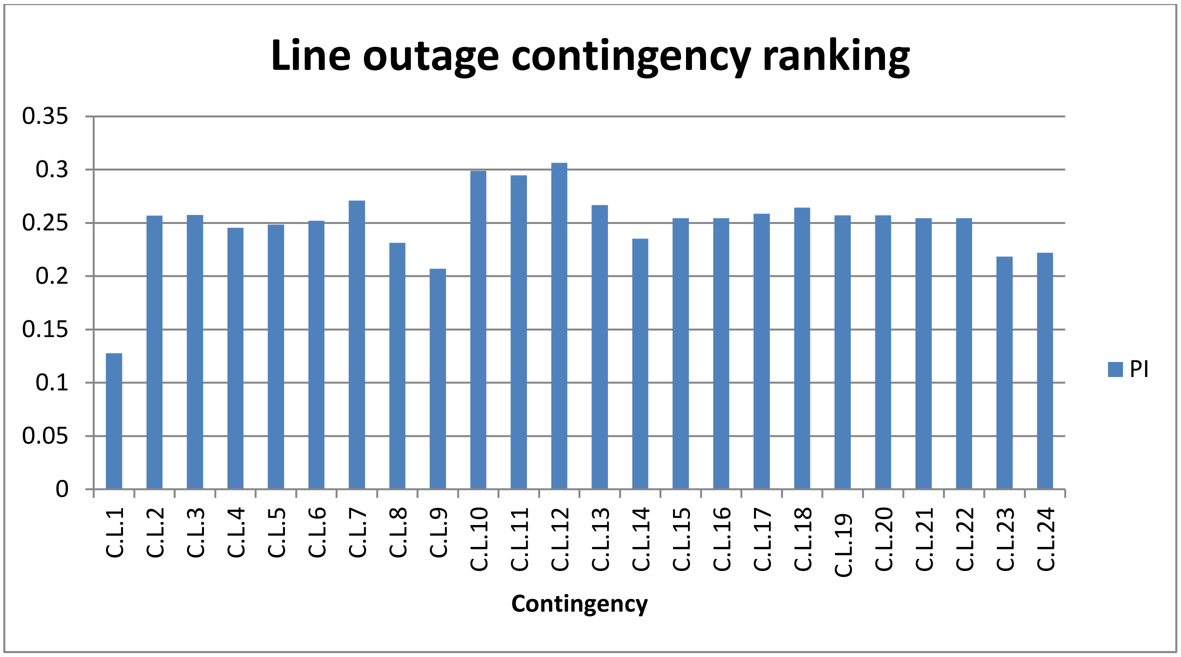


Figure 4- 24: Line outage contingency ranking

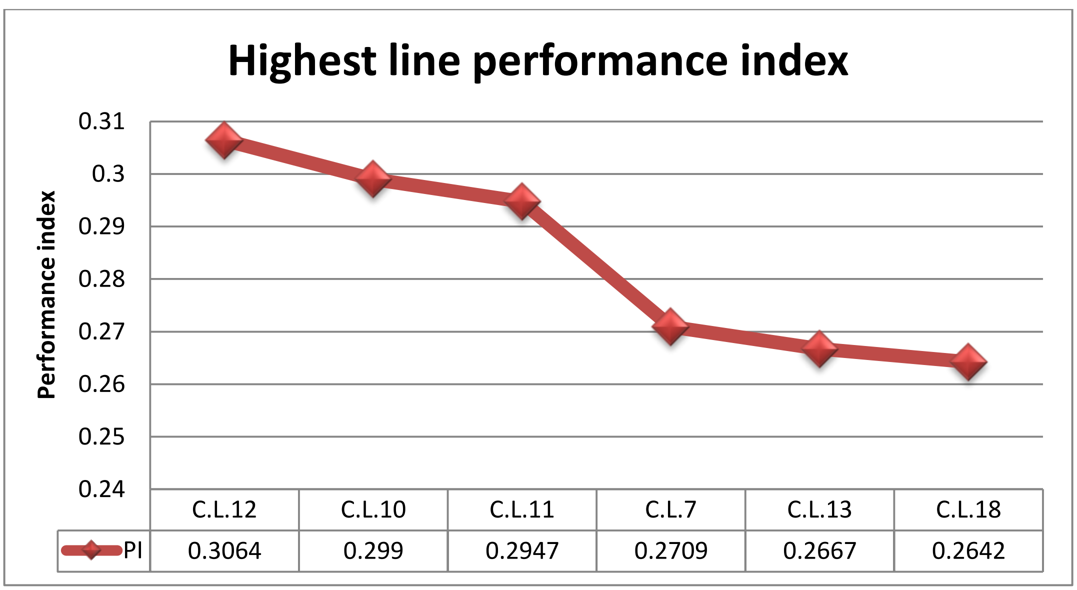


Figure 4- 25: Highest rated line contingencies

Even whilst the results obtained from the performance index does not show us exactly which elements have violated the thermal loadings and voltage limitations post contingency, it does however, allow pre-eminence be given to more severe cases which can save a lot of time for engineers in the planning and controlling stage of any network.

4.3.2 Generator Outage Contingency Ranking

From the depicted results in fig.4-26, we are able to detect that the generator outage that will cause the most violation is those associated with G.5, and the lowest being G.4. The six highest generator outage contingencies are presented in fig.4-27.

Table 4- 5: Generator outage performance index

Contingency	**PIv**	**PIp**	**PIq**
C.G.1	0.5	2.6883	3.1883
C.G.2	0.5	2.6883	3.1883
C.G.3	0.5	3.6726	4.1726
C.G.4	0.5	2.6358	3.1235
C.G.5	0.2813	4.1647	4.4459
C.G.6	0.5	2.9591	3.4591
C.G.7	0.5	2.9591	3.4591
C.G.8	0.5	2.9591	3.4591
C.G.9	0.5	2.9594	3.4594
C.G.10	0.5	2.6936	3.1936
C.G.11	0.5	2.6936	3.1936
C.G.12	0.5	2.6936	3.1936
C.G.13	0.5	2.6936	3.1936
C.G.14	0.5	2.6349	3.1349
C.G.15	0.5	2.6349	3.1349
C.G.16	0.5	2.6349	3.1349
C.G.17	0.5	2.6349	3.1349
C.G.18	0.5	2.6349	3.1349
C.G.19	0.5	2.6936	3.1936
C.G.20	0.5	2.6358	3.1235
C.G.21	0.2813	2.8887	3.1699
C.G.22	0.5	2.6349	3.1349

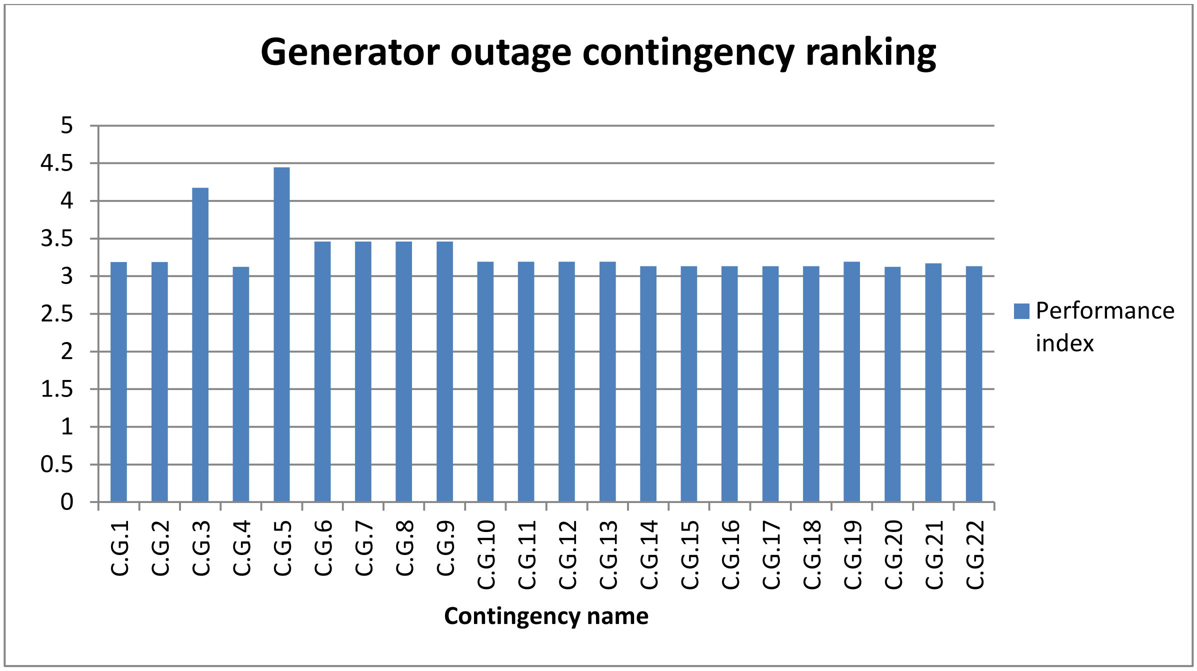


Figure 4- 26: Generator outage performance index

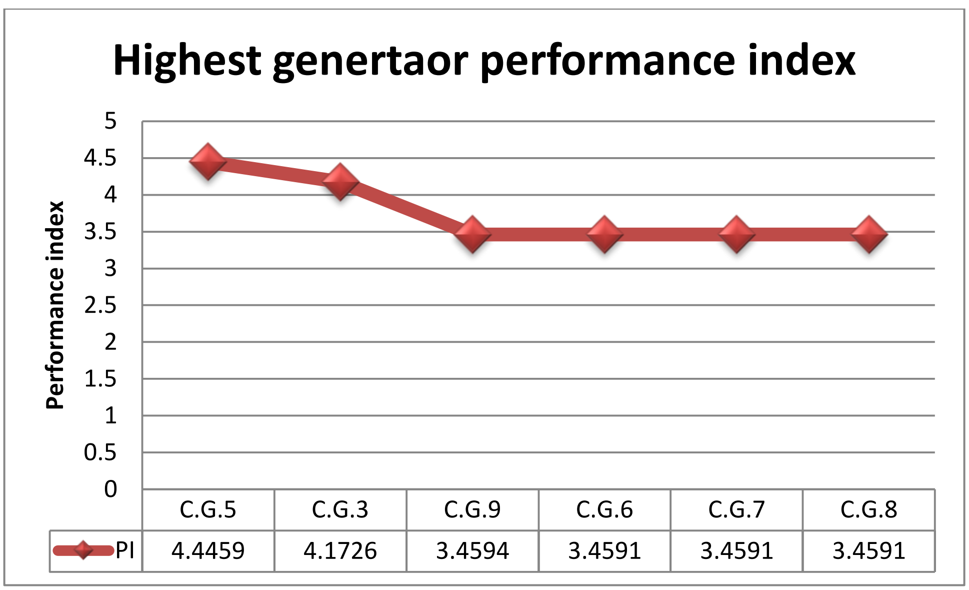


Figure 4- 27: Highest rated generator contingencies

A contingency analysis will be run for the six highest contingencies to see in detail the elements that violate the thermal and voltage limits post contingency in both the line and generators.

CHAPTER 5

SAPP CONTINGENCY ANALYSIS RESULTS

The contingency analysis for each contingency case was carried out in the DIgSILENT PowerFactory. The results that followed from each contingency analysis are represented in the figures below which represent the thermal loading, minimum voltage violation and maximum voltage violation results.

5.1 Contingency ranking

In chapter 4, it was discovered after contingency ranking that the highest rankings of violations in both the line and generator outages are as shown in table 5-1.

Table 5- 1: Contingency analysis selection elements

Contingency Name	Element Type	Element name	Performance index
C.L.12	Line	Harib-Kokerboom 2	0.3064
C.L.10	Line	Gaborone South - Spitskop 132kV	0.299
C.L.11	Line	Harib - Kokerboom 1	0.2947
C.L.7	Line	Camden - Normandie 400_1	0.2709
C.L.13	Line	Infulene – Matole 275_1	0.2667
C.L.18	Line	Maputo – Matola 275_1	0.2642
C.G.5	Generator	Synchronous Machine(2)	4.4459
C.G.3	Generator	Arnot Gen6	4.1726
C.G.9	Generator	Camden Gen 8	3.4594
C.G.7	Generator	Camden Gen 6	3.4591
C.G.8	Generator	Camden Gen 7	3.4591
C.G.6	Generator	Camden Gen 5	3.4591

The general aim of the contingency analysis is to detect areas of weakness in the network which can be strengthened by methods including transmission capacity increase and allows improvements in the transmission system that will enable the network to withstand disturbances.

The results from table 5-1 are represented using four main graphs below which illustrate the prognosis of each separate simulation. The graphs include the SAPP model network graph, the substation busbar graph, the voltage violation graph and the thermal violation graph.

5.2 SAPP Model Network Graph

The SAPP model network graphs show the separate substations interconnected together to represent a mega substation. After each simulation, this graph shows the response of each substation with respect to the corresponding disturbance that occurs. The colour difference is a primary representation of the voltage drops and rise that occur in the busbars of each substation.

5.3 Substation Busbar Network

The substation busbar network reveals the connection within each substation. It shows all the connections which comprise the generating units, transformers, busbars, load, reactors and transmission lines connecting two or more substations. This graph shows exactly which of the internal components are affected by each contingency presenting either a thermal or voltage violation.

5.4 Voltage Violation

The voltage violation graph is a tabular representation of the busbars that have violated the voltage security limitations. It gives a comparison between the base case and the post contingency case so the user can easily identify how much of a voltage step or lag has taken place in the busbar.

5.5 Thermal violations

These graphs represent the thermal loading of the transmission lines that are beyond the specified security limits. Once again this graph gives a clear comparison between the base case and the post contingency case

This is the analysis that is used for each of the different simulations that are run in this research. The visual aid makes it easy to set apart which sections of the network are undergoing changes post contingency and also gives a very clear comparison between pre contingency and post contingency.

5.6 Scenario 1: Contingency C.L.12 Harib – Kokerboom 2

Figures 5-1, 5-2 and 5-3 display the results that are obtained after the contingency C.L.12 has been run by inducing a fault and inactivating the Harib-Kokerboom 2 transmission line. Fig.5-1 represents the effect of an outage of line L.12 on the SAPP network. With comparison to the load flow graph (fig.4-14) which shows the pre contingency or base case graph of the SAPP network, we can see that even whilst the rest of the substations go unaffected, the NAMPOWER substation experiences an over voltage limit violation represented by the red colour.

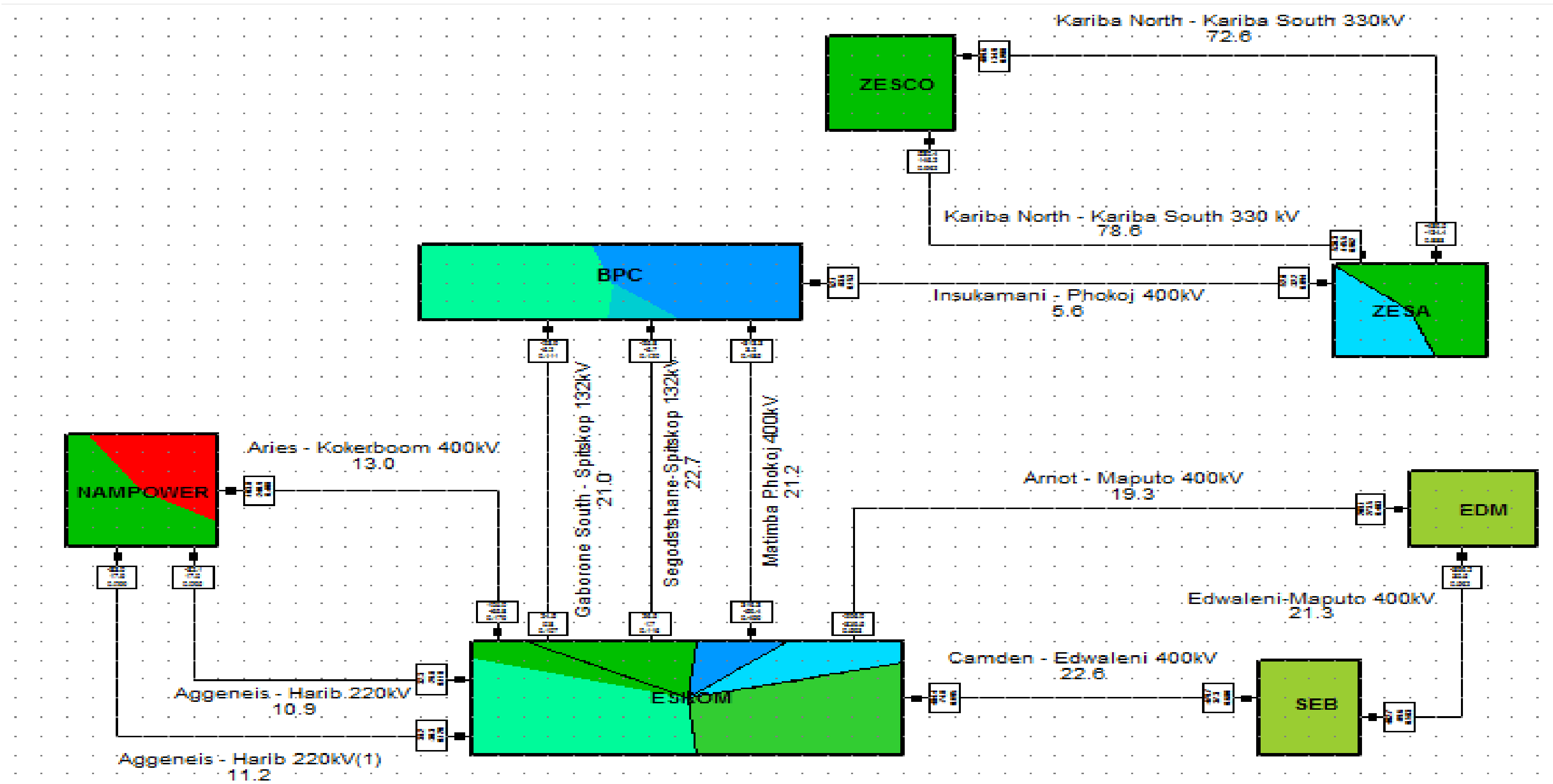


Figure 5- 1: SAPP network post contingency C.L.12

In comparison to the NAMPOWER load flow graph in fig.4-22, we can see from fig.5-2 which is under contingency C.L.12 that the Kokerboom 400 Bus1 busbar rises above the secure voltage limit by the change in colour from blue to red. The Kokerboom 220 Bus experienced a voltage drop below the secure limit and is indicated by a blue busbar.

