NELSON MANDELA UNIVERSITY

IMPACT OF INTERGRATING TEEBUS HYDRO POWER ON THE UNBALANCED DISTRIBUTION MV NETWORK

By:

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DECLARATION

I, **Lindani Mthethwa**, declare that the contents of this Dissertation represent my own unaided work, and that the Dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Nelson Mandela Metropolitan University (NMMU).

Signature:  **Date: 15 March 2018**

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NOMENCLATURE AND DEFINITION OF TERMS

Abbreviation	Description
CNC	Customer Network Centre
SAIDI	System Average interruption Duration Index
SAIFI	System Average Interruption Frequency Index
CNL	Customer Network Link
DSM	Demand Side Management
GIS	Geographical Information System
LV	Low Voltage (<1000V)
HV	High Voltage (>33kV)
MV	Medium Voltage (1000V-33kV)
LCC	Life-cycle Cost(ing)
LPU	Large Power User
QOS	Quality of Supply
S/S	Substation
GLF	Geo Load Forecast
NERSA	National Energy Regulator of South Africa
NDP	Network Development Plan(ning)
NMP	Network Master Plan(ning)
PEM	Project Evaluation Model
QoS	Quality of Supply
SPU	Small Power User
TDP	Transmission Development Plan
IPP	Independent Power Producer
Dx & Tx	Distribution & Transmission
MV90	Billing System or Remote Statistical Metering System
Trfr	Transformer
SVC	Static Var Compensator
STATCOM	Static Synchronous Compensation
MVA	Mega Volt Ampere
MW	Megawatt
kV	Kilovolts
MTS	Main Transmission Station
WEF	Wind Energy Facility
DC	Direct Customer
POC	Point of connection

Abbreviation	Description
PCC	Point of Common Coupling
p.u	Per Unit
REF	Restricted Earth Fault
DFIG	Double Fed Induction Generator
IG	Induction Generator
Hydroelectricity	Any electricity that is generated by flow of water
AUX	Auxiliary Contact
BT	Circuit Breaker Fail Isolate
BZ	Bus Zone
CT	Current Transformer
CB	Circuit Breaker
DIFF	Differential
E/F	Earth Fault
HIM	Human Machine Interface
IED	Intelligent Electronic Device
IDMTL	Inverse Definite Minimum Time Lag
LAP	List of Approved Products
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MTR	Master Trip Relay
OLA	Oil Level Alarm
PAC	Protection, Automation and Control
RTU	Remote Terminal Unit
RPRR	Rapid Pressure Rise Relay

ABSTRACT

Small hydro power sources have been identified as one of the renewable energy technologies that the South African government is focusing on in order to generate more electricity from renewable/independent resources. Due to the low carbon output of most renewable energy technologies and the carbon intensive power generation technologies that are currently being used in South Africa e.g. Hydro, coal, gas, and etc. further pressure is increasing to incorporate cleaner forms of generation. In 2002 a study focusing on the hydropower potential was compiled providing an assessment according to conventional and unconventional possibilities for all the provinces.

Nowadays, the power electricity demand is growing fast and one of the main tasks for power engineers is to generate electricity from renewable energy sources to overcome this increase in the energy consumption and at the same time reduce environmental impact of power generation.

Eskom Distribution Eastern Cape Operating Unit (ECOU) was requested to investigate the feasibility of connecting a small hydro power scheme located in the Teebus area in the Eastern Cape. The Eastern Cape in particular, was identified as potentially the most productive area for small hydroelectric development in South Africa for both the grid connected and off grid applications.

These network conditions are in contrast to the South African electricity network where long radial feeders with low X/R ratios and high resistance, spanning large geographic areas, give rise to low voltages on the network.

Practical simulation networks have been used to test the conditions set out in the South African Grid Code/NERSA standard and to test the impact of connecting small hydro generation onto the unbalanced distribution network. These networks are representative of various real case scenarios of the South African distribution network.

Most of the findings from the simulations were consistent with what was expected when comparing with other literatures. From the simulation results it was seen that the performance of the variable speed generators were superior to that of the fixed speed generators during transient conditions. It was also seen that the weakness of the network had a negative effect on the stability of the system.

It is also noted that the stability studies are a necessity when connecting the generators to a network and that each case should be reviewed individually. The fundamental cause of voltage instability is identified as incapability of combined distribution and generation system to meet excessive load demand in either real power or reactive power form.

Chapter 1. INTRODUCTION

1.1 Introduction

One of the major concerns, particularly in the Teebus area is that the existing distribution network already contains the quality of supply issues due to the nature of the customers being agricultural load (irrigation for livestock). The integration of hydro generation into an existing unbalanced distribution network system has many impacts on the network, including amongst others, the power quality, network performance, voltage stability, voltage regulation and power protection. Further, unbalancing of the supply systems may distort the supply voltage at the point of common coupling (PCC).

The research indicates that voltage rise is likely to form a key constraint to the widespread application of small Hydro plants in South Africa and other African countries. The research will look at the investigation and analysis of the impact that integration of small hydropower may have on power quality, voltage regulation, voltage instability, network performance and frequency of the unbalance on the distribution network.

1.1.1 Electrical Energy in South Africa

Small-scale Hydropower is a proven, mature technology with a long track record. Although not well documented, small-scale Hydro technology has played an important role in the provision of energy to urban and rural areas in South Africa. The gold mines at Pilgrims' Rest, for example, were powered by two 6kW hydro turbines as early as 1892. Two years later, a 45kW turbine augmented those turbines to power the first electrical railway in 1894. [1]

Nowadays, the power electricity demand is growing fast and one of the main tasks for power engineers is to generate electricity from renewable energy sources to overcome this increase in the energy consumption and at the same time reduce environmental impact of power generation

In the "Baseline study on Hydropower in South Africa", which was developed as part of the Danish support to the South African Department of Minerals and Energy, Barta [2] investigates the installed capacities of hydropower in South Africa and the potential for new developments. He concludes that twice more the installed capacity of the present installed hydropower capacity below 10 MW can be developed in the rural areas of the Eastern Cape, Free State, KwaZulu Natal and Mpumalanga. In South Africa 247MW potential for new small-scale Hydro development is believed to exist in the rural areas of the Eastern Cape, Free State, KwaZulu-Natal and Mpumalanga and embedded in water transfer and gravity-fed systems throughout the country. Of the country's hydro potential, South Africa only has an installed capacity of 38 MW [2].