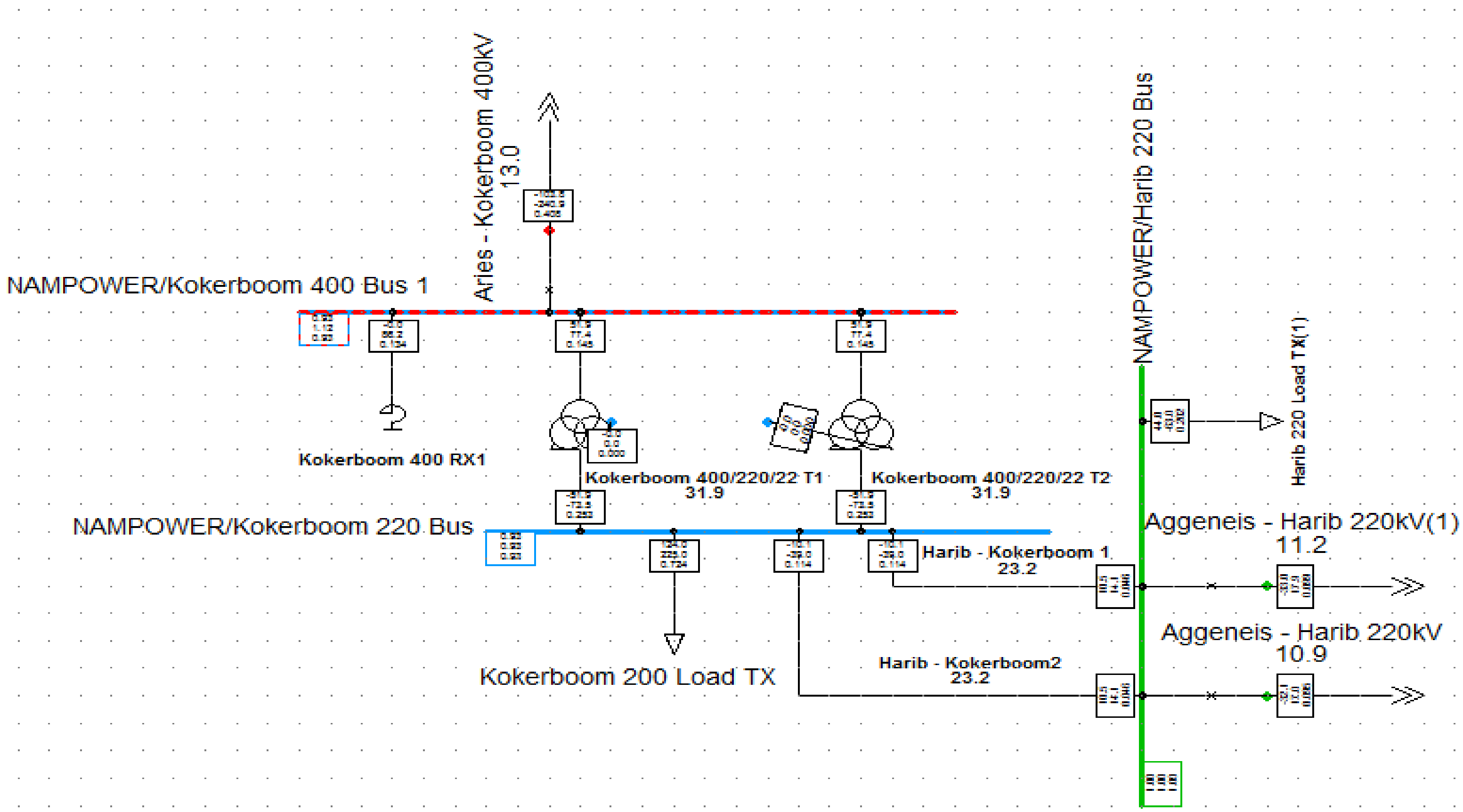


Figure 5- 2: NAMPOWER substation network post contingency C.L.12

Fig.5-3 Shows the voltage violation that takes place in the Kokerboom 400 Bus 1 after the C.L12 contingency. The voltage base is indicated at a per unit value of 0.928 which is below the required security limits and the post contingency voltage rises to 1.124 p.u, which is above the required security limit of 1.05 p.u. This is represented by a red bar in the graph to indicate that a violation has occurred.

Component	Substation	Voltage Max. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Base Case and Post Voltage [0.928 p.u. - 1.124 p.u.]
Kokerboom 400 Bus 1	NAMPOWER	1.12	0.20	0.93	

Figure 5- 3: Contingency C.L.12 voltage violation

5.7 Scenario 2: Contingency C.L.10 Gabarone South – Spitskop 132kV

Figures 5-4, 5-5 and 5-6 below show the post contingency results obtained after the contingency C.L.10 has been run by inducing a fault in the Gaborone South – Spitskop 132kV transmission line. In Fig.5-4 we examine the outage of line L.10 in which we see the BPC substation is affected by dropping below the voltage limit represented by the blue colour. NAMPOWER substation shows a voltage drop occurs by the alteration of colour from green to blue in one section and from yellow to green in the other section. A section of the ZESA substation experienced a voltage drop below the security limit.

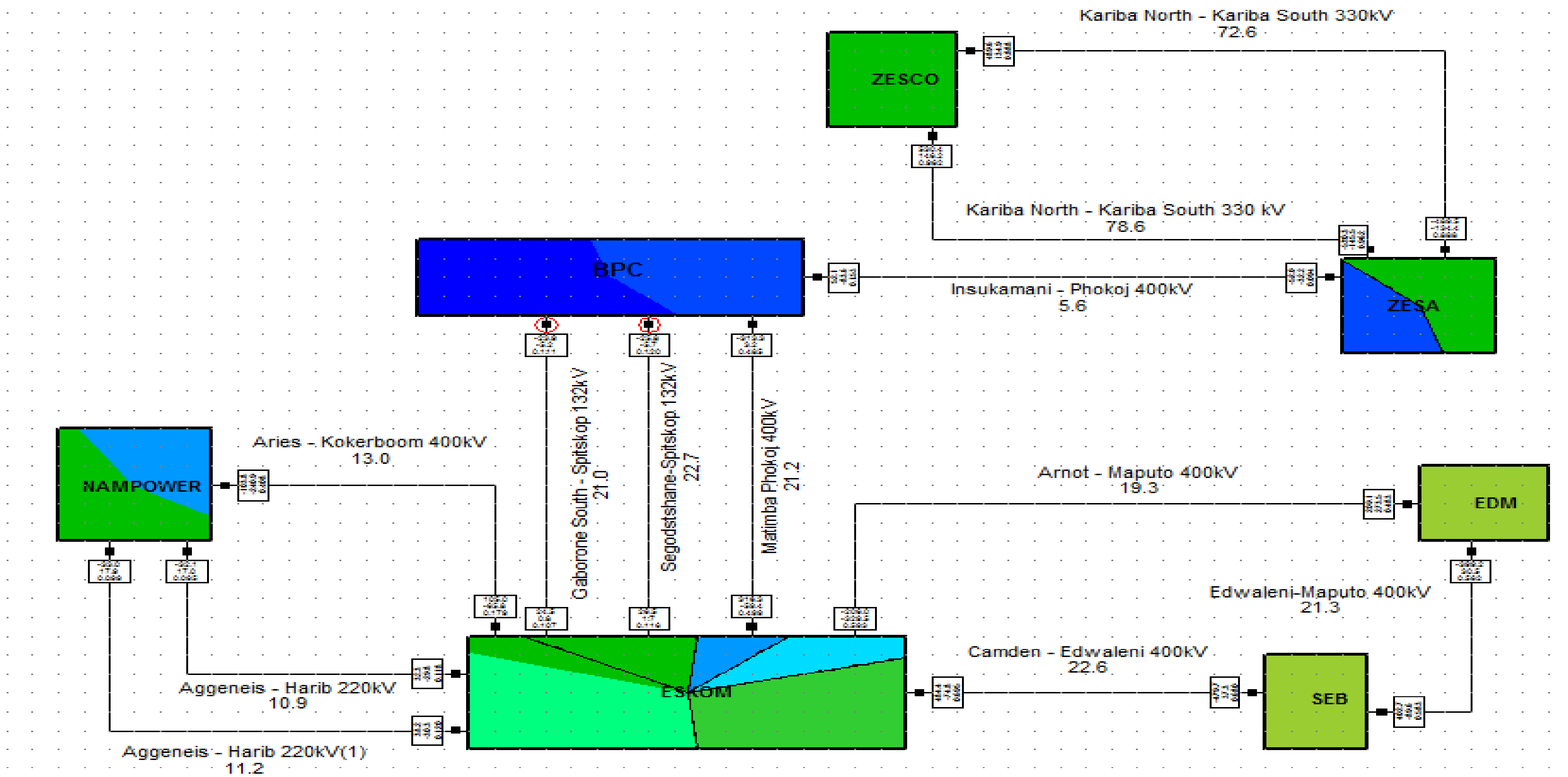


Figure 5- 4: SAPP network post contingency C.L.10

Fig.5-5 on the other hand shows that all the busbars in the network experience voltage drops below the secure limit when under contingency C.L.10.

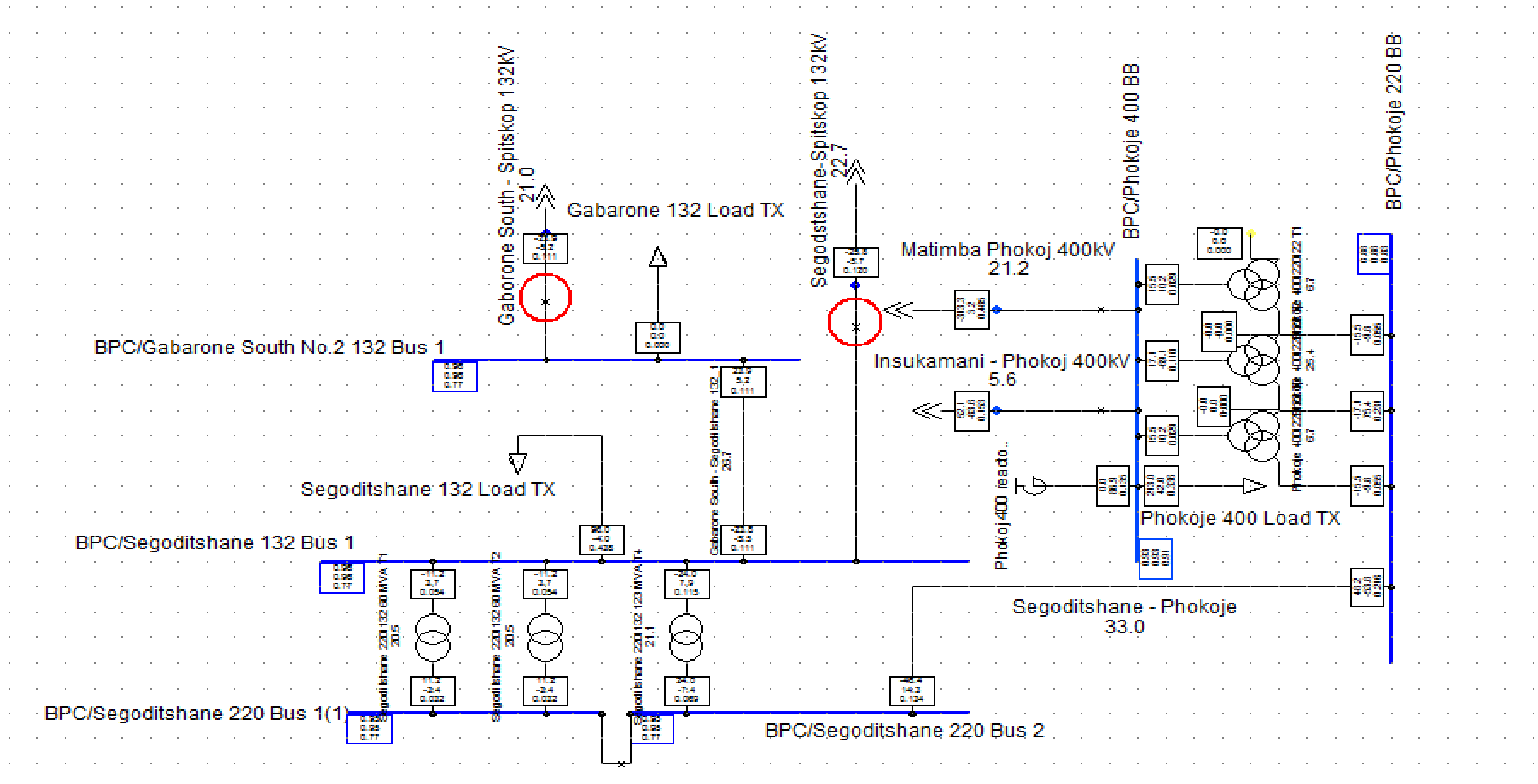


Figure 5- 5: BPC substation network post contingency C.L.10

Fig.5-6 displays the voltage violations caused from contingency C.L.10. A total of 8 busbars undergo a change of voltage levels post contingency. The first busbar, Segoditshane 220 Bus 1, is seen to have a base voltage of 0.954 p.u which then drops to 0.770 p.u post contingency. This change in voltage is represented by a differentiation in colour as the voltage drops from a voltage that is within the required security limits to one that is not. The bar in the graph is multi coloured, green in the far right side to show the voltage lies within the specified security limit to a dark red colour in the far left to indicate that the voltage now falls outside the required security limit. This proves true for the next three busbars that follow. The Phokojoe 220 BB busbar in the same figure however has a different set of colours. The bar corresponding to Phokojoe 220 BB is coloured bright red in the far right to show that its base case voltage of 0.877 p.u is not within specifies limits and drops further to 0.833 p.u represented by a dark red colour in the far left of the bar. This analysis can be used to interpret the three busbars that follow which all have base voltages below the security limit and drop even further.

Component	Branch, Substation or Site	Voltage Min. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Base Case and Post Voltage [0.770 p.u. - 0.964 p.u.]
Segoditshane 220 Bus 1(1)	BPC	0.770	-0.184	0.954	
Segoditshane 220 Bus 2	BPC	0.770	-0.184	0.954	
Gabarone Sth No.2 132B1	BPC	0.771	-0.193	0.964	
Segoditshane 132 Bus 1	BPC	0.771	-0.189	0.960	
Phokoje 220 BB	BPC	0.833	-0.044	0.877	
S. Phikiwe 22 BB	BPC	0.833	-0.044	0.877	
Phokoje 400 BB	BPC	0.907	-0.025	0.932	
Insakumani 400 Bus 1	ZESA	0.914	-0.026	0.941	

Figure 5- 6: Contingency C.L.10 voltage violations

5.8 Scenario 3: Contingency C.L.11 Harib – kokerboom 1

Figures 5-7, 5-8 and 5-9 show the results that are obtained after contingency C.L.11 is run and considering Harib-Kokerboom 1 faulty and inactive. Once again the NAMPOWER substation experiences an over voltage limit violation represented by the red colour.

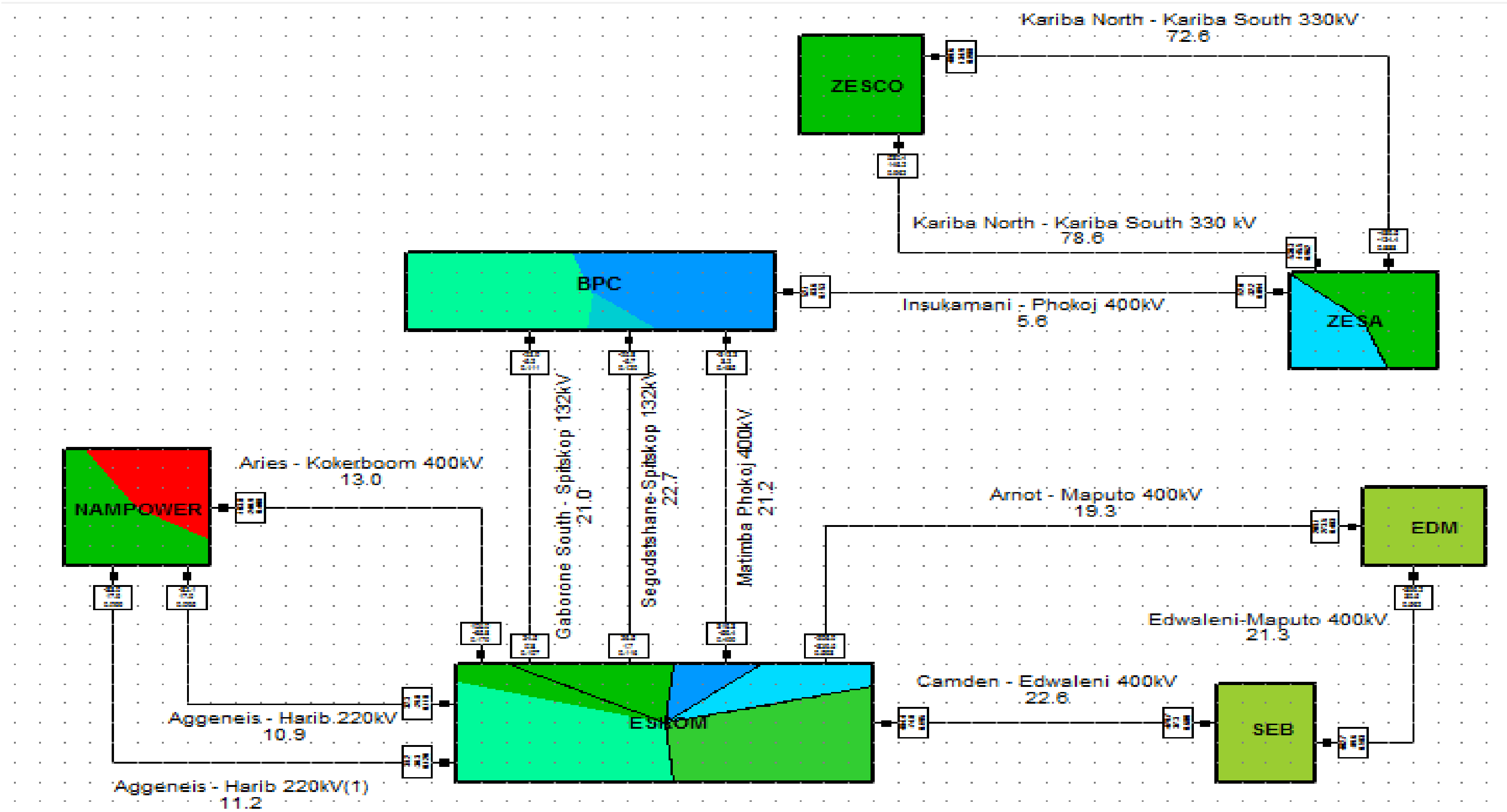


Figure 5- 7: SAPP network post contingency C.L.11

Similar to the previous case, fig.5-8 shows the kokerboom 400 Bus1 busbar rise above the secure voltage limit by the change in colour from blue to red whilst the Kokerboom 220 Bus experienced a voltage drop below the secure limit and is indicated by a blue busbar.

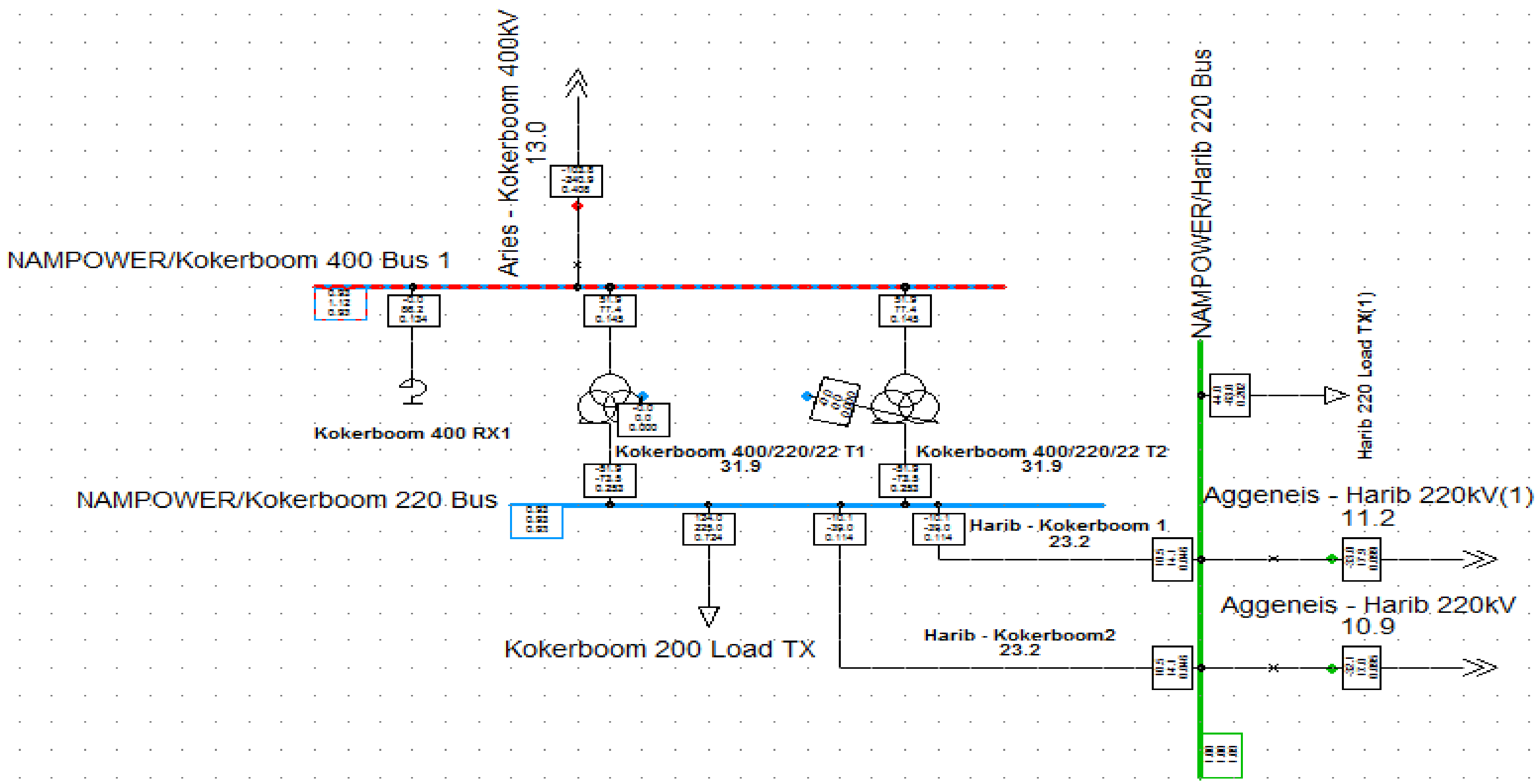


Figure 5- 8: NAMPOWER substation network post contingency C.L.11

In fig.5-9 the voltage base is indicated at a per unit value of 0.93 which is below the required security limits and the post contingency voltage rises to 1.12 p.u, which is above the required security limit of 1.05 p.u. This is represented by a red bar in the graph to indicate that a violation has occurred.

Component	Substation	Voltage Max. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Base Case and Post Voltage [0.928 p.u. - 1.124 p.u.]
Kokerboom 400 Bus 1	NAMPOWER	1.12	0.20	0.93	

Figure 5- 9: Contingency C.L.11 voltage violation

5.9 Scenario 4: Contingency C.L.7 (Camden - Normandie 400_1)

Figures 5-10, 5-11 and 5-12 display the results that are obtained when the contingency C.L.7 has been run after considering the Camden-Normandie transmission line faulty and inactive. The upper section of the NAMPOWER substation experiences a voltage drop indicated by the blue colour whilst the lower section now has its voltage within limits.

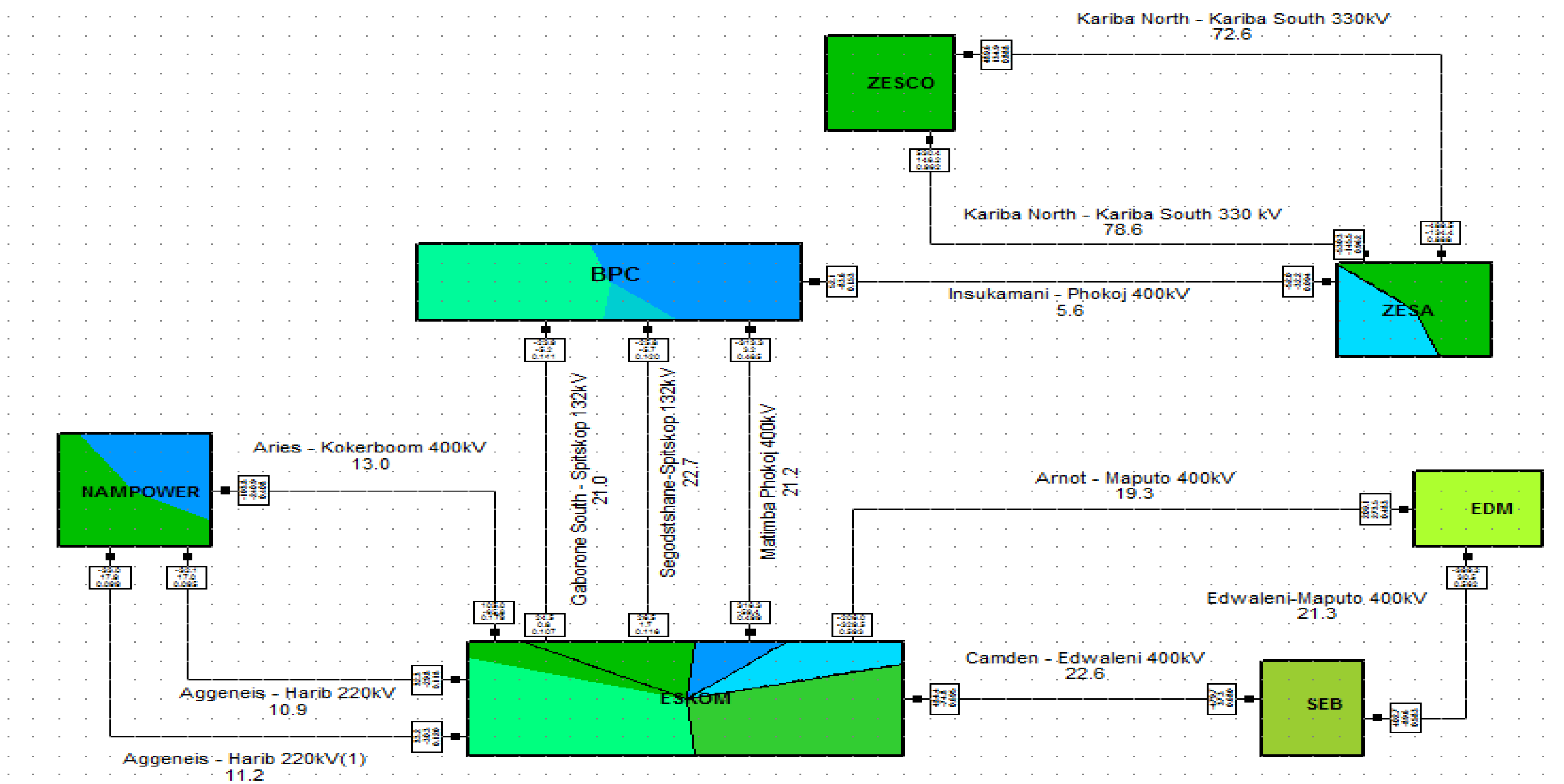


Figure 5- 10: SAPP network post contingency C.L.7

Figure 5-11 indicates the transmission line that is presumed to be undergoing a fault, however, no significant changes are seen in the figure in comparison with the network's pre contingency state in figure 4-22. It should be noted however, that figure 5-11 has been enlarged so as to clearly indicate and focus on the area where the contingency occurred.

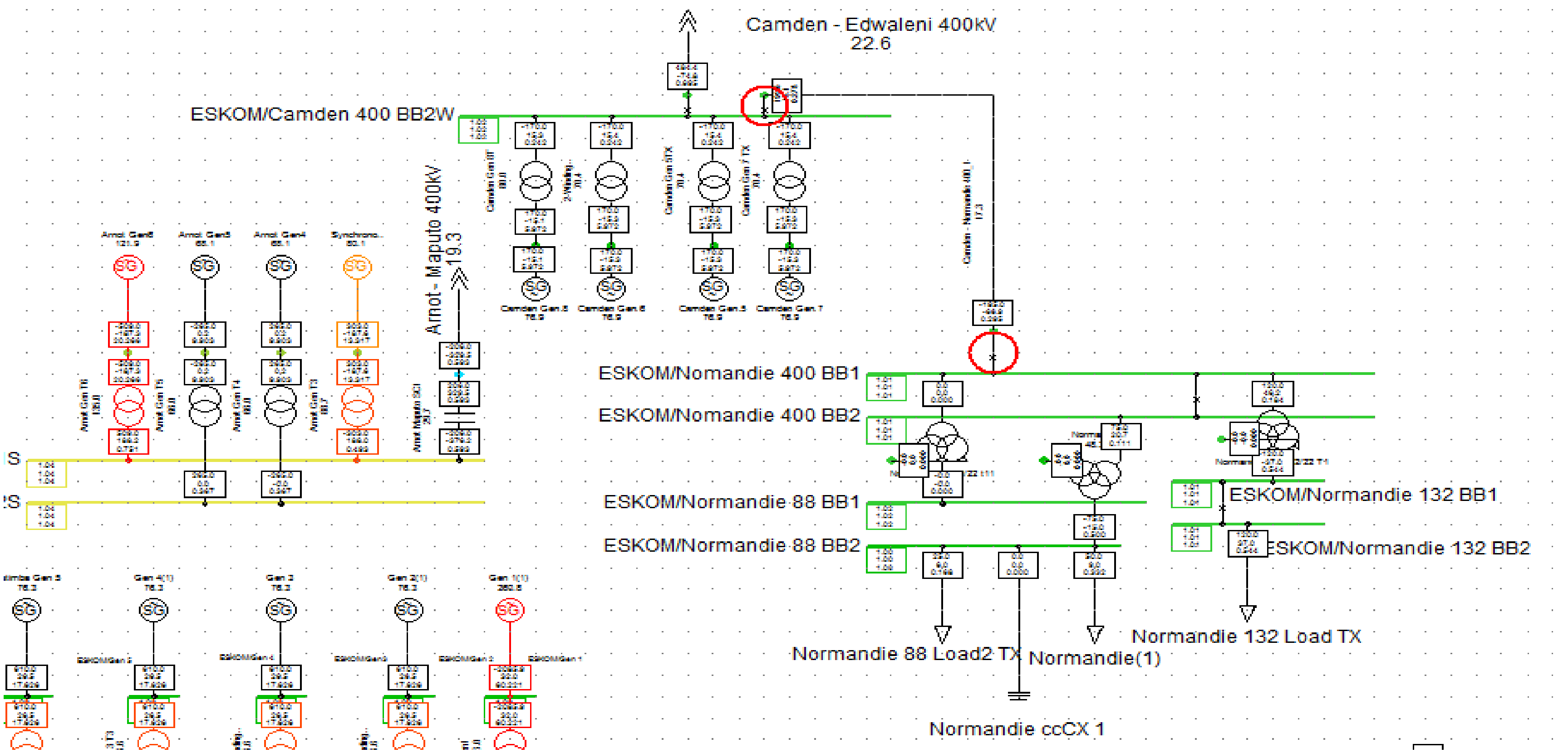


Figure 5- 11: ESKOM C substation post contingency C.L.7

Fig.5 -12 shows the results after the simulation of contingency C.L.7. From the figure we see that the transformer Arnot Gen T6 has a base case loading of 135% and increases to 176.9%, both of which are beyond the security limit and hence are represented by a bar that is coloured bright red and dark red to show the increment in violation. In the same figure is the Arnot Gen T3 transformer that has a loading base case of 88.7% represented by a dark green colour in the bar and drops to 84.4% post contingency and is represented by a light green colour as they are both in the specified security limit.

Component	Branch, Substation or Site	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Base Case and Continuous Loading [0.0 % - 296.0 %]
Gen1	ESKOM	296.0	296.0	296.0	
Arnot Gen T6	ESKOM	176.9	176.9	135.0	
Arnot Gen T3	ESKOM	88.7	88.7	88.7	
Arnot Gen T3	ESKOM	84.4	84.4	88.7	
Kariba North T - 1(1)	ZESCO	88.4	88.4	88.4	
Kariba North T-3	ZESCO	88.0	88.0	88.0	
Kariba North T1	ZESCO	88.0	88.0	88.0	
Kariba North T-1	ZESCO	88.0	88.0	88.0	
Kariba North T-2	ZESCO	88.0	88.0	88.0	
2-Winding Transformer(3)	ESKOM	86.6	86.6	86.6	
2-Winding Transformer(2)	ESKOM	86.6	86.6	86.6	
2-Winding Transformer(1)	ESKOM	86.6	86.6	86.6	
Gen 3 T3	ESKOM	86.6	86.6	86.6	

Figure 5- 12: Contingency C.L.7 thermal violation

5.10 Scenario 5: Contingency C.L.13 (Infulene – Matole 275_1)

Figures 5-13, 5-15 and 5-15 show the results post contingency C.l.13, where the Infulene-Matola 275_1 transmission line is considered faulty. Fig.5-13 shows that the SEB substation experiences a voltage rise slightly above the required security limit whilst the upper part of the NAMPOWER substation changes from a light green to blue indicating a voltage drop. The upper part of the ESKOM network changes from a light blue to green in colour indicating a voltage increase within the required limits.

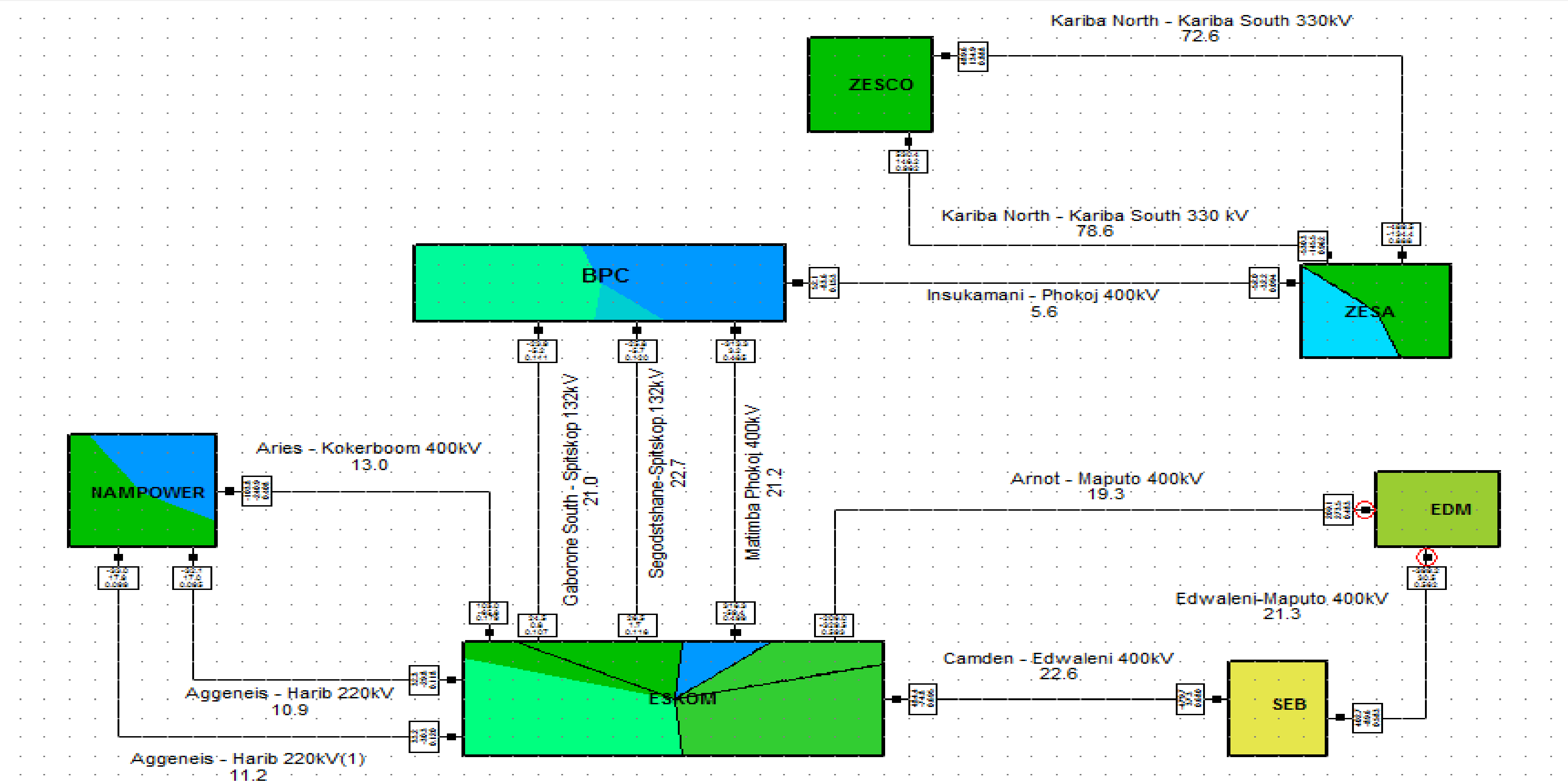


Figure 5- 13: SAPP network post contingency C.L.13

Figure 5-14 shows that no significant changes occurred in the EDM substation post contingency but does indicated the transmission lines that are interconnected to other substations in which voltage drops and increase were experienced as explained in the figure 5-13.