Government support for renewable energy is governed through the 2003 Renewable Energy White paper, which sets a target of 10 000 GWh of renewable energy to be achieved by 2013 [3]. No specific targets were set in this White Paper for the different renewable energy technologies and very little has been done to ensure the country will reach this target. An update process for the White Paper was started in 2009 with support of the DBSA and World Bank, but has not resulted in an updated White Paper and/or target.

In 2010 the Department of Energy presented the Integrated Resource Plan (IRP2010), outlining the electricity generation mix for the period up to 2030. According to the policy adjusted development plan that was approved by cabinet, the country will see 17.8 GW of renewable energy as part of the energy mix in 2030. The main source of hydropower in the IRP2010 will come from imported electricity (approx. 5.2 GW by 2030), while local, small scale hydropower shares an allocation of 125 MW with landfill gas based electricity [2].

South Africa dominates the region in terms of both installed small hydropower capacity and available potential. Its potential includes the novel development of harnessing hydropower using existing infrastructure such as water distribution channels.

Although South Africa is classified as a water-scarce country it is believed that substantial hydropower development is possible. In a collaborative study conducted by the Department of Minerals and Energy (DME), Council for Scientific and Industrial Research (CSIR) and Eskom it was established that the total potential small (1 MW–10 MW) and micro hydropower capacity in South Africa is 5,16 GW with an additional long-term possible exploitation of some 2 GW [3]. The Eastern Cape was identified as potentially the most productive area for macro hydroelectric development in South Africa and it has been determined that 6 000 – 8 000 potential sites exist along the eastern escarpment [3].

At this stage no internationally agreed definitions of the different hydro sizes exist. A generic distinction though is between “large” hydro and “small” hydro. The most generally accepted definition of “small” has been set by the World Commission on Dams, which set the upper limit for small hydro at 10 MW of installed capacity, although large countries as China and India tend to put the limit higher at 50 MW and 25 MW respectively. Recently some international donors seem to use a maximum capacity of 15 MW when referring to small hydro. Within the range of small hydro, distinction can be made between the following [3]:

- Mini ≤ 1MW
- 300kW ≥ Micro ≥ 100kW
- 20kW ≥ Pico ≥ 5kW

Micro and pico hydro installations are mostly found in developing countries for energy provision to isolated communities where the national electricity grid is not available, whereas mini hydro tends to be grid connected. Small hydro power plants less than 10MW can provide electricity in remote areas with minimal environmental impact and a lifespan of 30 years or more.

1.1.2 Small Hydro – South Africa

To support the development of small-scale Hydro resources, the South African government, through the Departments of Energy, Water and Sanitation and National Treasury, conducted a feasibility study in 2011 for small-scale hydropower at twenty-six dams; part of the National Water Resource Infrastructure under the Department of Water and Sanitation (DWS). The study identified 22 sites with high potential feasibility for development. Based on the study findings, policy to regulate the development of these resources is being augmented by the DWS [4]

It has been shown in an assessment conducted by the DME (2002), that there is a significant potential for development of all categories of hydropower in the short- and medium-term in specific areas of the country. Figure 1-1 shows all areas with hydro potential in South Africa.

For example, the Eastern Cape and KwaZulu-Natal provinces are endowed with the best potential for the development of small (i.e. < 10 MW) hydropower plants. Previous research identified the Eastern

Cape Province (particularly the area of the former Transkei) and the Lower Orange River as potentially the most productive areas for macro hydroelectric development in South Africa.