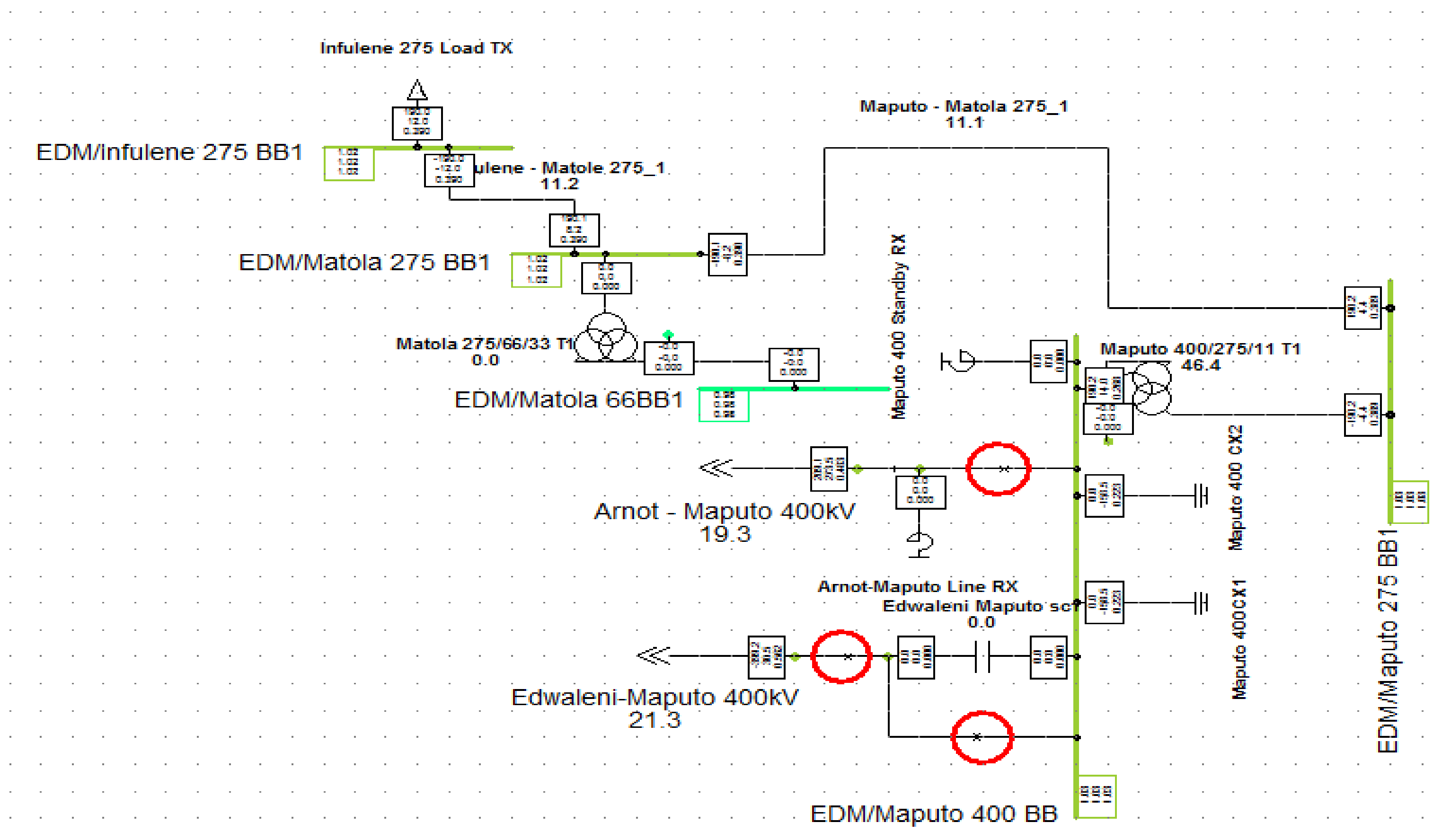


Figure 5- 14: EDM substation network post contingency C.L13

Figure5-15 shows that the Camden Gen 8T generator experienced a thermal loading increase 79.98% to 112.03 which is over the accepted secure limit.

Component	Substation	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Base Case and Continuous Loading [0 % - 296 %]
Gen1	ESKOM	296.05	296.05	296.05	
Arnot Gen T6	ESKOM	135.01	76.44	135.01	
Camden Gen 8T	ESKOM	112.03	112.03	79.98	
Arnot Gen T3	ESKOM	88.72	76.46	88.72	
Kariba North T - 1(1)	ZESCO	88.38	88.38	88.38	
Kariba Borth T1	ZESCO	88.05	88.05	88.05	
Kariba North T-1	ZESCO	88.05	88.05	88.05	
Kariba North T-2	ZESCO	88.05	88.05	88.05	
Kariba North T-3	ZESCO	88.05	88.05	88.05	
Karina North T-1(2)	ZESCO	88.05	88.05	88.05	
2-Winding Transformer(1)	ESKOM	86.65	86.65	86.65	
2-Winding Transformer(2)	ESKOM	86.65	86.65	86.65	
2-Winding Transformer(3)	ESKOM	86.65	86.65	86.65	
Gen 3 T3	ESKOM	86.65	86.65	86.65	

Figure 5- 15: Contingency C.L.13 thermal violations

5.11 Scenario 6: Contingency C.L.18 (Maputo – Matola 275_1)

Figures 5-16, 5-17 and 5-18 display the results obtained post contingnecy C.L.18 after the Maputo – Matola 275_1 is considered faulty and inactive. The results reflect a similarity with those obatined from the contingency C.L.13 which interpret that the severity of violation caused by both contingency cases is almost identical. This is also proved in the derivation of the contingency ranking showing a slight difference between the performance index of C.1.13 and C.L.18 rated at 0.2667 and 0.2642 respectively.

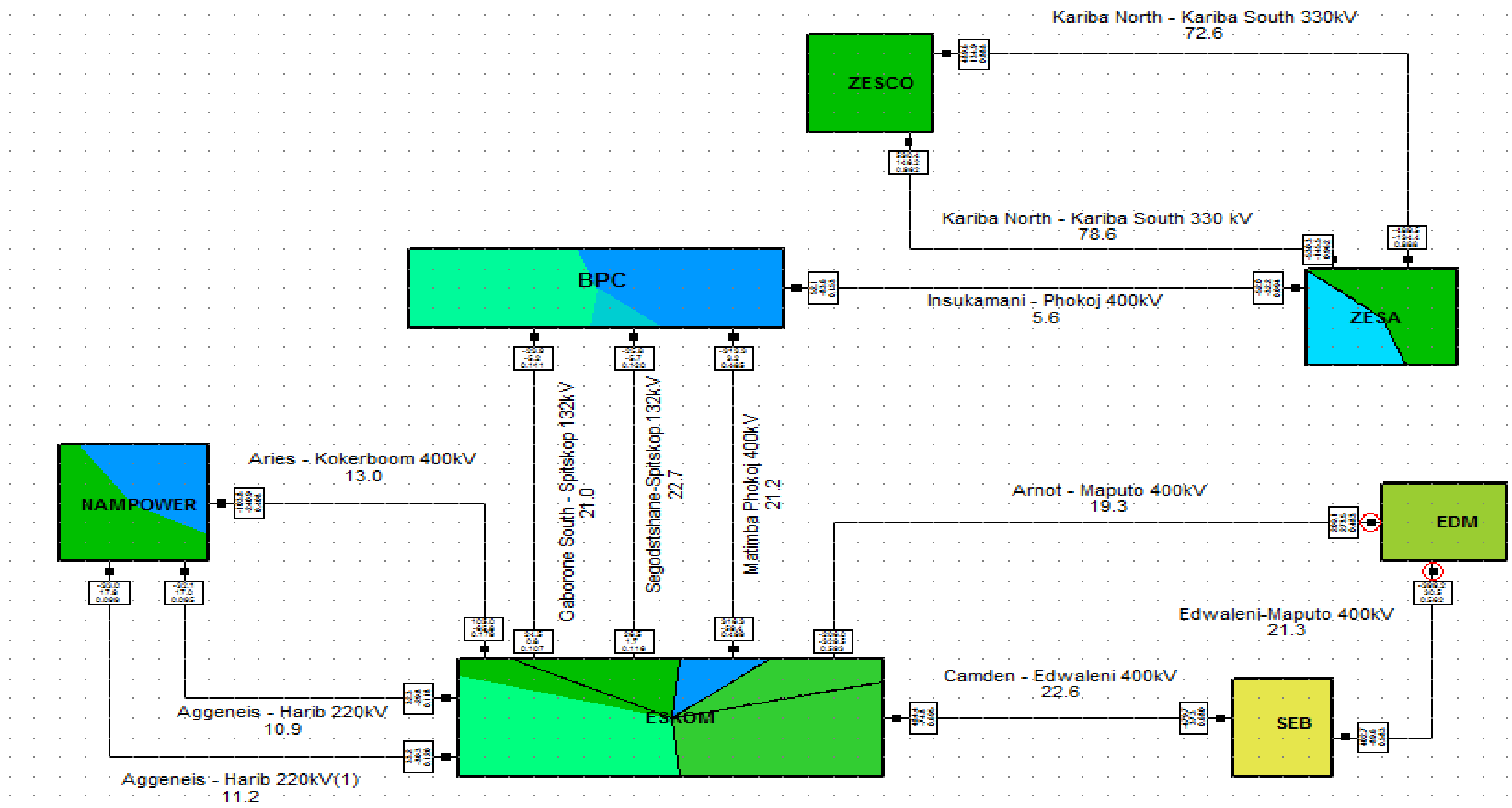


Figure 5- 16: SAPP network post contingency C.L.18

Figure 5-17 shows no significant changes in the EDM substation post contingency but does indicated the transmission lines that are interconnected to other substations in which voltage drops and increase were experienced.

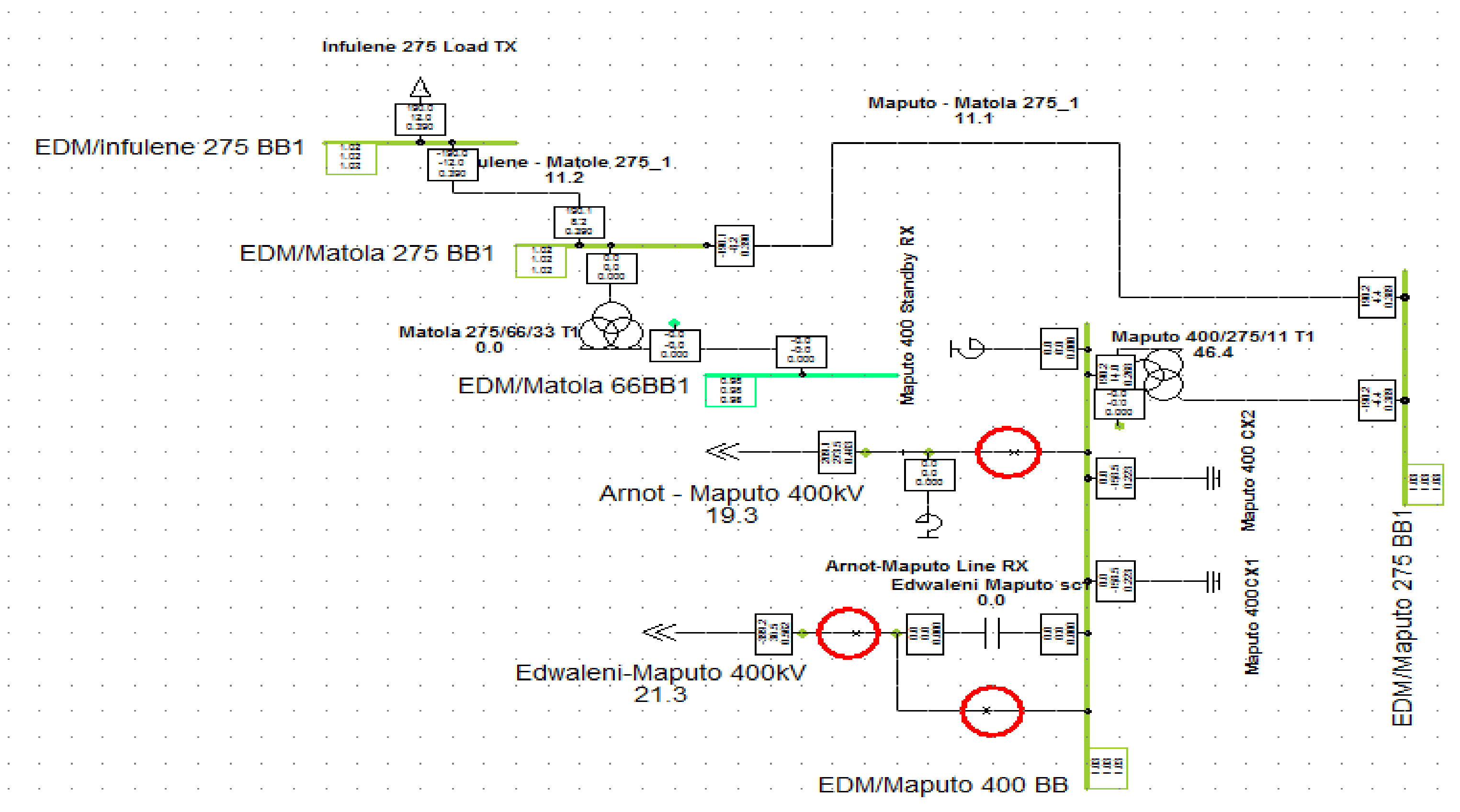


Figure 5- 17: EDM substation network post contingency C.L.18

Fig.5-18 shows the scenario after contingency C.L.18 is run. Only one thermal violation was recorded and that is in the Camden Gen 8T transformer which shows a thermal loading increase from 79.98% to 112.03%. This is represented in the bar by a bar that is coloured green and converts into a red colour to show thermal overload has occurred.

Component	Substation	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Base Case and Continuous Loading [0 % - 296 %]
Gen1	ESKOM	296.05	296.05	296.05	
Arnot Gen T6	ESKOM	135.01	76.44	135.01	
Camden Gen 8T	ESKOM	112.03	112.03	79.98	
Arnot Gen T3	ESKOM	88.72	76.46	88.72	
Kariba North T - 1(1)	ZESCO	88.38	88.38	88.38	
Kariba Borth T1	ZESCO	88.05	88.05	88.05	
Kariba North T-1	ZESCO	88.05	88.05	88.05	
Kariba North T-2	ZESCO	88.05	88.05	88.05	
Kariba North T-3	ZESCO	88.05	88.05	88.05	
Karina North T-1(2)	ZESCO	88.05	88.05	88.05	
2-Winding Transformer(1)	ESKOM	86.65	86.65	86.65	
2-Winding Transformer(2)	ESKOM	86.65	86.65	86.65	
2-Winding Transformer(3)	ESKOM	86.65	86.65	86.65	
Gen 3 T3	ESKOM	86.65	86.65	86.65	

Figure 5- 18: Contingency C.L.18 thermal violations

5.12 Scenario 7: Contingency C.G.5 (Synchronous Machine (2))

Figures 5-19, 5-20 and 5-21 show the results obtained when the generator Synchronous machine (2) is considered faulty and no longer generating power. The results in fig.5-19 show several voltage violation. The BPC and lower section of the ZESA substation indicate an extreme voltage drop below 0.9p.u. The upper section of the NAMPOWER substation post contingency changed from green to blue indicating a voltage drop whilst the lower section of the area changes from yellow to green also indicating a voltage drop. Lastly, the ESKOM section connected to the NAMPOWER substation shows a voltage rise.

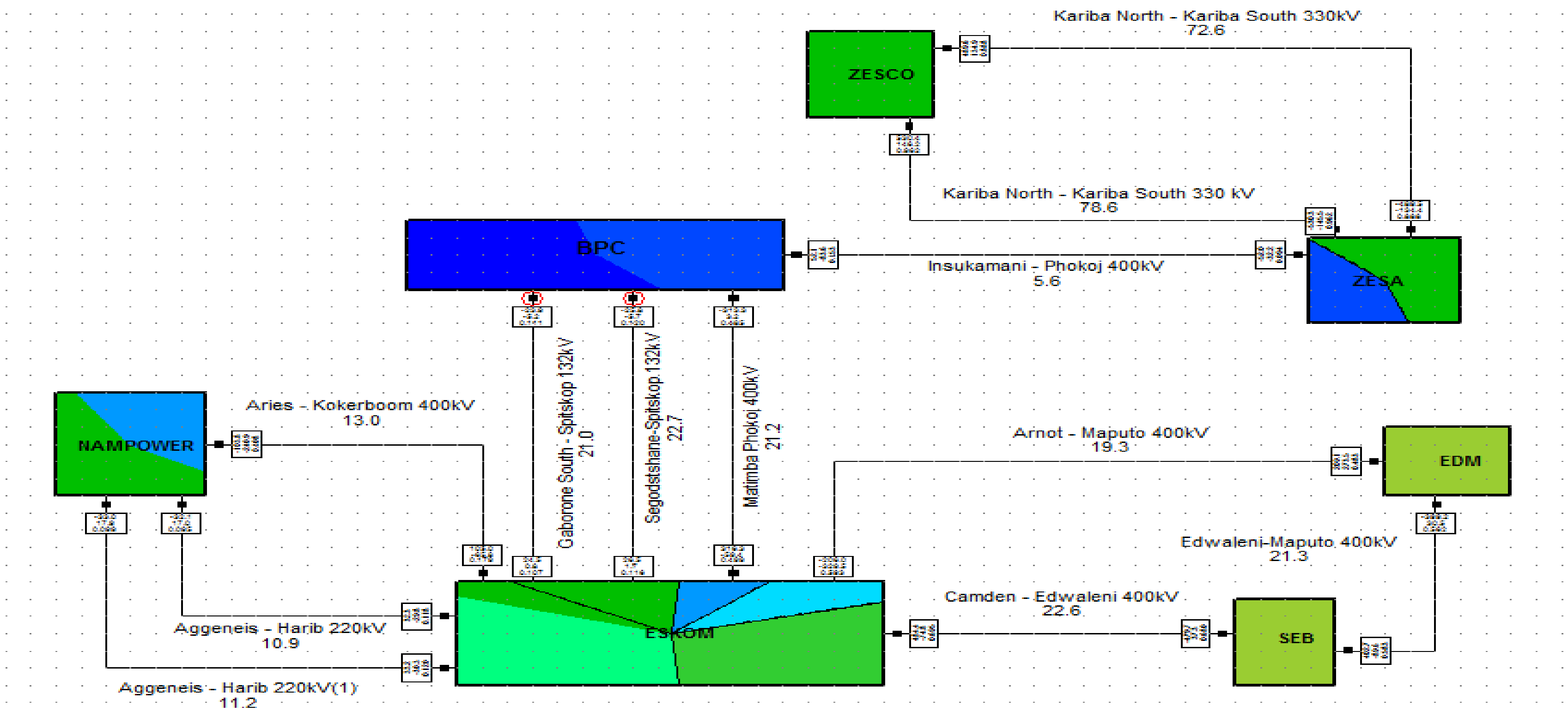


Figure 5- 19: SAPP network post contingency C.G.5

Figure 5-20 shows that post contingency, a voltage drop below 0.9 p.u in all the busbars of the BPC network occurs.

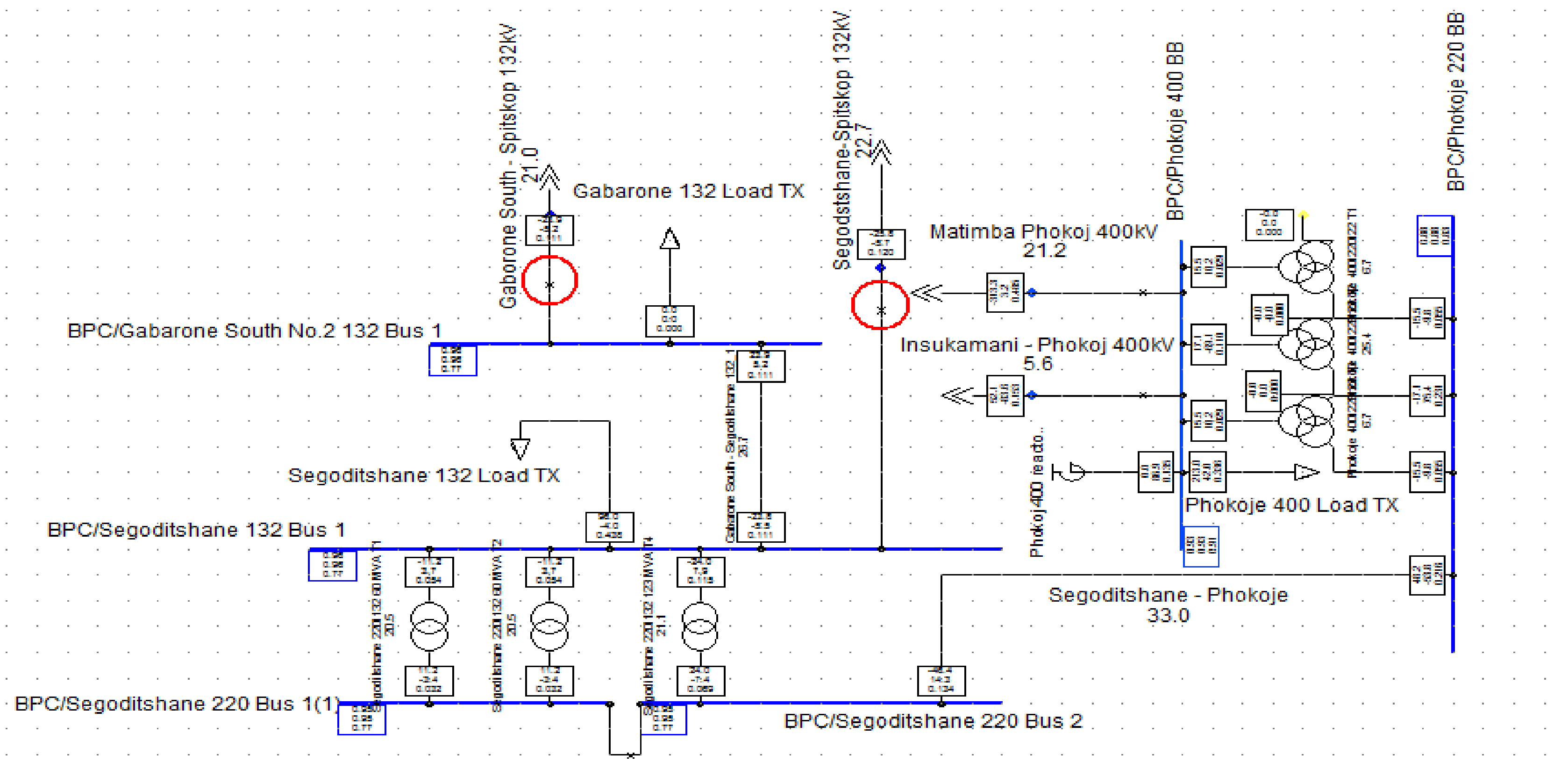


Figure 5- 20: BPC substation network post contingency C.G.5

Figure 5-21 shows voltage drops were experienced in the Segoditshane 200 Bus 1, Segoditshane 200 Bus 2, Gabarone No2 132 Bus 1 and the Segoditshane 132 Bus 1 all of which were within the secure limit pre contingency and dropped lower that limit post contingency. The other four buses; Phokojoe 220 BB, S. Phikiwe 22 BB, Phokojoe 400 BB and Insakumani 400 Bus 1 were all below the acceptable secure limit pre contingency and dropped even lower post contingency.

Component	Substation	Voltage Min. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Base Case and Post Voltage [0.770 p.u. - 0.964 p.u.]
Segoditshane 220 Bus1	BPC	0.77	-0.18	0.95	
Segoditshane 220 Bus 2	BPC	0.77	-0.18	0.95	
Gabarone Sth No.2132Bus1	BPC	0.77	-0.19	0.96	
Segoditshane 132 Bus 1	BPC	0.77	-0.19	0.96	
Phokoje 220 BB	BPC	0.83	-0.04	0.88	
S. Phikiwe 22 BB	BPC	0.83	-0.04	0.88	
Phokoje 400 BB	BPC	0.91	-0.03	0.93	
Insakumani 400 Bus 1	ZESA	0.91	-0.03	0.94	
Kokerboom 400 Bus 1	NAMPOWER	0.93	0.00	0.93	
Spitskop 400 BB1A	ESKOM	0.93	0.00	0.93	
Spitskop 400 BB2A	ESKOM	0.93	0.00	0.93	
Matimba 400 BB1 B6	ESKOM	0.93	0.00	0.93	
Matimba 400 BB2 B3	ESKOM	0.93	0.00	0.93	
Kokerboom 220 Bus	NAMPOWER	0.93	0.00	0.93	

Figure 5- 21: Contingency C.G.5 voltage violations

5.13 Scenario 8: Contingency C.G.3 (Arnot Gen6)

Figures 5-22, 5-23, 5-24 and 5-25 display the results obtained post contingency C.G.3 where the Arnot Gen 6 generator is considered faulty and inactive. Fig.5-22 shows that the SEB and EDM substations experience a voltage increase higher than 1.1 p.u and the NAMPOWER experiences both a voltage increase and drop in its substation. Addistionally the section of the ESKOM substation connected to the NAMPOWER substation experiences a voltage slight rise.

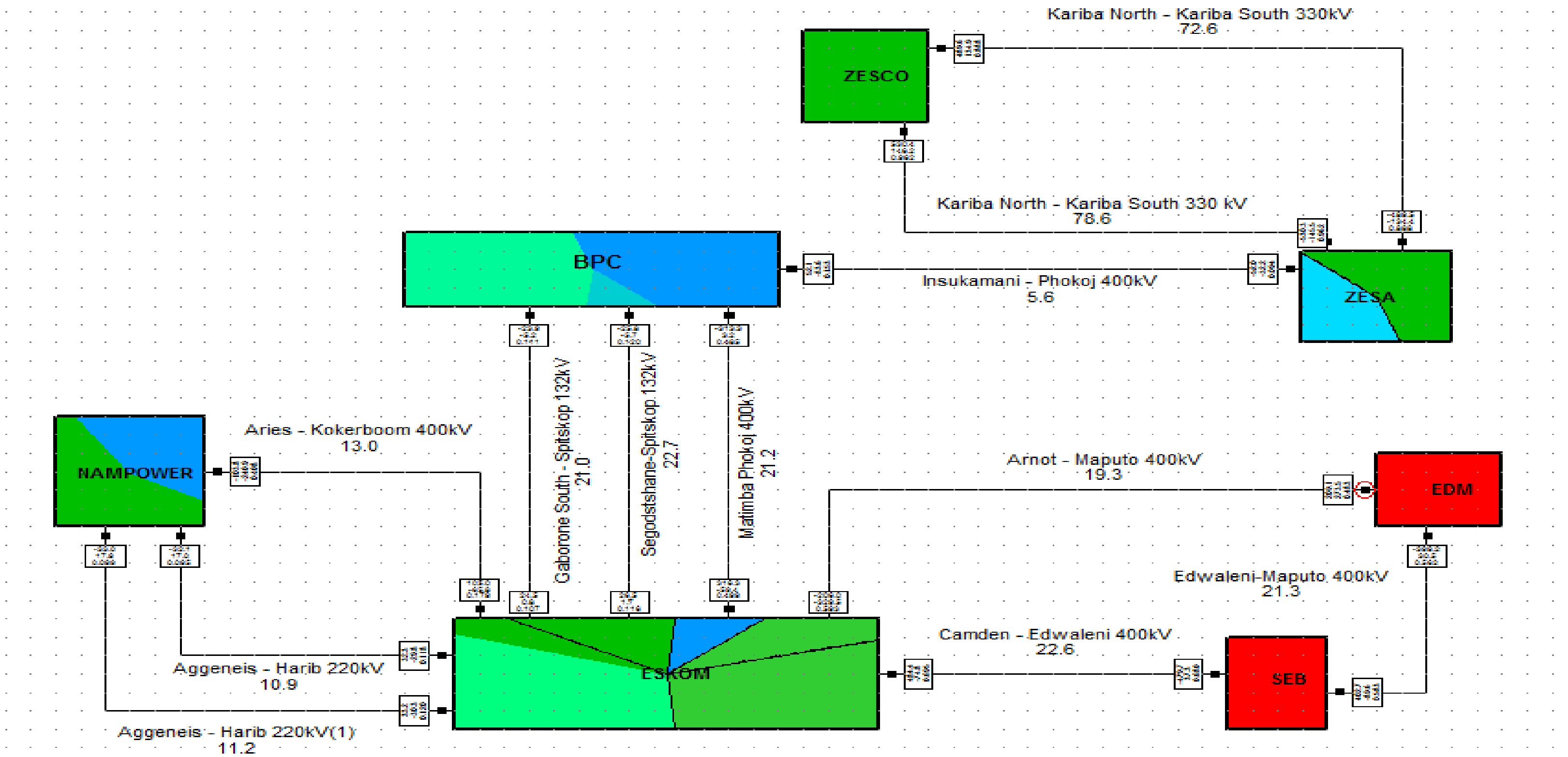


Figure 5- 22: SAPP network post contingency C.G.3

Figure 5-23 shows that post contingency all the busbars in the EDM substation experiences voltage rise beyond 1.1 p.u.

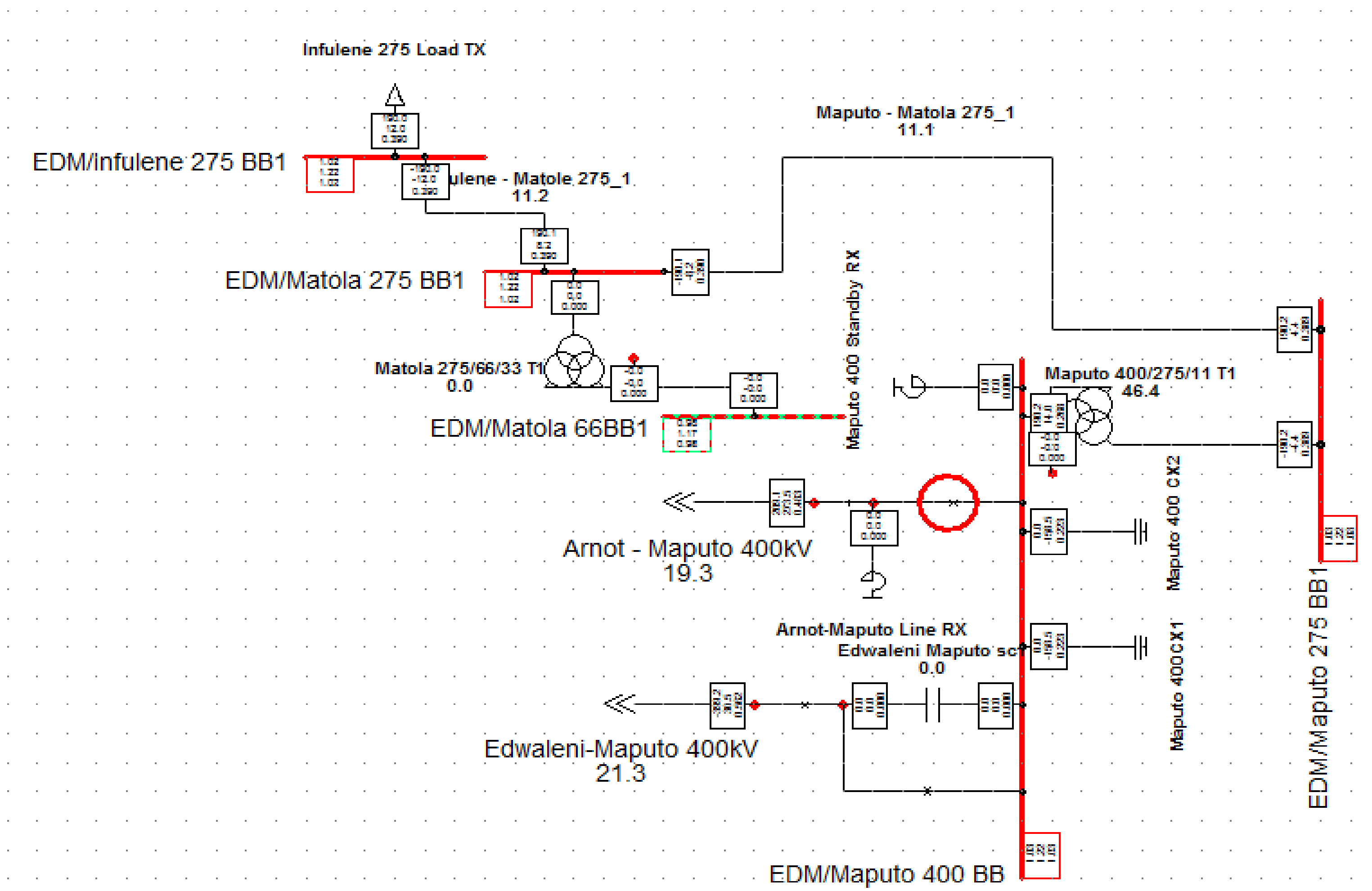


Figure 5- 23: EDM substation network post contingency C.G.3

Figure 5-24 shows that the SEB network also experiences a voltage rise of over 1.1 p.u in all its busbars.

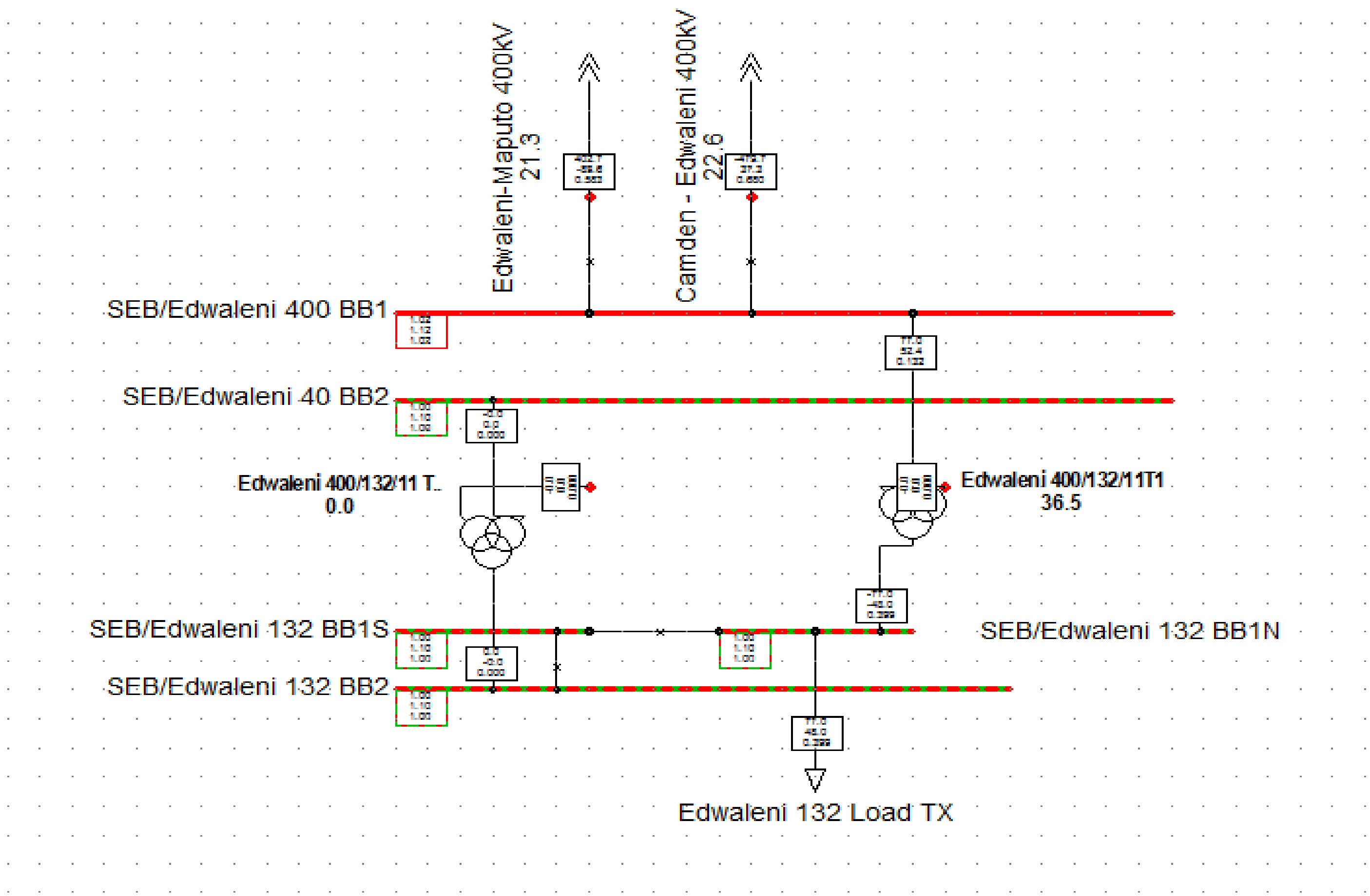


Figure 5- 24: SEB substation network post contingency C.G.3

Figure 5-25 shows the values of voltage increase that the several busbars in the SAPP network experienced post contingency.

Component	Branch, Substation or Site	Voltage Max. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Base Case and Post Voltage [0.976 p.u. - 1.224 p.u.]
Maputo 400 BB	EDM	1.22	0.20	1.03	
Maputo 275 BB1	EDM	1.22	0.20	1.03	
Matola 275 BB1	EDM	1.22	0.20	1.02	
Infulene 275 BB1	EDM	1.22	0.20	1.02	
Matola 66BB1	EDM	1.17	0.19	0.98	
Edwaleni 400 BB1	SEB	1.12	0.10	1.02	
Edwaleni 132 BB1S	SEB	1.10	0.10	1.00	
Edwaleni 132 BB2	SEB	1.10	0.10	1.00	
Edwaleni 40 BB2	SEB	1.10	0.10	1.00	
Edwaleni 132 BB1N	SEB	1.10	0.10	1.00	

Figure 5- 25: Contingency C.G.3 voltage violations

5.14 Scenario 9:Contingency C.G.9 (Camden Gen 8), C.G.7(Camden Gen 6), C.G.8(Camden Gen 7), C.G.6(Camden Gen 5)

Figures 5-26, 5-27 and 5-28 show the results obtained from the contingencies C.G.9, C.G.7, C.G.8 and C.G.6 in the Camden Gen 8, Camden Gen 6, Camden Gen 7 and Camden Gen 5 generators (respectively) are considered faulty. The displayed results applied for each separate contingency case, this is also in correlation with the results obtained in table 5-1 in which the performance index for all these cases were equivalent, in the exception of C.G.9 which varied slightly.