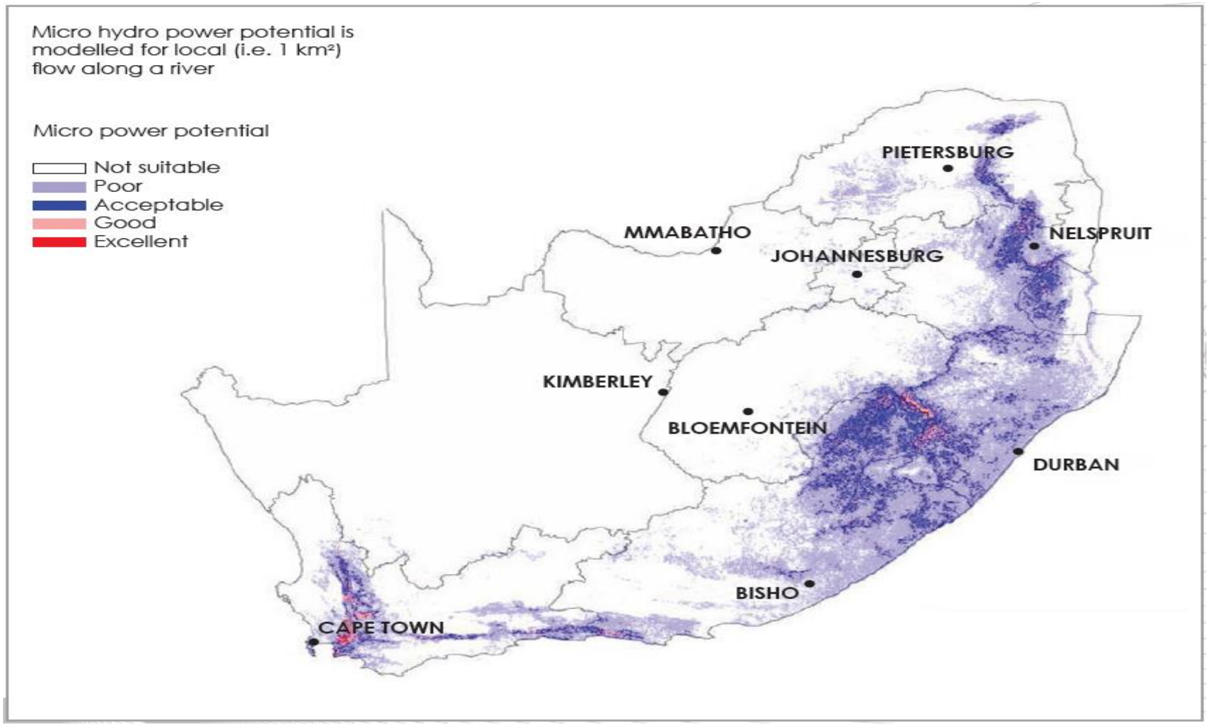


Figure 1-1: Areas with micro hydro potential in South Africa **[4]**

ECOU was requested to investigate the feasibility of connecting a small hydro power scheme located in the Teebus area in the Eastern Cape. The main purpose of the Teebus tunnel is to transfer water from Gariep Dam via an underground pipe and feed to the Eastern Cape for irrigation, urban and industrial use. A small hydro power plant of approximately 600kW was installed almost 40 years ago but has never been in operation due to switchgear damage just after commissioning. The waterways exist and all the major infrastructure investments have been done long ago. Based on the available hydraulic data for 40 years a preliminary study showed that with the available head and flow a configuration with two horizontal shaft turbines, each with 3.5 MW is possible. There is a plan to rehabilitate the Teebus Hydro station. According to ''Hydro Power Station Phase 2 report'' the prefeasibility study was concluded in August 2014 and the study investigated at concept level of the detail possible turbine and generator configuration that could be retrofitted within the existing turbine hall with minimal breaking of the cavern. The existing generators will be replaced with 2 x 5.64MW vertical Francis turbines. The project will contribute to sustainable development in South Africa through supporting the development of renewable energy in the country and support Eskom's aspirations for Renewables Energy. In this paper the upper limit of 10MW installed capacity is used when referring to small hydro and this is all grid-connected.

The geographical study area shown in Figure 1-2 below is the focus of this research:

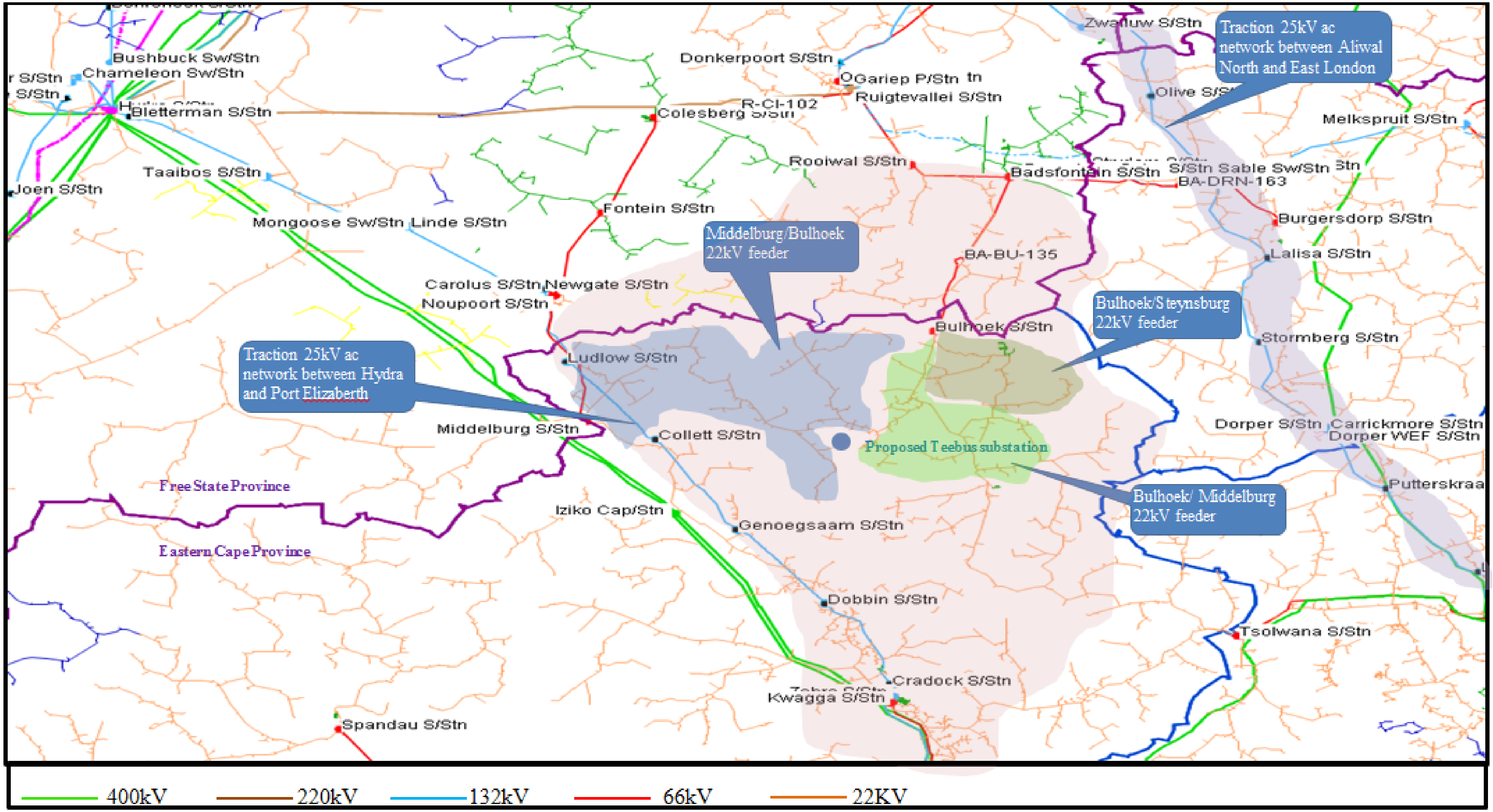


Figure 1-2: Network Study Area

1.2 Impact of Distributed Generation on Distribution Networks

In the past electrical power was generated solely at central generation plants and distributed through an extensive transmission and distribution network to the end users. Traditionally the electrical power industry was dominated by large utilities that owned the generation, transmission and distribution facilities and operated within market monopolies. During the past 15-20 years the concept of distributed (dispersed, embedded) generation (DG) has grown, referring to smaller power sources feeding into the system at distribution voltages. In recent years, DG has enjoyed great interest and international policy has been inclined towards its incorporation.

The integration of the Small Hydro power plant into the distribution grid (22kV) is something that impacts a lot of stakeholders; network companies (both distribution and transmission), the owners and operators (developers) of the distribution generation units, other end-users of the power grid (including normal consumers) and not in the least policy makers and regulators.

The effects of connecting distribution generators onto the unbalance distribution system is well documented and include amongst others, the power quality, network performance, voltage stability, voltage regulation and power protection. Further, unbalancing of the supply systems may distort the supply voltage at the point of common coupling (PCC). One of the major concerns, particularly in the Teebus area is that the existing distribution network already contains the quality of supply issues due to the nature of the customers being agricultural load (irrigation for livestock- uses single phase motors).

1.4.1 Voltage regulation and network instability

The connection of hydro generators to distribution network could influence degradation in system reliability of power supply provided to the customers. The integration of the small hydro could affect voltage regulation and cause over voltages due to too much injection of active and reactive power. Over-voltages due to reverse power flow: if the downstream distribution generation output exceeds the downstream feeder load, there is an increase in the voltage with increasing distance. Voltage variation (limits should not be exceeded) at the PCC may annoy the customers (also damage customer’s equipment) connected closer to the generator plant [5]

1.4.2 Network performance, protection and reliability of power supply

The connection of hydro generation will impact the network stability and further interrupt the demand side, therefore, affect the utility’s SAIDI and SAIFI monthly targets [6], [7]. Short circuit power of a distribution network changes when its state changes. Short circuit power also changes when some of the generators in the distribution system are disconnected, this will be observed in the practical scenarios that will be analyzed. Small Hydro generators may cause the loading levels of power system equipment such as transformers and lines to increase. Equipment thermal loadings ratings could be exceeded [7]

1.4.3 Voltage Unbalance on the existing MV and LV Networks [8]

The MV standard voltages refers to 11kV, 22kV and 33kV, the standard LV voltage is 230 phase to neutral i.e. 400V phase to phase for three phase and 460V phase to phase for dual phase supplies. In Eskom Distribution MV and LV distribution networks the primary cause of voltage unbalance is unequally loaded three phase backbones, where the load imbalance is caused by the connection of non-three phase loads and network technologies e.g. phase to phase laterals and single phase transformers. The magnitude of the load imbalance is dependent on the phase connections used.

1.3 Assumptions

There are a number of developers that have requested for capacity check to connect small Hydro generators and IPPs to the Eskom distribution grid in the Teebus area (Eastern Cape). The total potential power in the Teebus area is approximately 30MW including the planned Teebus generation. The study is done based on the approved applications; however the feasible solution also caters for the future growth/developments in the area. The study will be carried out using different scenarios to ensure the network capabilities during faults. During the analysis, Hydro generation unit are set to operate at the power factor of one.

1.4 Research Hypothesis and Methodology

The hypothesis regarding the problem statements are indicated below.

- Quality of supply
  To ensure that quality of supply issues that are highlighted in the problem statement are resolved, the installation of a STATCOM/SVC will alleviate the voltage unbalance and improves voltage regulation in the network. This will ensure Grid Code compliance. To address the issue of the unbalance on the MV and LV networks, the load balancing will be performed at each and every electrification household in order to ensure optimal phase balancing.
- Reliability of supply
  To ensure redundancy in the MV network, an additional overhead line and transformer are required to be installed in the existing network. This will also improve the back-feeding capabilities and further reduce SAIDI impact on the distribution network.
- Voltage regulation
  In order to ensure that the compatibility limits are not violated, the NRS 042-1 and National Grid Code will be applied.
- Protection
  To ensure that both sides the utility and power producer are protected from any faults that can result from either side adequate and relevant protection schemes must be installed. The protection studies will need to be performed to assess the validation of protection.

1.5 Research Methodology

For this study an existing rural distribution network (Bulhoek/Middleburg 22kV) in South Africa with small scale hydro generation is analysed to determine the effect of distributed Hydro generation on the performance of this network, particularly its stability, performance and quality of supply.

The research will analyse the simulation results of Small Hydro generators modelled in PowerFactory tool and confirm the voltage unbalance results using the hand based calculations (excel spreadsheet). A real test system with about two generators that are already approved and three future potential hydro generating units will be set up to examine their dynamic and steady state performance using the PowerFactory tool[1].

The following scenarios will be modelled in PowerFactory:

- Case 1: Impact to customers when one critical infeed losses power (N-1 scenario).
- Case 2: Voltage variation test at the PCC when small hydro generator is switched on and off (before the adjustment of tap changers)
- Case 3: Impact of the two generators during high and low load on the network.
- Case 4: The behaviour of the grid when the generator continues to energize a portion of the utility system that has been separated from the main utility system [islanding (not allowed in the Grid Code)].

The statistical loading measurements will be taken from the MV90 tool and recorder/instruments installed at each substation. The planning and national Standards as well as Guidelines will be utilised when evaluating the solutions to ensure the compliance.

The dissertation will include literature review which will be divided into different sections or chapters describing various aspects on impact caused by penetrating hydro schemes.

1.6 Structure of the Dissertation

Following the introduction to the research in Chapter 1, Chapter 2: gives a nominal amount of literature review information that has been published regarding this topic. An overview of the previously published literature, demonstrating the effects on stability, performance and quality of supply when connecting Small Hydro plants to distribution networks.

1.7 Summary

The research began with an introduction that contains the importance of having Hydro Power plant in the entire ECOU and South Africa at large. The impacts regarding connection of Hydro plants were reviewed. The shortcomings were pointed out leading to the formulation of the objective for this investigation. The structure of the dissertation outlining the methodology used is also included in the above chapter.

The SA grid code does not sufficiently describe the conditions for connection of generation, to ensure stable operation when connected to distribution network in the presence of small hydro generation. For this study an existing MV distribution network in South Africa with small scale hydro generation is analysed to determine the effect on the protection, voltage regulation, QOS, and performance of this

[1] PowerFactory is a registered trademark of DigSilent [34]

network, particularly its stability. For use in this study, the voltage levels that are considered are 132kV, 66kV and 22kV.