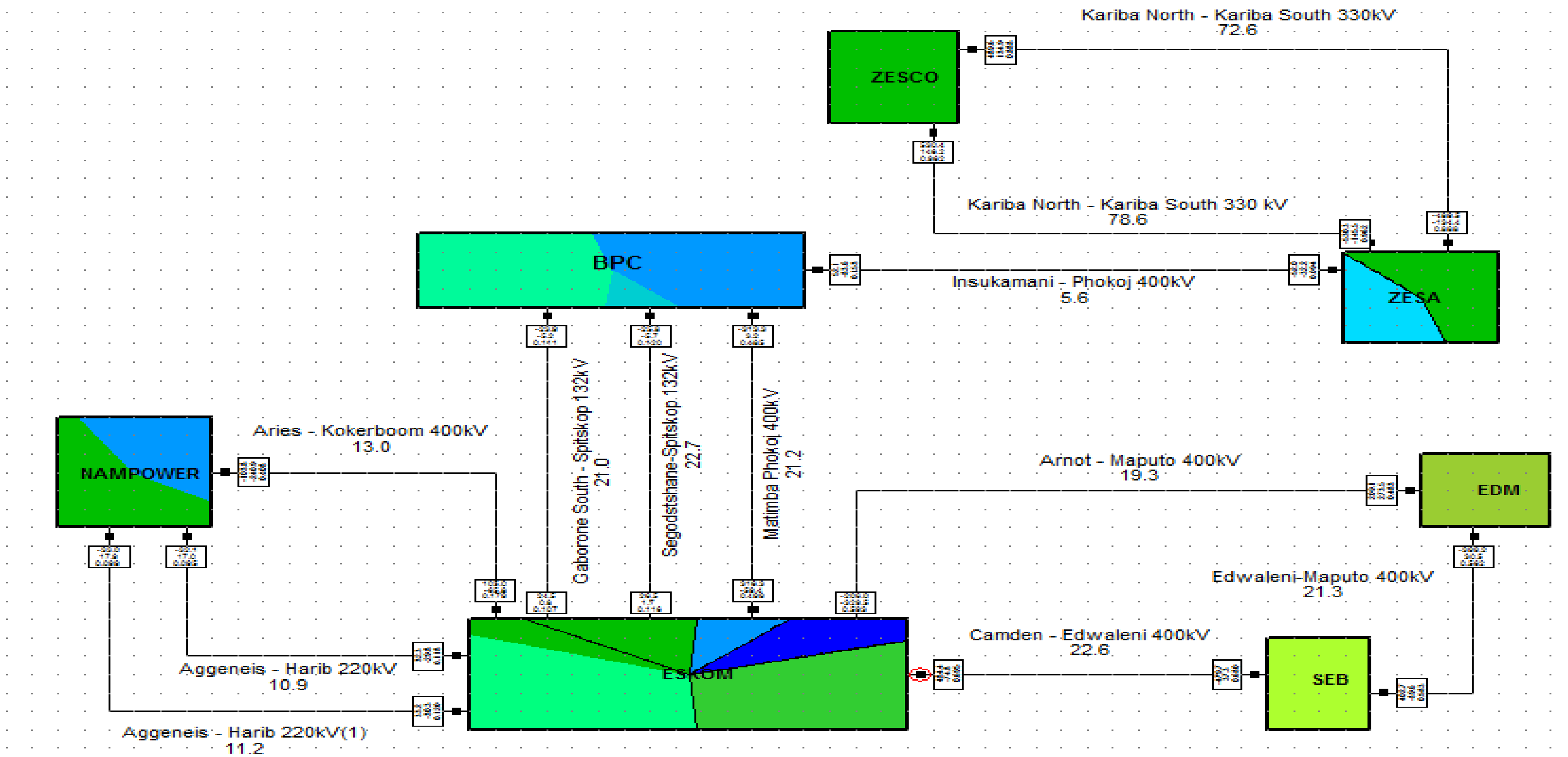


Figure 5- 26: SAPP network post contingency C.G.9, C.G.7, C.G.8, C.G.6

The figure 5-27 shows the ESKOM C network in which the Camden Gen 8 generator and the Arnot Gen T3 transformer both experience an increase in thermal loading.

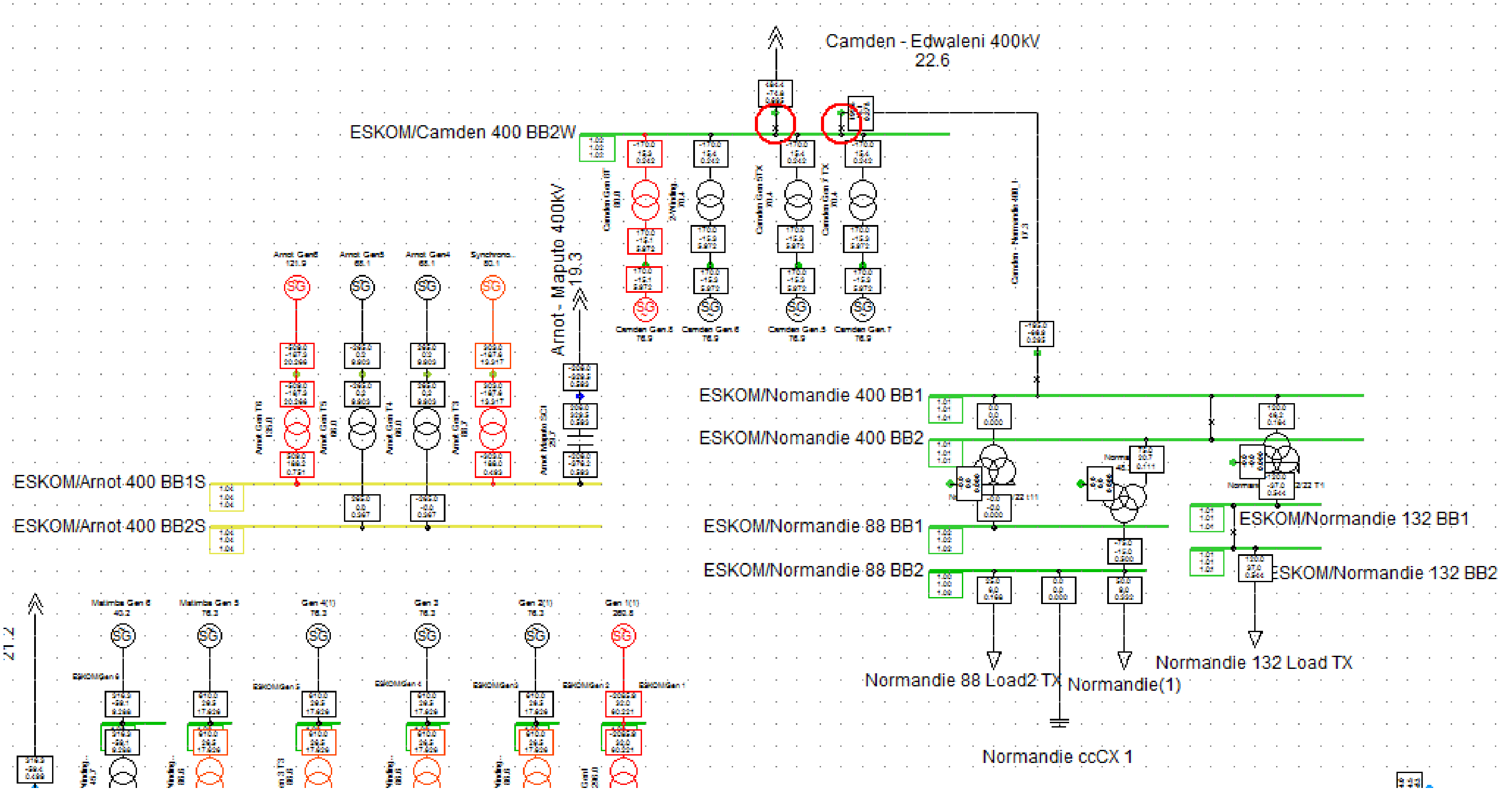


Figure 5- 27: ESKOM C substation network post contingency C.G.9, C.G.7, C.G.8, C.G.6

Figure 5-28 shows the Camden Gen 8T generator and the Arnot Gen T3 transformer becoming overloaded post contingency.

Component	Substation	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Base Case and Continuous Loading [0.0 % - 296.0 %]
Gen1	ESKOM	296.05	296.05	296.05	
Camden Gen 8T	ESKOM	238.99	238.99	79.98	
Arnot Gen T6	ESKOM	135.01	135.01	135.01	
Arnot Gen T3	ESKOM	100.71	100.71	88.72	
Arnot Gen T3	ESKOM	88.72	88.72	88.72	
Kariba North T - 1(1)	ZESCO	88.38	88.38	88.38	
Kariba North T - 1(1)	ZESCO	88.38	88.38	88.38	
Kariba Borth T1	ZESCO	88.05	88.05	88.05	
Kariba Borth T1	ZESCO	88.05	88.05	88.05	
Kariba North T-2	ZESCO	88.05	88.05	88.05	

Figure 5- 28: Contingency C.G.9, C.G.7, C.G.8, C.G.6 thermal violations

5.15 Scenario 10: Contingency C.G.10 (Gen 3)

Figures 5-29, 5-30 and 5-31 show the results obtained from contingency C.G.10. Even though not part of the six highest contingencies, these results were placed to display a broader range of results that were obtained after the contingency simulations were run. The results show the response of the network to a disturbance cause in the Gen 3 generator.

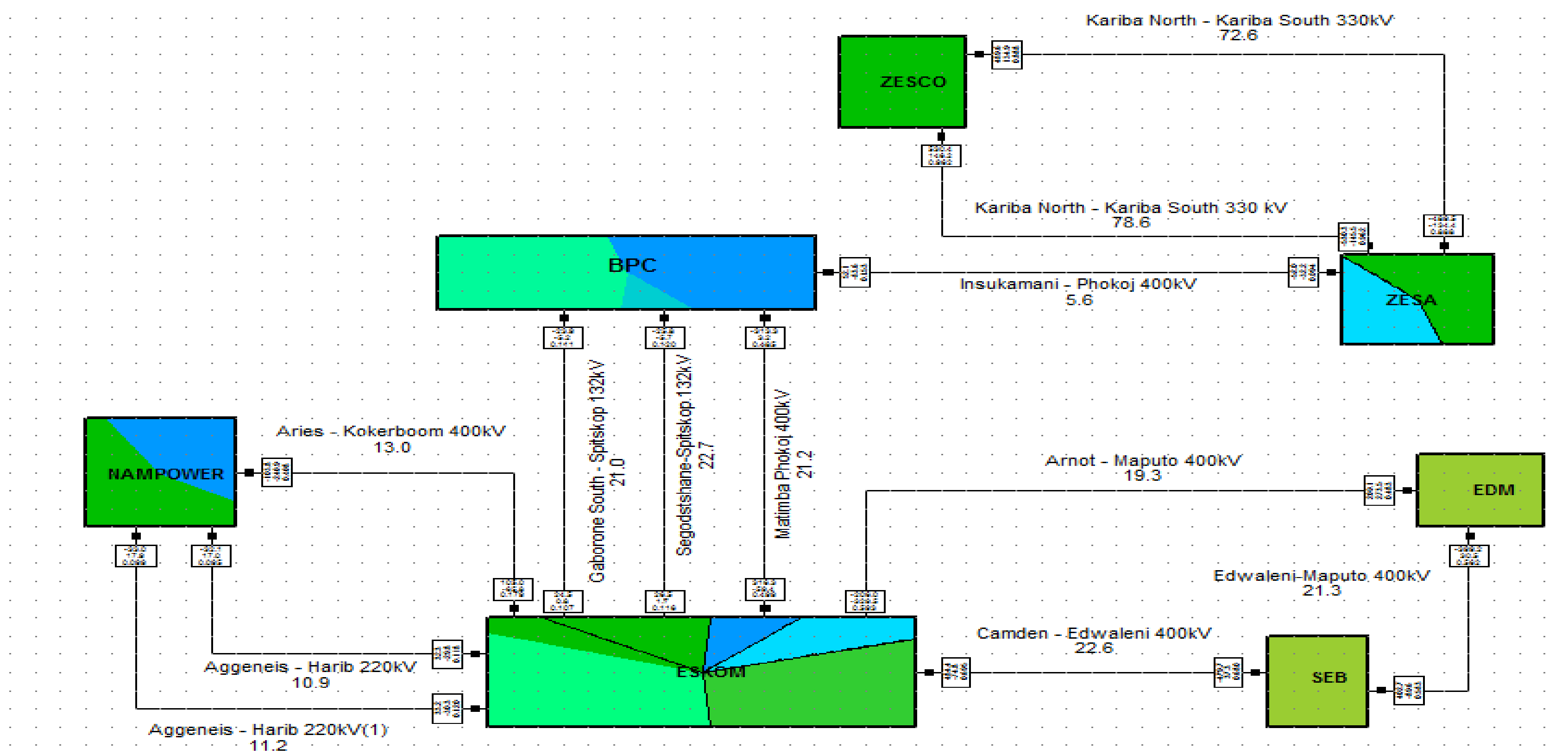


Figure 5- 29: SAPP network post contingency C.G.10

Figure 5-30 shows no significant difference in any of the components post contingency.

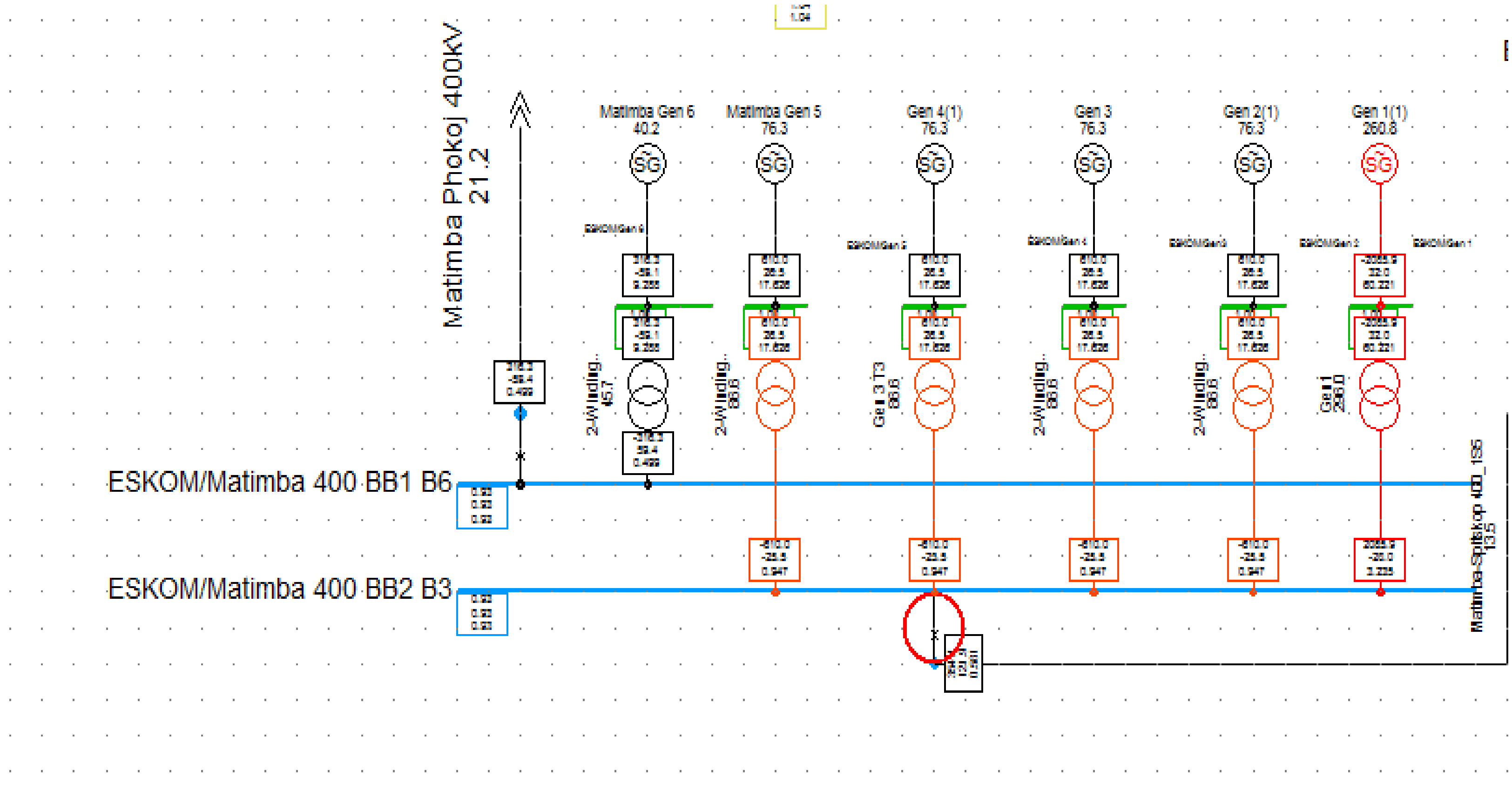


Figure 5- 30: ESKOM C substation post contingency C.G.10

The fig.5-31 shows that post contingency, the Gen1 generator thermal loading from 296.05% to an even higher 346.27%. This explained why no change was seen in fig.5-30 previously as the generator was already overloaded.

Component	Substation	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Base Case and Continuous Loading [0 % - 346 %]
Gen1	ESKOM	346.27	346.27	296.05	
Arnot Gen T6	ESKOM	135.01	135.01	135.01	
Arnot Gen T3	ESKOM	88.72	88.72	88.72	
Kariba North T - 1(1)	ZESCO	88.38	88.38	88.38	
Kariba Borth T1	ZESCO	88.05	88.05	88.05	
Kariba North T-1	ZESCO	88.05	88.05	88.05	
Kariba North T-2	ZESCO	88.05	88.05	88.05	
Kariba North T-3	ZESCO	88.05	88.05	88.05	
Karina North T-1(2)	ZESCO	88.05	88.05	88.05	
2-Winding Transformer(1)	ESKOM	86.65	86.57	86.65	
2-Winding Transformer(2)	ESKOM	86.65	86.57	86.65	
2-Winding Transformer(3)	ESKOM	86.65	86.57	86.65	
Gen 3 T3	ESKOM	86.65	86.57	86.65	

Figure 5- 31: Contingency C.G.10 thermal loading

Table 5-2 shows collectively the several elements that were affected after each named contingency was run.