The research will cover the SAIFI and SAIDI problems faced by the customers during the contingency (N-1) conditions. The connection to the existing traction system will be done in future to be able to connect the additional generation in the area. The future research need to incorporate various scenarios which will include the traction system dynamics.

The load flow analysis will be done using DigSilent/PowerFactory tool. The focus will be on the areas indicated on the highlighted study area (see Figure 1-2). Powerfactory has a substantial list of simulation functionalities, some of which will be used in this study namely load flow analysis, low voltage analysis, voltage unbalance, voltage stability analysis, distribution network optimization and contingency analysis. The research will further look at the major issues with over-current and voltages and protection coordination of distribution systems. Different scenarios results will be demonstrated in Powerfactory tool.

The research will also look at the mitigation methods to correct voltage unbalance on the existing 22kV network; this mainly emerges from electrification projects and single phase distribution generators. For use in this study, the voltage levels that are considered are 132kV, 66kV and 22kV

Chapter 2. REVIEW OF RELEVANT LITERATURE

2.1 Introduction

When compiling this document, the related research topics on impact caused by Small Hydro generators on the unbalanced distribution network have been reviewed. Various relevant literature documents and conference papers that have already been published were reviewed.

2.2 Small Hydropower in the Eastern Cape

Unlike large hydro power plants, small hydro power installations have less of an impact on the environment as large areas do not have to be converted into dams to store water. Most small hydro power plants use water from small perennial rivers and are “run of river” types where water is directly diverted from a river to electricity-generating turbines and returned back to the river downstream. An advantage of small hydro power installations is that they can either operate on their own or in a hybrid combination with other renewable energy sources. Small hydro power installations rely on regular flow of water [9], [10].

South Africa is one of the 15 countries with the highest total CO2 emissions and Eskom is one of the largest single emitters of CO2 in the world. Almost 90% of South Africa’s electricity is generated in coal fired power stations. Five percent is provided by hydroelectric and pumped storage schemes. To reduce its carbon footprints, Eskom and the Department of Energy have therefore launched the integrated Resource Plan (IRP2010) in 2011 with the focus on proven renewables technologies, including amongst them the small Hydro Power plant [2].

In 1980, the former Transkei government financed the development of Hydro power schemes in the Eastern Cape. Four small Hydro-electric stations were built between 1980 and 1984 in the region and there were handed over to Eskom in 1995. Various power generation sources have been investigated as part of Eskom’s drive to increase national electricity supply. These include construction of new plant, as well as the upgrading of existing assets at Teebus area. In terms of upgrading existing plant, three of the hydropower schemes in the Eastern Cape, namely Mbashe, First Falls and Second Falls and Ncora have been identified. This process is referred to as “The Small Hydro Programme’’ [9].

The existing four ECOU small Hydro plant statuses are provided on Table 2-1 below [3]:

Table 2-1: ECOU Existing Small Hydro Plants **[3]**

Hydro Name	Installed Capacity	Position/Location
Collywobbles/Mbashe	3 x14MW units	Collywobbles on the Mbashe river system approximately 30km east of Idutywa. Provision for a future fourth machine
First Falls	3MW	First Falls on the Mthatha river situated approximately 5km east of Mthatha
Second Falls	5.5MW	Second Falls on the Mthatha River locate approximately 15km down the stream from First falls.
Ncora	1.6MW	Ncora on the Tsomo River located at about 50km west of Engcobo in the North.

Energy from water can come from waves, tides, waterfalls and rivers. In South Africa, there is a mix of small hydroelectricity stations and pumped water storage schemes. In a pumped water storage scheme, water is pumped up to a dam. Pumping the water uses some electricity but this is done in off-peak periods. During peak hours, when extra electricity is needed, the water is released through a turbine that drives an electric generator. Peak hours are usually from 06h00 to 08h00 and 18h00 to 20h00 [2].

South Africa used to import electricity from the Cahora Bassa hydropower station in Mozambique and will do so again when the transmission line is repaired. There is also the potential to import more hydropower from countries such as Zambia, Zimbabwe and Zaire. If this happens, South Africa could become less dependent on coal-fired power stations [11].

Municipal small hydro power installations contribute 4MW to South Africa’s electricity generation and one privately owned small hydro power installation generates 3MW.

Table 2-2: Small hydro power installation [12]

Owner	Hydropower Installation	Generation Capacity
Municipal	Lydenburg	2MW
Municipal	Ceres	1MW
Municipal	Piet Retief	1MW
Private	Friedenheim	3MW

Table 2-3: Hydro Power installed in Southern Africa [12]

Country	Potential [MW]	Installed Capacity [MW]
Lesotho	20	3.82
Namibia	108.5	0.5
South Africa	247	38
Swaziland	8	0.8
TOTAL	**383.5**	**43.12**

The Department of Energy aims to secure an additional 75 MW of electricity through small hydro power (1-10MW) as part of the Renewable Energy Independent Power Producer programme. At present the total generation capacity of all Eskom’s installations is 39 794 MW [12]

2.3 Hydropower

A hydroelectric power station uses water that is stored in a reservoir in a dam or from run-of-river to drive the turbine. As the water rushes through the turbine, it spins the turbine shaft, which produces mechanical power, as shown in Figure 3. The mechanical power is then converted to electrical power through the generator, which is connected to the turbine [13].