Table 5- 2: Highest voltage and thermal violations after contingencies

Contingency name	Element affected	Element type	Status
C.L.12	Kokerboom 400 Bus1	Busbar	A voltage step of 0.196p.u is experienced increasing the post contingency busbar voltage to 1.124p.u
C.L.10	Segoditshane 220 Bus 1	Busbar	A voltage drop was experienced from 0.954p.u to the out of limit 0.770p.u
	Segoditshane 220 Bus 2	Busbar	A voltage drop was experienced from 0.954 p.u to 0.770p.u
	Gabarone South No.2 132kV	Busbar	A voltage drop from 0.964p.u to 0.771p.u
	Segoditshane 132 Bus1	Busbar	A voltage drop from 0.960 p.u to 0.771 p.u
	Phokojoe 220 BB	Busbar	A voltage drop from the already out of limit 0.877 p.u to a further 0.833 p.u
	S. Phikiwe 22 BB	Busbar	A voltage drop from 0.877p.u to 0.833 p.u
	Insakumani 400 Bus 1	Busbar	A voltage drop from out of limit value of 0.941p.u to 0.914 p.u
	Phokojoe 400 BB	Busbar	A voltage drop from 0.932 p.u to 0.907 p.u
C.L.11	Kokerboom 400 Bus 1	Busbar	The voltage at the busbar increases post contingency to 1.124 p.u
C.L.7	Arnot Gen T6	Transformer	The thermal loading increases to 176.9% post contingency
	Arnot Gen T3	Transformer	The thermal loading drops slightly to 84.4%
C.L.13	Camden Gen 8T	Transformer	The thermal loading increases to 112% from 80%
C.L.18	Camden Gen 8T	Transformer	The thermal loading increases to 112% from 80%
C.G.5	Segoditshane 220 Bus1	Busbar	A voltage drop from 0.954 p.u to 0.770 p.u
	Segositshane 220 Bus 2	Busbar	A voltage drop from 0.954 p.u to 0.770 p.u

C.G.5	Gabarone South No.2 132	Busbar	A voltage drop from 0.964 p.u to 0.771 p.u
	Segoditshane 132 Bus 1	Busbar	A voltage drop from 0.960 p.u to 0.771 p.u
	S. Phikiwe 22BB	Busbar	A voltage drop from 0.877 p.u TO 0.822 p.u
	Phokojoe 220 BB	Busbar	A voltage drop from 0.877 p.u to 0.833 p.u
	Phokojoe 400 BB	Busbar	A voltage drop from 0.932 p.u to 0.907 p.u
	Insakumani 400 Bus 1	Busbar	A voltage drop from 0.941 p.u to 0.914 p.u
C.G.3	Maputo 400 BB	Busbar	A voltage increase is experienced from 1.028p.u to 1.224 p.u
	Maputo 275 BB1	Busbar	A voltage increase from 1.025p.u to 1.224 p.u
	Infulene 275 BB1	Busbar	A voltage increase from 1.024 p.u to 1.223 p.u
	Matola 66 BB1	Busbar	A volatgte increase from 0.976 p.u to 1.165 p.u
	Edwaleni 400 BB1	Busbar	A voltage increase from 1.022 p.u to 1.122 p.u
	Edwaleni 132 BB 1S	Busbar	A voltage increase from 0.996 p.u to 1.099 p.u
	Edwaleni 132 BB2	Busbar	A voltage increase from 0.996 p.u to 1.099 p.u
	Edwaleni 400 BB2	Busbar	A voltage increase from 0.996 p.u to 1.099 p.u
	Edwaleni 132 BB1N	Busbar	A voltage increase from 0.996 p.u to 1.099 p.u
	2-wind8ing transformer(5)	Transformer	A thermal loading increase is experienced from 70.4% to 86.6%
	Camden Gen 5TX	Transformer	A thermal loading increase is experienced from 70.4% to 86.6%
	Camden Gen 7TX	Transformer	A thermal loading increase is experienced from 70.4% to 86.6%
C.G.20	Camden Gen 8T	Transformer	The thermal loading rose drastically from 80% to 239%
	Arnot Gen T3	Transformer	The thermal loading increased from 88.7% to 100.7%
C.G.7 **C.G.8** **C.G.9** **C.G.6**	Camden Gen 8T		A drastic thermal load increase from 80% to 239%
	Arnot Gen T3		Thermal loading increase from 87% to 100.7%
C.G.10	2 Winding transformer		A thermal loading load is experienced from an exceptionally high 296% to an even higher 346%

CHAPTER 6

POWER SYSTEM SECURITY ENHANCEMENT

There are several methods that are used to enhance the security of power networks that do not conform to the security limits after unforeseen disturbances occurs, some of these methods include;

- Integration of HVDC links into the power grid. In addition to its obvious advantage of maintaining reliability and security, HVDC transmission is also cost effective. As compared to HVAC transmission, its cost reduces as the length of the transmission line increases. HVDC continues to gain popularity globally because of its many advantages and due to technological advances which make it more practical than it was previously makes it more desirable than HVAC.

- Using synchrophasors. An advanced synchrophasor is a device that measures the electrical waves on the grid using a common time source for synchronization. This technological device is one that has only recently become of interest and is used in the power network to enhance reliability and is likely to gain even more popularity with due time. Some of the applications that make the advanced synchrophasor a good option include[56];

  - Improved power system monitoring and visualization to aid power system operators' situational awareness and assist in forestalling a grid collapse through better recognition and response to evolving grid events

  - Validation and derivation of system parameters used in power system models and analytical tools to design and operate a more reliable grid

  - Enhance grid throughput and utilization of existing grid assets.

  - Faster and improved forensic analysis following a disturbance that impacts the power system, especially one that results in a blackout.

  - All of the above results help in improving reliability, power quality, asset utilization and efficiency in grid planning and operations.

- Integrating FACTS into the grid. These are devices that are used to increase controllability and enhance the transmission capability of existing interconnections. FACTS devices are categorised into either series compensators or shunt compensators. Series compensators

- Strategic placement of new interconnections. Theses transmission lines are often referred to as redundant transmission lines as they are used only in the event that the primary transmission line is unable to transfer power due to a fault or disturbance and an alternative route is needed to transfer power.

6.1 Security Enhancement of the SAPP Network Post Contingency C.L.10 (Gaborone south – spitskop)

In order to enhance the security of the SAPP network after the contingency C.L.10, a shunt capacitor rated at 50Mvar was placed in the BPC network in order to inject reactive power into the network to increase the voltage profile. Placement of security enhancement tools is always placed on weakest busbars or points of disturbance[57]. The results show that the BPC network busbars are increased to a level within the required security limit. This can be seen in fig.6-1 which shows the busbars with the green colour to indicate that they are approximately 1.00 p.u. The figure shows the placement of the shunt filter labelled Gab – Spitskop shunt located on the Phokojoe 220 BB.

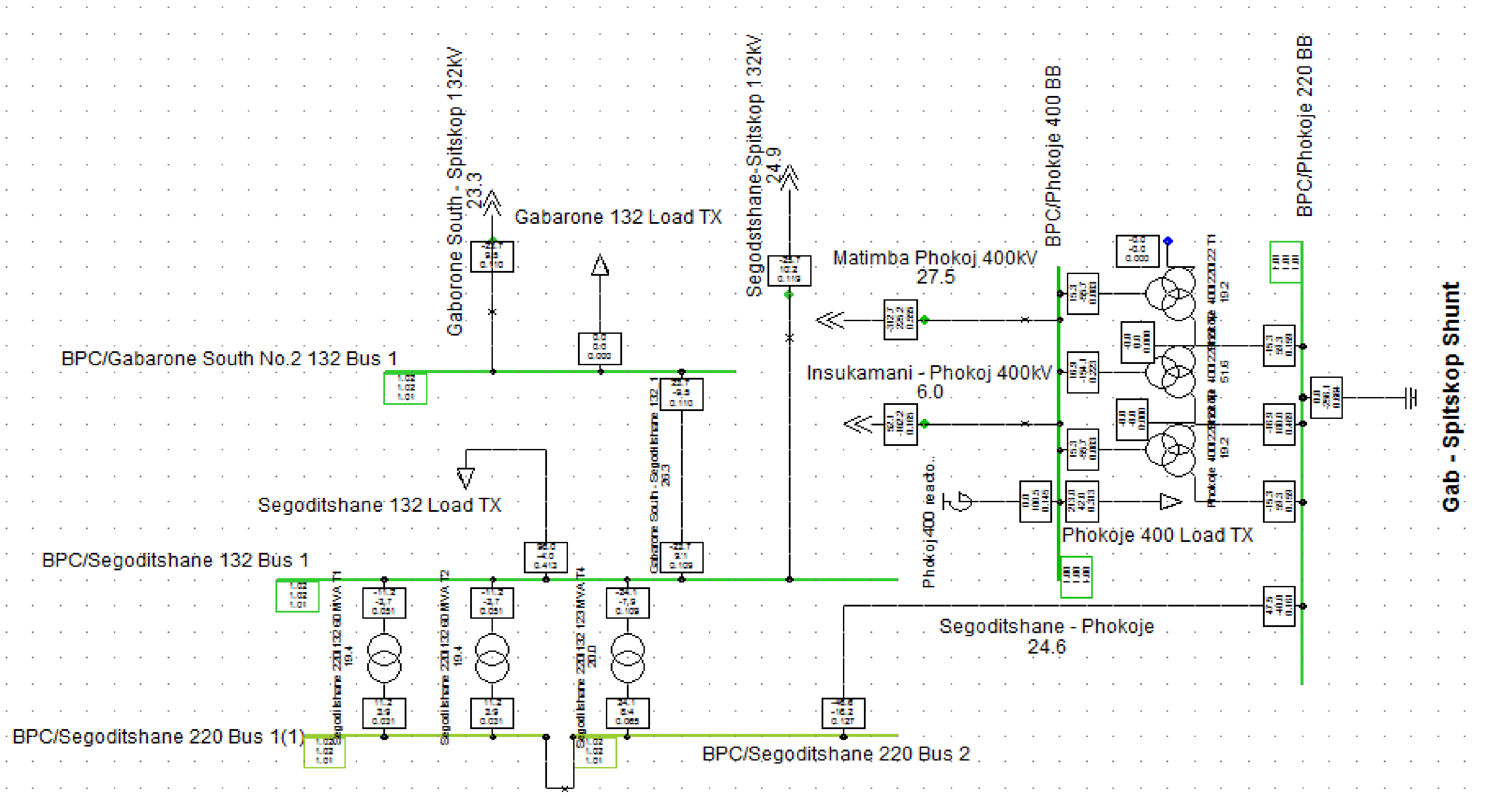


Figure 6- 1: BPC substation after implementation of security enhancement using shunt capacitor post contingency C.L.10 (Gaborone south – spitskop)

The fig.6-2 shows the SAPP network after strategic placement of the shunt capacitor to enhance the security of the network. The substations that dropped previously below the secure voltage post contingency are restored to voltage levels within the accepted range, indicated by the colour change.

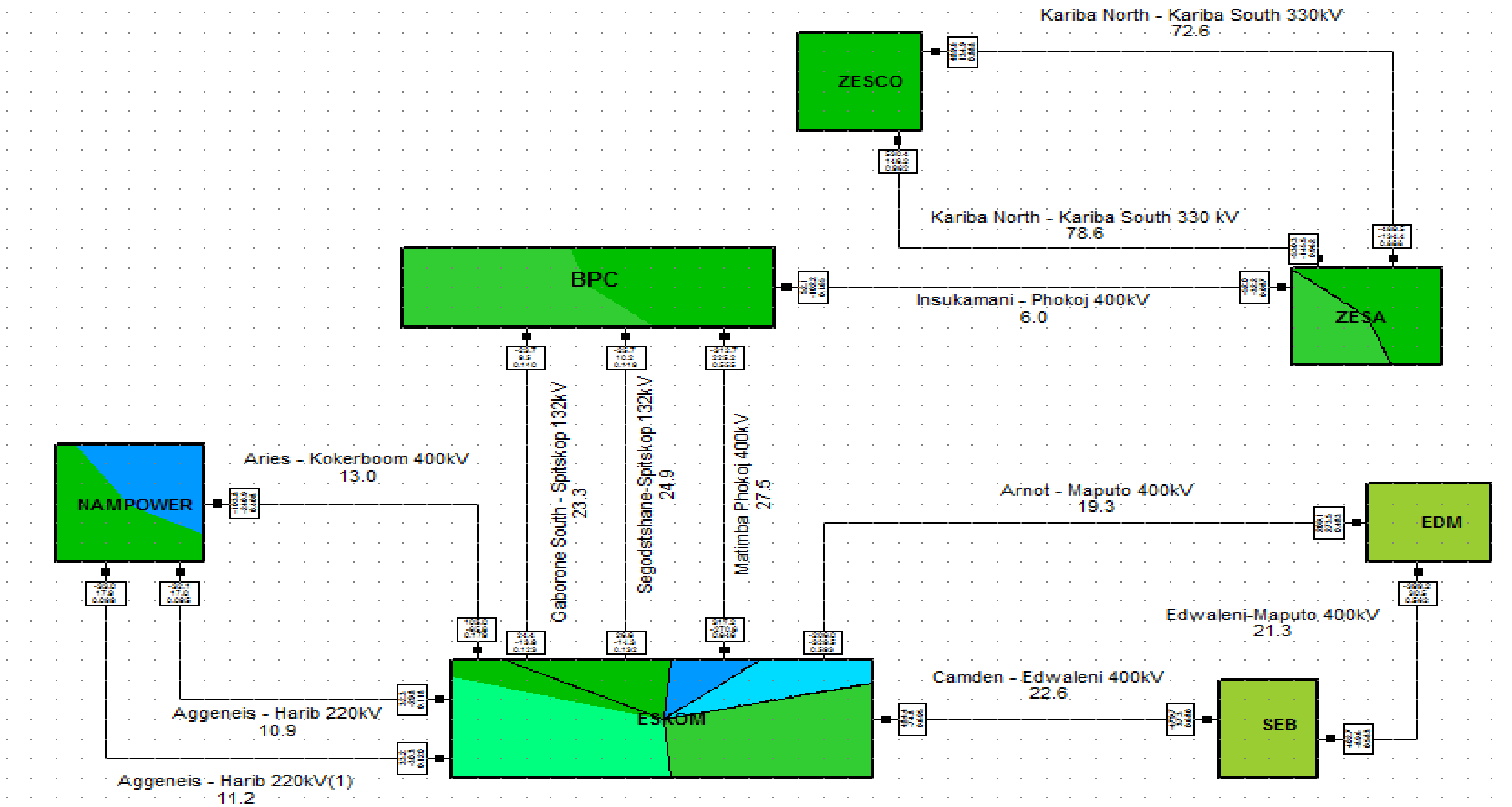


Figure 6- 2: SAPP network after implementation of security enhancement using shunt capacitor post contingency C.L.10 (Gaborone South-Spitskop)

Another analysis was run in which an SVC of the same rating (50Mvar) was placed in the same position as the shunt capacitor. The results obtained from the BPC network after the SVC is placed to enhance the voltage profile is displayed in fig 6-3. The SVC, labeled Phokojoe SVC is located on the Phokojoe 220 BB busbar. The SVC increases the voltage profile of the previously low voltages obtained post contingency.

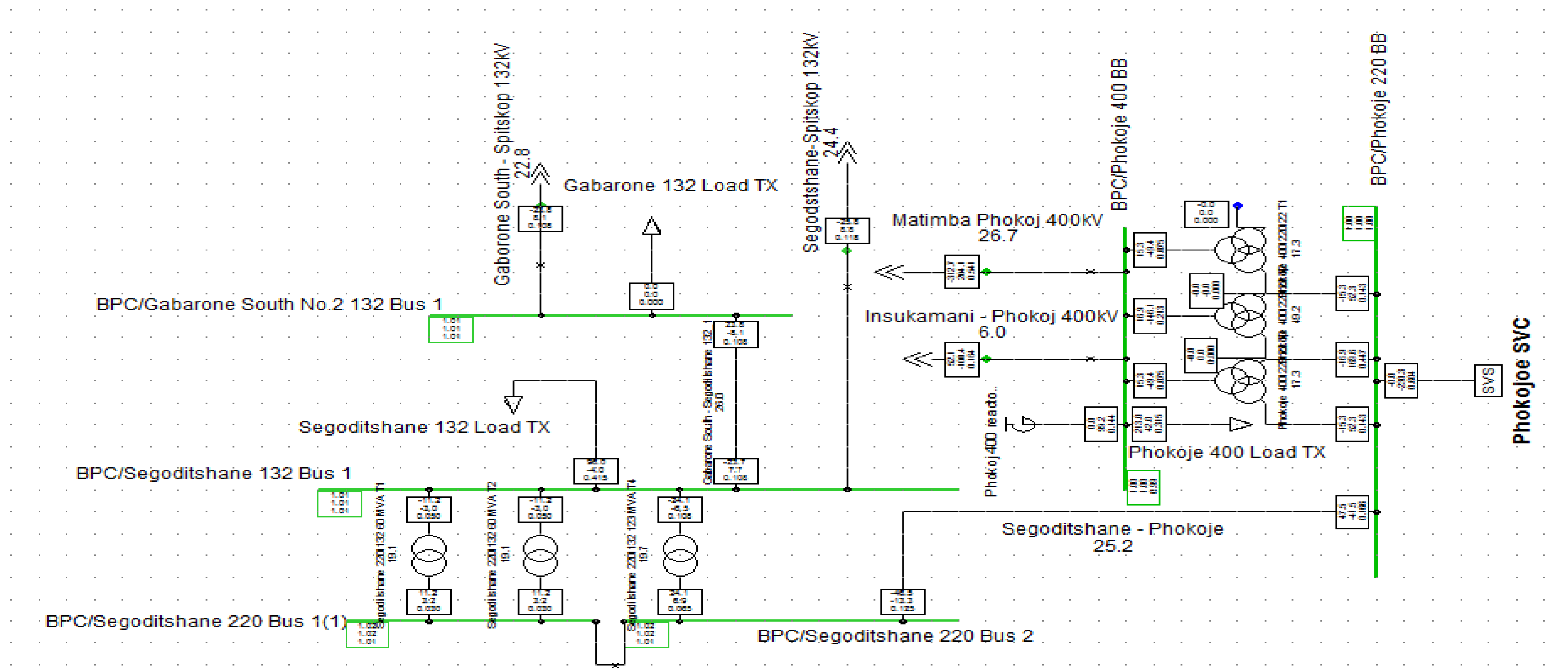


Figure 6- 3: BPC substation after implementation of security enhancement using SVC post contingency C.L.10 (Gaborone south – spitskop)

Table 6-1 shows the comparison in the value of the voltages after the contingency C.L.10 occurred and the results after the shunt capacitor and SVC were placed in the network to enhance the network security.

Table 6- 1: Busbar voltages before and after security enhancements post contingnecy C.L.10 (Gaborone South - Spitskop)

Busbar name	Voltage before security enhance (p.u)	Voltage after application of shunt capacitor (p.u)	Voltage after application of SVC (p.u)
Segoditshane 220 Bus 1	0.77	1.02	1.02
Segoditshane 220 Bus 2	0.77	1.02	1.02
Gaborone South No2 132 B1	0.77	1.02	1.01
Segoditshane 132 Bus 1	0.77	1.02	1.01
Phokojoe 220 BB	0.83	1.01	1.00
S. Phikiwe 22 BB	0.83	1.01	1.00
Phokojoe 400 BB	0.91	1.00	1.00
Insukumani 400 Bus 1	0.91	1.01	1.00

It can be seen from table 6-1 that the results obtained after security enhancement using both the shunt capacitor and the SVC were similar. The table shows an improvement in the networks security by 23.6% using the shunt capacitor and by 22.87% using the SVC. Inspite its slightly higher level of security increment, the shunt capacitor is a more desirable option because it is more economical than the most FACTS devices, the SVC included. A comparison can be seen in table 6-2 which shows the price in US$ per Kvar [58] in the global market. The advantage the SVC has over the shunt capacitor, however, is that beyond a certain level of compensation it is still able to maintain a good voltage regulation which is not possible with the shunt capacitor. The shunt capacitor delivers reactive power that is proportional to the square of the terminal voltage, thus creating a problem when/if the terminal voltage drops too low.

Table 6- 2: Comparative prices of shunt capacitor,SVC's and STATCOM's in US$

Shunt controller	**Cost (US$)**
Shunt capacitor	8/Kvar
SVC	40/Kvar
STATCOM	50/Kvar

6.2 Security Enhancement of the SAPP Network Post Contingency C.L.12 (Harib-Kokerboom2)

The shunt reactor is applied in the C.L.12 (Harib-Kokerboom 2) contingency in which an overvoltage was experienced in the busbars after a disturbance occurred in the Harib-Kokerboom 2 transmission line. After the disturbance occurs in the line there is an increase in the reactive power causing an increase in the voltage profile. The shunt reactor is used to absorb or consume the reactive power reducing the voltage profile of the line.

There was a shunt reactor already present in the network connected to the Kokerboom 400 bus1 busbar pre contingnecy with a rated reactive power of 100 Mvar. Since less reactive power was needed in the network in order to drop the volatge profile, this value was reduced to 70Mvar. This resulted in a voltage drop in in the busbars to the acceptable secure limit. Fig 6-4 shows the NAMPOWER substation after the securitry enhancement has been applied. The shunt reactor that was adjusted is labeled kokerboom 400 RX1and is connected to the Kokerboom 400 bus 1 busbar.

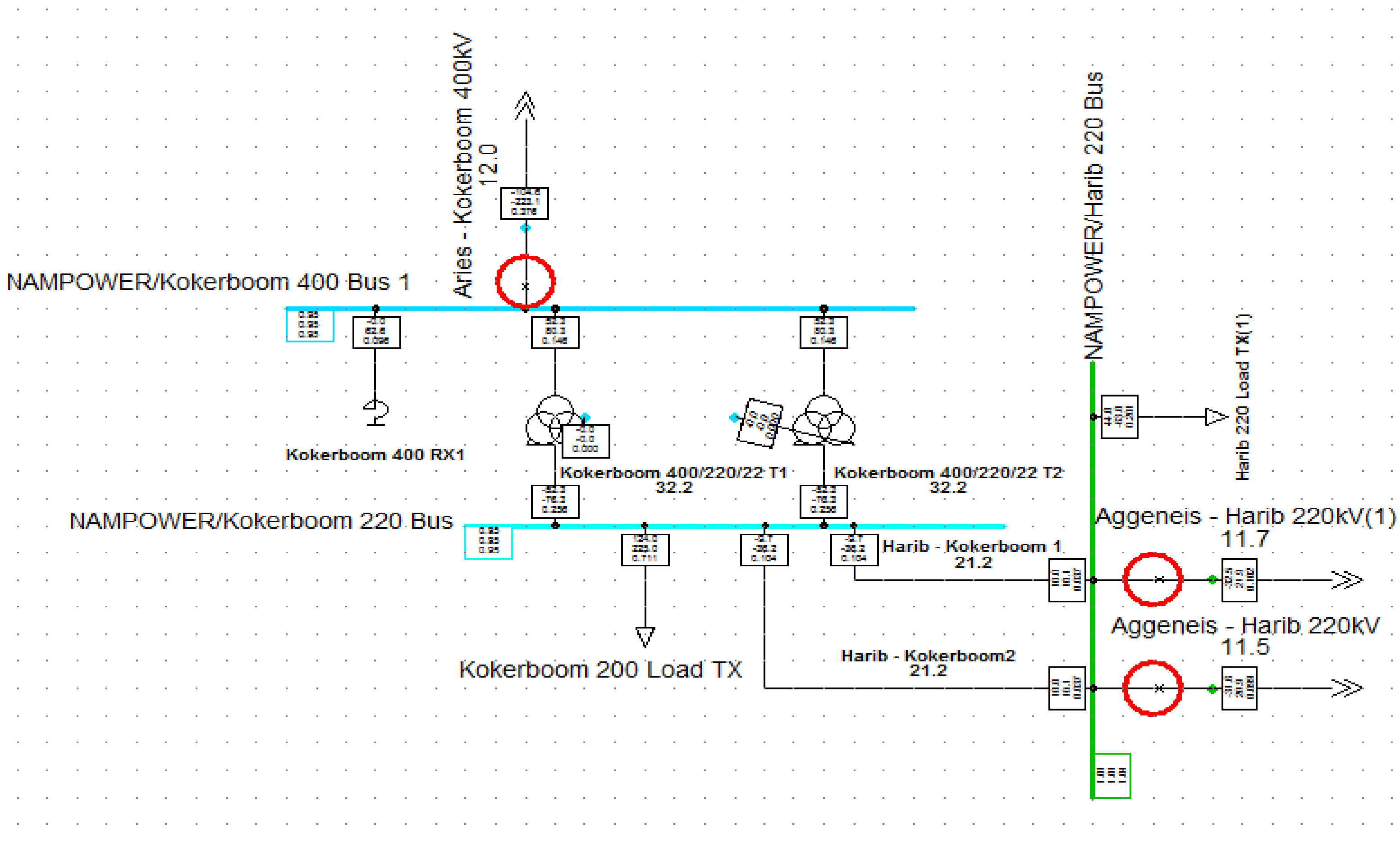


Figure 6- 4: NAMPOWER substation after security enhancement implementation post contingency C.L.12 (Harib - Kokerboom 2)

Fig.6-5 shows the SAPP network after the security enhancement post contingency C.L.12. Most of the substations are restored to the correct value of voltages within the accepted secure limits as indicated by the blue and green colours.

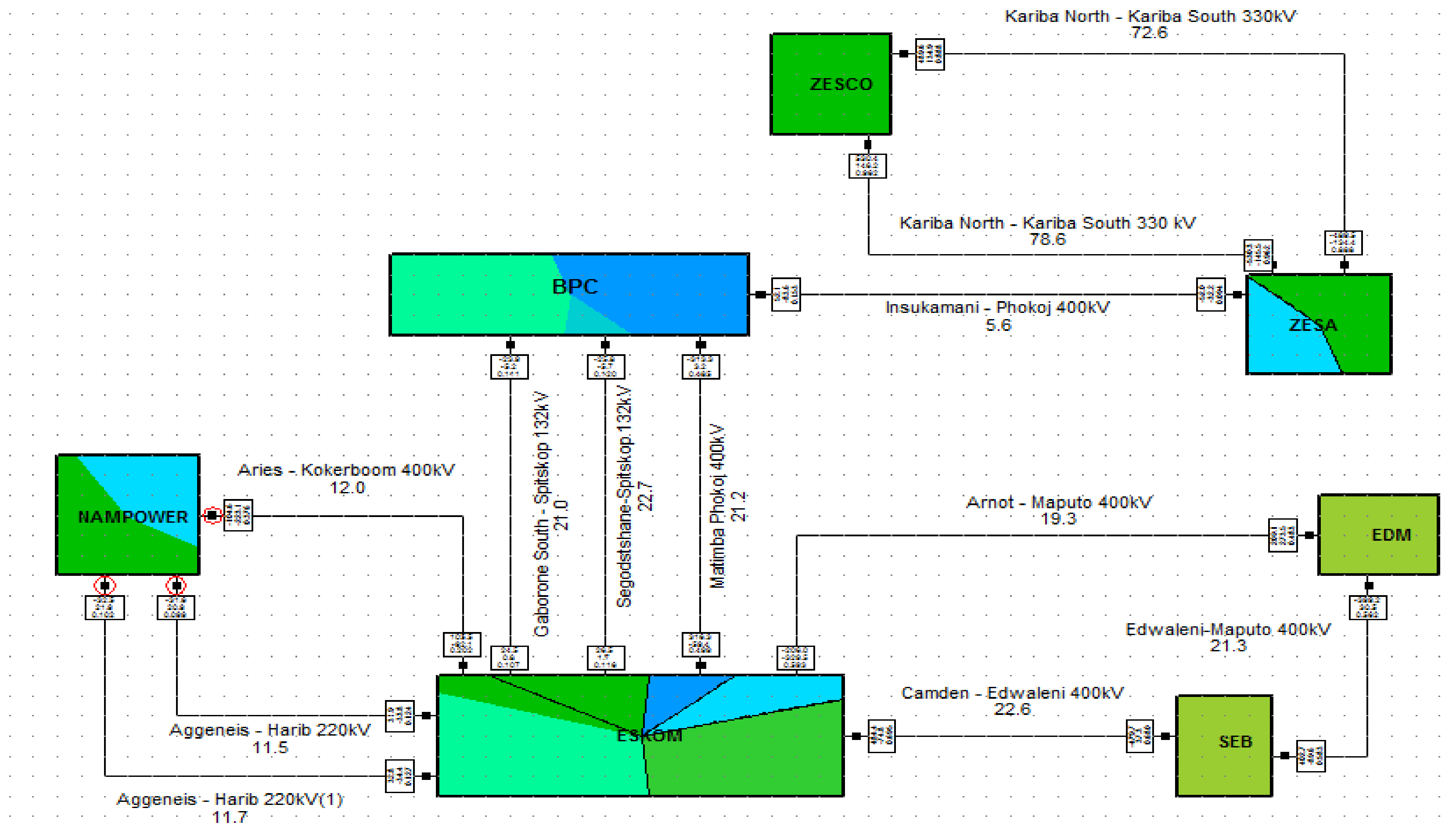


Figure 6- 5: SAPP substation after security enhancement implementation post contingency C.L.12 (Harib - Kokerboom 2)

Table 6-3 displays the value of the busbar voltage before and after the compensation of the kokerboom 2 using the shunt reactor. Before compensation the busbar voltage was beyond the required 1.05p.u required limit but dropped to 0.95p.u which is within the security limit.

Table 6- 3: Busbar voltage of the Kokerboom busbar1 before and after security enhancement post contingency C.L.12

Busbar name	Before compensation	After compensation
Kokerboom busbar 1	1.12	0.95

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

The SAPP network was modelled and built using DIgSILENT PowerFactory. The entire SAPP network, consisting of 1407 busbars (Appendix 1) incurred computational constraints due to the size of the network. Therefore, the model was reduced to only include the path that is directly used by SAPP in the transferring of power from one member state to the next and consisted only 58 busbars (Appendix 2). The simplified network was modelled to facilitate the HV network consisting of transmission voltage levels of 132kV, 220kV, 330kV and 400kV.

The contingency ranking method used in this paper to determine the severity of security violations in the SAPP network is very systematic and methodological and can be applied to several networks, both larger and smaller, in order to comprehensively study several types of first level contingencies. This is reflected in the correlation of results yielded from the MATLAB codes and the contingency analysis graphs simulated in DIgSILENT PowerFactory. The simulations were focused on the primary contingency disturbance (N-1 criterion) of the generators and transmission lines in the network because these are the highest recorded faults that are likely to occur in any power network. The vulnerability of the SAPP network is exposed after the contingency analysis simulation of the designed model. The results attained not only reveal the extent to which the power network is unsecure in accordance with the SAPP transmission criteria but also reveal the severity with which each exact component is affected after each possible disturbance. These disturbances lead to differed levels of security severities that are characterized by voltage and thermal loading discrepancies. From the results obtained from the simulations the most severe were those induced by the Harib-Kokerboom 1 transmission line and the Synchronous machine (2) generator which both led to voltage and thermal loading violations.

This research highlights the SAPP networks weak spots and this allows for the necessary reinforcements in these areas of the network that will mitigate and prevent the problems that are caused by various disturbances. This research demonstrates the use of shunt capacitors and shunt reactors as being the most necessary security enhancement tools that can be used for the disturbances encountered. The factors taken into consideration were the levels to which the busbar voltages had either dropped and/or increased to post contingency and the price of these devices in comparison to the equally applicable FACTS devices.

7.2 Future work

Finally, other encouraged works include performing a further study by considering the reaction of the network when an N-1-1 contingency occurs. This is a secondary contingency in which more than one element is outaged at each instance for example, any two transmission lines, or two generators and so on. This will prove highly advantageous with the growing complexity of power networks and the increased probability of the occurrence of secondary contingencies.

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Appendix 1. SAPP Base case system summary before network was minimized.

```
-----------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                 Total System Summary |
-----------------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence          |  Automatic Model Adaptation for Convergence          No          |
|    Automatic Tap Adjust of Transformers         Yes   |  Max. Acceptable Load Flow Error for                             |
|    Consider Reactive Power Limits               Yes   |     Nodes                                            1.00 kVA    |
|                                                       |     Model Equations                                  0.10 %      |
-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
| Total System Summary                          | Study Case: Base Case                 | Annex:                      / 1  |
-----------------------------------------------------------------------------------------------------------------------------
|                                                                                                                           |
| No. of Substations    187      No. of Busbars       1407      No. of Terminals     9343      No. of Lines          622     |
| No. of 2-w Trfs.      338      No. of 3-w Trfs.     418       No. of syn. Machines 184       No. of asyn.Machines  0       |
| No. of Loads          226      No. of Shunts        206       No. of SVS           10                                     |
|                                                                                                                           |
| Generation          =   34208.38  MW        2691.17  Mvar   34314.08  MVA                                                |
| External Infeed     =       0.00  MW           0.00  Mvar       0.00  MVA                                                |
| Load P(U)           =   33642.78  MW        8188.44  Mvar   34624.95  MVA                                                |
| Load P(Un)          =   33678.70  MW        8173.66  Mvar   34656.36  MVA                                                |
| Load P(Un-U)        =      35.92  MW         -14.78  Mvar                                                                 |
| Motor Load          =       0.00  MW           0.00  Mvar       0.00  MVA                                                |
| Grid Losses         =     565.60  MW       -5340.28  Mvar                                                                 |
| Line Charging       =                     -18932.50  Mvar                                                                 |
| Compensation ind.   =                       7287.98  Mvar                                                                 |
| Compensation cap.   =                      -7444.97  Mvar                                                                 |
|                                                                                                                           |
| Installed Capacity  =   45165.72  MW                                                                                      |
| Spinning Reserve    =   10952.67  MW                                                                                      |
|                                                                                                                           |
| Total Power Factor:                                                                                                       |
|   Generation        =         1.00  [-]                                                                                   |
|   Load/Motor        =  0.97 / 0.00  [-]                                                                                   |
|---------------------------------------------------------------------------------------------------------------------------|
```

Appendix 2. SAPP model base case summary of the minimized network

```
-------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                              Grid Summary |
-------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence          |  Automatic Model Adaptation for Convergence         No      |
|    Automatic Tap Adjust of Transformers        No     |  Max. Acceptable Load Flow Error for                        |
|    Consider Reactive Power Limits              No     |     Nodes                                           1.00 kVA |
|                                                       |     Model Equations                                 0.10 %   |
-------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------
| Grid: Grid               System Stage: Grid          | Study Case: Study Case              | Annex:            / 1 |
-------------------------------------------------------------------------------------------------------------------
| Grid: Grid               Summary                                                                                  |
|                                                                                                                   |
| No. of Substations     8        No. of Busbars      58       No. of Terminals     143      No. of Lines          24 |
| No. of 2-w Trfs.       24       No. of 3-w Trfs.    21       No. of syn. Machines 22       No. of asyn.Machines  0  |
| No. of Loads           17       No. of Shunts       15       No. of SVS           0                                  |
|                                                                                                                   |
| Generation          =   2475.88  MW        410.56  Mvar    2509.69  MVA                                           |
| External Infeed     =   -948.93  MW       -376.24  Mvar    1020.80  MVA                                           |
| Inter Grid Flow     =      0.00  MW          0.00  Mvar                                                          |
| Load P(U)           =   1504.69  MW        896.09  Mvar    1751.30  MVA                                           |
| Load P(Un)          =   1504.69  MW        896.09  Mvar    1751.30  MVA                                           |
| Load P(Un-U)        =      0.00  MW          0.00  Mvar                                                          |
| Motor Load          =      0.00  MW          0.00  Mvar       0.00  MVA                                           |
| Grid Losses         =     22.27  MW       -843.04  Mvar                                                          |
| Line Charging       =                    -1281.63  Mvar                                                          |
| Compensation ind.   =                      299.32  Mvar                                                          |
| Compensation cap.   =                     -318.06  Mvar                                                          |
|                                                                                                                   |
| Installed Capacity  =   8031.14  MW                                                                              |
| Spinning Reserve    =   6095.25  MW                                                                              |
|                                                                                                                   |
| Total Power Factor:                                                                                               |
|   Generation        =        0.99  [-]                                                                           |
|   Load/Motor        =  0.86 / 0.00  [-]                                                                           |
|-------------------------------------------------------------------------------------------------------------------|
```

Appendix 3. Line outage coding using MATLAB

```
% Active power performance index (PIp)
% Vi is the Voltage at bus i by NR load flow
Vi=[0.992,0.997,0.997,0.928,0.968,1.019,1.018,0.96,0.964,0.931,0.931,1.02
9,0.932,1.001,1.001,1,1.03,0.932,0.931,0.877,0.877,0.954,0.96;];
% Vj is the Voltage at bus J by NR load flow
Vj=[1,0.98,0.98,1,1.033,1.018,1.033,0.964,1,0.997,0.997,1.03,0.941,1,1,1.
026,1.031,0.931,0.929,0.877,0.877,0.877,1;];
% X is the Reactance of the line connecting bus I and j in p.u
X=[0.357,0.263,0.256,0.589,0.231,0.216,0.233,0.026,0.354,0.59,0.59,0.022,
0.33,0.002,0.003,0.612,0.022,0.281,0.011,0.014,0.014,0.694,0.351;];
% Pimax is the MW maximun capacity of line I in p.u
Pimax= [Vi.*Vj./X];
```

```
% Pi MW capacity of line i
Pi=[-0.159,-0.064,-0.066,-0.208,-0.783,1.36,1.188,-0.048,-0.048,-0.02,-
0.02,-0.38,0.104,1.061,0.979,0.142,-0.38,-0.627,0.708,0,0,-0.093,-
0.052;];
% W is the real non-negative weighting factor
W=1;
% n is the Penalty function
n=1;
% Active power performance index is calculated using the below equation
PIp=[W/2*n]*[Pi./Pimax].^(2.*n);
% Sum
PIpsum=sum(PIp)
%Reactive power performance index PIV is calculated using the equations
below
%Visp is the specified voltage of each busbar which can also be referred
to as the nominal voltage which is normally 1 p.u
Visp=1;
% dvilim is the voltage deviation limit
dvilim=[-0.008,0.017,0.017,-0.072,-0.065,0,-0.015,-0.004,-0.036,-0.066,-
0.066,-0.001,-0.008,0.001,0.001,-0.026,-0.001,0.002,0.002,0,0,0.077,-
0.04;];
% PIV is found by the formular
PIv = [w/2*n]*[(abs(Vi) - abs(Visp))/dvilim].^(2.*n);
% Sum
PIvsum=sum(PIv)
```

Appendix 4. Generator outage MATLAB coding

```
% The generator outage
Active power performance index (PIp)
% Vi Voltage at bus i by NR load flow
Vi=[1.03,1.03,1.03,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1.03,1,1;];
% Pimax is the MW maximun capacity of line i in p.u
Qi=[0,0,-0.422,-0.045,-0.045,-
0.045,0.064,0.053,0.053,0.053,0.148,0.14,0.148,0.148,0.151,0.148,0.053,-
0.118,-0.423,0.005,0.639;];
Qimax=[0.432,0.432,0.378,0.437,0.437,0.437,0.4  0.4 0.4 0.4
0.45,0.45,0.45,0.45 0.45,0.45,0.4,0.4,0.378,1,0.4];
% W is the real non-negative weighting factor
W=1;
% n Penalty function
n=1;
% PIp
% Qi max is the Reactive power limit at bus I in p.u
% Qi is the reactive power at bus i in p.u
PIp=[W/2*n]*[Qi./Qimax].^(2.*n);
% Sum
PIpsum=sum(PIp)
%Visp is the specified voltage of each busbar which can also be referred
to as the nominal voltage which is normally 1 p.u
Visp=1;
% dvilim is the voltage deviation limit
dvilim=[0.03,0.03,0.03,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0.03,0,0;];
% PIV of the generator outage is found using the equation belo
PIv = [w/2*n]*[(abs(Vi) - abs(Visp))/dvilim].^(2.*n);
% Summation of all calculated values
```

```
PIvsum=sum(PIv)
% hence the generator outage performance index is found by adding the two
equations as shown below
PIq=PIvsum +PIpsum
```