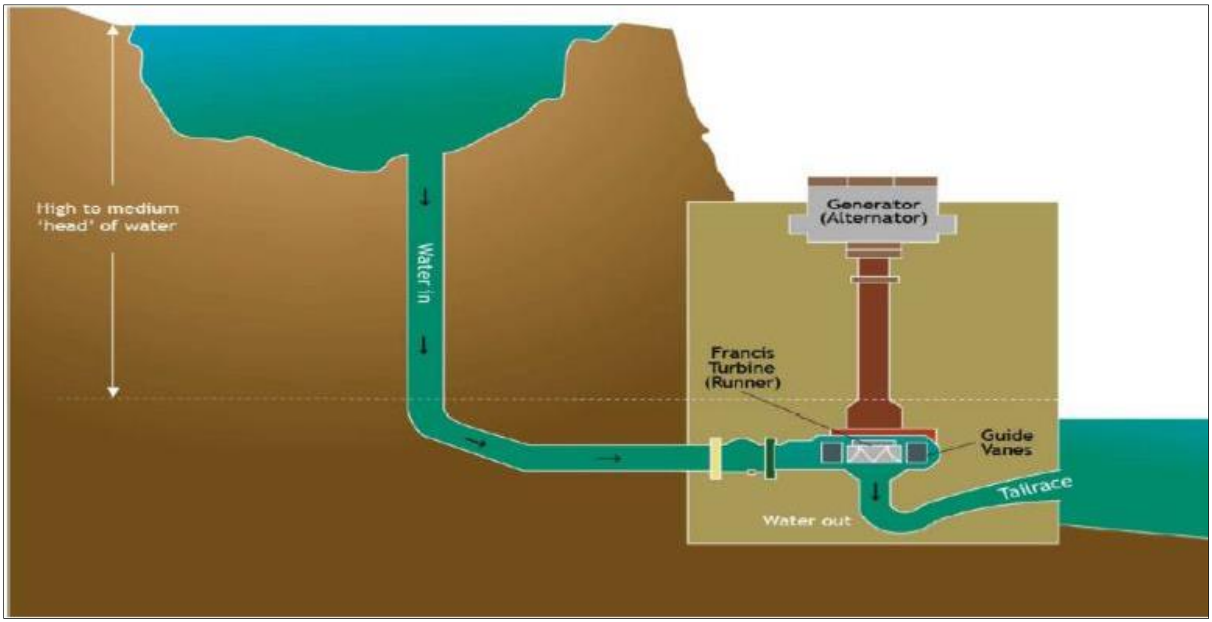


Figure 2-1: Pondage Hydro Power Scheme [13]:

2.3.1 Hydropower schemes are generally of three types [13], [10]:

- Run-of-river
  Run-of-river uses the natural flow of a river without causing an appreciable change in river flow and the surrounding environment. Such a system is usually built on a small dam that impounds a small amount of water.
- Peaking or pumped storage
  A peaking or pumped storage station releases water when the energy is needed. In this method, excess energy is used to pump water from a lower reservoir to an upper reservoir. During periods of high electricity demand, the water is released to the lower reservoir to generate electricity.
- Impoundment
  An impounded facility allows water to be released constantly to generate electricity (depending on the availability of water). Some small hydro schemes drive induction machines, while larger hydro schemes drive synchronous machines for grid connection.

One of the main advantages of hydropower is that it does not produce or emit any pollutant as a by-product. In addition, its operating cost is very low and hydropower can respond quickly to utility load demand. The main disadvantages include high initial capital cost and potential environmental impact. The environmental impact can be avoided or reduced with proper planning in the initial stage of implementation.

2.4 Technology Overview

2.4.1 Generator types

There are several popular types of power generators which are rotary and static generator types. The use of these generator types has advantages and disadvantages depending on the operating conditions. The commonly used type which is rotary generators involves the conversion of mechanical energy to electrical energy. This is done in the air-gap space between the fixed winding (stator) and the rotating windings (rotor) outside edge when the rotor is driven by a prime mover transferring mechanical power. Energy conversion takes place in the form of a suitable magnetic field, known as magnetic flux which is produced in the air gap and keeps flowing from the rotor winding, and induced into the stator winding, or vice versa. [14], [15].

The rotor winding must be at a speed above the magnetic field velocity in order to generate power; or else it will function as an induction motor. Various technologies are used for generating electricity from other forms of energy. These generator technologies can be grouped as follows [14]

- Rotating machines coupled to synchronous AC generators
    - Steam turbines
    - Gas turbines
    - Diesel engines
    - Spark ignition engines
    - Large water turbines
- Rotating machines coupled to induction generators
    - Small water turbines
    - Fixed speed wind turbines
    - Variable speed wind turbines (doubly fed induction generators)
- AC current sources coupled via electronic inverter systems:
    - Variable speed wind turbines
    - Wave and tidal devices
- DC current sources coupled to electronic inverter systems:
    - Fuel cells
    - Photovoltaics
    - Some wind turbines [15]

2.4.2 Synchronous generators [14]

A synchronous generator is a generator consisting of an armature winding that is connected to the three phases of the network, and a rotor winding that is supplied by a source of direct current, which is driven at a fixed rotational speed by a prime mover. The DC supply for the field winding is derived from the excitation system of the generator. A synchronous generator has an exciter that enables the synchronous generator to produce its own 'reactive' power, thus it can operate at a lagging or leading power factor and thereby regulate its voltage. A synchronous generator's excitation system falls into one of two broad categories:

- Self-excited, where the power for the exciter is taken from the main terminals of the generator; or
- Separately excited, where excitation is provided by a separate source, a permanent magnet generator.

A synchronous generator runs at a constant speed and draws its excitation from a power source external to or independent of the load or network it is supplying. Synchronous generators can operate in parallel with the utility or in 'stand-alone' or 'island' mode.

2.4.3 Asynchronous generators [14], [16]

An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. An induction generator therefore does not require mechanical commutation, separate excitation or self-excitation for all or part of the energy transferred from stator to rotor an induction generator's rotor can be either wound type or squirrel cage induction generator type.

2.4.4 Differences between synchronous and asynchronous generators

There are several differences between synchronous and asynchronous generators that relate to the mechanism of operation.

Table 2-4: Differences between synchronous and asynchronous generators **[14]**

Synchronous generators	**Asynchronous generators**
Can inject or absorb reactive power.	Always absorb reactive power.
Can supply islanded networks, without the need for an external power supply.	An external source of reactive power is required.
Operate at synchronous speed.	Operate with a slip frequency above the synchronous speed. The magnitude of the slip determines the injected power.
Short-circuit contribution takes longer to decay due to the sub-transient and transient behaviour of the generator.	Short-circuit contribution reduces quickly, typically before the sub-transient time period has been exceeded.
The power transmitted depends on the prime mover and the load angle between the rotor and the system.	The power transmitted is dependent on the prime mover and the slip frequency.

Synchronous generators	Asynchronous generators
Require an excitation system.	Require the system to supply excitation power.
Require synchronizing equipment.	Connect to system when operating faster than system and with slip.

2.5 Environment

However the generation of hydroelectricity is not without environmental impact. Large areas of land may be flooded when dams are built. This will disrupt wildlife habitats and residential and farming areas. Another problem is that cold water released from deep in a dam may have little dissolved air in it. If large amounts of this water are released into rivers, fish may be killed. But proper management can avoid this.

Global pressures regarding the environmental impact and displacement of settlements by huge storage dams will likely limit the exploitation of hydropower on a large scale. Irrespective of the size of installation, any hydropower development will require authorisation in terms of the National Water Act (Act 36 of 1998) [17].

2.6 Islanding of a Generator

2.6.1 Understanding of the term Islanding

A condition in which a portion of the utility network, which contains load and generators, remains energized while isolated from the rest of the utility network.

A separated part of the power system where voltage and frequency is maintained and customers are supplied due to internal generation and demand balance, however it is asynchronous (not connected) from the rest of the power system [18].

This is normally not a desirable situation to operate in as reclosing the island to the main system if out of synchronism could cause high torques in generation and large current flow in the network [2]

Islanding can be dangerous to utility workers, who may not realize that a circuit is still powered, and it may prevent automatic re-connection of devices. For that reason, distributed generators must detect islanding and immediately stop producing power; this is referred to as anti-islanding.

The reasons for anti-islanding are given as (in no particular order) [19]:

- **Safety concerns**: if an island forms, repair crews may be faced with unexpected live wires
- **End-user equipment damage**: customer equipment could theoretically be damaged if operating parameters differ greatly from the norm. In this case, the utility is liable for the damage.
- **Ending the failure**: Reclosing the circuit onto an active island may cause problems with the utility's equipment, or cause automatic reclosing systems to fail to notice the problem.
- **Inverter confusion**: Reclosing onto an active island may cause confusion among the inverters (in a case of PV Solar).
- **Equipment damage**: due to grid not being able to control its frequency and voltage.

Many utilities use an “instantaneous” reclosing practice, where breakers and circuit reclosers reenergize the protected circuit without any intentional delay and this could result in out of phase reclosing of the distribution system. If a generator is located behind an auto-recloser there may be a possibility that an island could be sustained. Reclosing onto an island out of synchronism could cause damage to equipment, particularly that of directly connected motors or synchronous generators [18].

2.7 As a result of out of phase reclosing [20]

- Large mechanical torques and currents are created, which can damage the generator or the prime mover.
- Transients are created which are potentially damaging to utility and other customer equipment.
- Out-of-phase reclosing, if it occurs at a voltage peak, will generate a very severe capacitive switching transient. In a lightly damped system, the crest over-voltage can approach three times rated voltage.

2.8 Prevention [20]

- Inverter controls are designed to raise a rising frequency or lower a dropping frequency
- The power system frequency acts to correct the inverter frequency
- Without the power system to correct the frequency, the destabilizing signal in the inverter control quickly causes an over- or under-frequency condition, and frequency relays trip the inverter.
- Load/generation imbalance relies on an intentional and significant difference between the DG output and the local load. DG is operated at constant power factor or constant reactive power, and not permitted to regulate voltage. When an island forms, the mismatch between the DG and the load will quickly cause detectable voltage and/or frequency variations

2.9 Impact of DG on Feeder Protection

The literature review shows that, for renewable energy to have a positive benefit, it must be at least suitably coordinated with the system operation philosophy and feeder design. Small hydro generators are connected to the network through an interconnection point called the point of common coupling (PCC). The PCC has to be properly protected to avoid any damage to both, the developer equipment and the utility equipment during fault conditions. Interconnection protection is usually dependent on size and, type of generator, interconnection point and interconnecting transformer connection.

Distributed generation can cause many challenges in the existing protection of distribution networks. Since DG is usually connected at the distribution level, the introduction of new generation sources can provide a redistribution of the source fault current on the feeder circuits causing loss of relay coordination and potential over-voltages. One of the principal features of distribution systems is that the power flows radially, from the main generating station down to the feeders to support all loads. In this design, protection devices will be placed on feeders and laterals of the distribution network, in order to maintain continuous supply to all loads and to protect equipment and different appliances of the system from power outages [19]

During the design of this protection equipment, some characteristics have to be taken into consideration, keeping in mind that it is not possible to protect the entire network straight from the substation. Normally, in large networks the protection is provided by the use of various protection devices based on the fact that any protection device has a reach or maximum distance to cover. Moreover, when designing the protection scheme of a network, coordination between the mentioned protection devices must be considered to be able to reach a highly reliable network that will isolate only the faulted zones and will maintain the healthy parts energised. This purpose increases the global reliability of the network [19].

The introduction of DG in the radial configuration causes a number of problems with the protective device coordination. For example in the traditional system, when using over current protection, it is possible to assume that the fault current only flows in one direction, whilst, this is not always true if there are DG in the network [19]

The presence of DG in a network will have a great impact on the coordination of the protective device, thus it affects the distribution feeder protection. It also has a great impact on the utility protection devices. The research will also focus on coordinating various protection devices such as over current (definite current) relays and time relay; all these will be covered under the literature review [20]

Traditionally distribution networks have been designed to operate radially so that the power flows from upper voltage levels down to customers situated along the radial feeders. This has enabled a relatively straightforward protection strategy. When applying over-current protection, for example, it has been possible to assume that the fault current can have only one direction. However, this is now not always true if there are DG units such as wind turbines in the network. As the share of DG increases, distribution networks are becoming more like transmission networks where generation and load nodes are mixed, and a more complex protection system design is unavoidable [21]

In order to analyse the effects of small hydro generators on the requirements for the protection of distribution networks, power system simulation studies are required. The dynamic modelling of various types of Hydropower technologies such as mini hydro energy is a necessity [21].

2.10 Potential Problems to Protection

Power system simulation and modelling studies have shown that distributed generation causes several challenges to the protection of distribution networks. The most commonly mentioned problems are the following [19]

- False tripping of feeders (sympathetic tripping)
- Nuisance tripping of production units
- Blinding of protection
- Increased or decreased fault levels
- Unwanted islanding
- Prohibition of automatic reclosing
- Unsynchronized reclosing

Different issues related to power quality when distributed generation is integrated with the existing power system has been discussed. It can be concluded from this discussion that when interconnecting a generator to the power system, these issues must be considered which could affect power quality and even safety. Penetration of Hydro generator can be successfully integrated with the power system as long as the interconnection designs meet the basic requirements that consider not only power quality but also system efficiency and power reliability [19]

2.10.1 Medium and High Voltage Protection

This following specifies the technical requirements for a single protection scheme that is suitable, via specific ordering options, for use in three different applications [22]

- For the control of Medium- and High Voltage bus coupler and bus section circuit-breakers, including back-up and circuit-breaker failure protection
- For protection of Medium Voltage, predominantly overhead, distribution lines including auto reclose capability
- For interconnection of Embedded Generators to Eskom's electrical networks, protecting the Eskom network and its customers from possible adverse effects of local sources of generation.

2.10.2 Bus Coupler and Bus Section Protection and Control:

The scheme will be used for the control of Medium- and High Voltage (up to and including 132kV) bus coupler and bus section circuit-breakers, and shall include circuit-breaker failure protection. Over current and earth fault protection shall be used to prove the protection on adjacent power lines and transformers during energisation following construction or maintenance [22]

2.10.3 Medium Voltage rural feeder protection:

The scheme is used on Eskom's 3.3 kV, 6.6kV, 11 kV, 22 kV and 33 kV overhead distribution lines. These lines normally lead off a busbar fed by a star-delta transformer with a neutral earthing compensator and neutral resistor (NEC/R) that limits the earth fault current to either 360 A or 800 A at the above mentioned voltages, depending on the specific NEC/R type employed. The earth fault level may increase by having two or more NEC/R units in parallel. The fault levels vary widely depending on the station location, transformer capacity and transformer arrangement. Transformer capacities vary between 2.5 MVA to 20 MVA and higher. It is also possible, depending on the switchgear and busbar rating capacities, to parallel the transformer secondaries resulting in increased fault levels [22].

The distribution lines have downstream auto-reclosers, sectionalisers and fuses. The sectionalisers have differing operating principles. In some instances the lines are arranged in a closed loop (a ring type network). The scheme shall include over current, earth fault and sensitive earth fault protection with directional control a user-settable option. The scheme shall provide auto reclose control [22].

System protection performance and transient stability of the electrical network are significantly affected by each other. The larger the time delay in which protection detects and clears the fault, the more likely loss of synchronism will be, especially in the networks with internal generation. Over current protection schemes inherently operates with considerable delay. Moreover, system dynamic oscillations discernibly aggravate their performance. Therefore utilizing them as main protection is controversial and even abortive in order to maintain system stability. In this paper, transient stability of a real industrial network is studied. The study is investigated using critical clearing time (CCT) criterion for different network configuration. Equipment such as generators and motors are modelled and simulated by DIgSILENT software. In addition, the operation of over current relays adjusted by conventional methods is investigated dynamically and its performance is examined under different network configurations [21]

2.10.4 Embedded Generation Interconnection:

The protection for a generator shall be used as an embedded generator interconnection protection scheme on Medium- and High Voltage networks, providing protection, control and measurement functions at the Point of Utility Connection (PUC) in accordance with SA Grid Code.

A second, simplified embedded generator interconnection protection scheme is intended for application in conjunction with an existing HV feeder or transformer protection scheme, so as to provide the necessary protection and control functions (i.e. synch check, reverse power protection, synchronism and system checks etc.) [22].

2.10.5 Synchronism Check Protection for Generators:

Where two network sections are switched in by control command or following a 3-pole auto-recloser, it must be ensured that both network sections are mutually synchronous. For this purpose, a synchronism-check function is provided. After verification of the network synchronism, the function releases the close command [22].

In addition, reclosing can be enabled for different criteria, e.g. when the busbar or lines are not carrying a voltage (dead line or dead bus) [22].

At Synchro check mode the variables ΔV, Δf, $\Delta\alpha$ are checked. If they reach set values, a release command is issued for as long as all three conditions are met, but at least for a settable time [22].

2.10.6 Switching Synchronous Networks

The characteristic of synchronous networks is their identical frequency ($\Delta f \approx 0$). This state is detected, and fulfilment of the ΔV and $\Delta\alpha$ (rotor angle) conditions is checked. If the conditions remain met for a set time, the CLOSE command is issued [22].

2.10.7 Switching Asynchronous Networks

This state occurs in the power system and generator (open generator circuit-breaker). A check is made for fulfilment of ΔV and Δf conditions and the connection time is calculated, taking account of $\Delta\alpha$, and the circuit-breaker making time. By means of balancing commands (for voltage and frequency), the generator can automatically be put into a synchronous condition. Synchronization is not activated until the set limits are reached. Then the remaining parameters are checked [22]

According to SA Grid Code [50], the generator shall be equipped with effective detection of islanded operation in all system configurations and capability to shut down generation of power in such condition within 0.2 seconds. Islanded operation with part of the transmission or Distribution system is not permitted unless specifically agreed with the developer.

2.10.8 Transformer Protection

Transformer protection schemes shall be provided for two main application groups [23]:

- Protection for coupling and /or distribution transformers installed on the network, where the HV potential of these transformers is normally higher than 132 kV
- Protection for regional distribution transformers normally with HV potential lower than or equal to 132kV.

The transformer protection schemes related to both application groups make provision for the following fault conditions [23]

- Faults within the transformer protection zone, i.e. faults between the transformer HV and MV Current Transformer's (CT's).
- Faults between the HV CT and HV breaker and between MV CT and MV breaker.
- Overheating.
- Un-cleared HV or MV system faults.

The transformer protection scheme is required for application on the following transformer types [23]

- Auto – transformers.
- Two- or three-winding transformers.
- Traction transformers – single phase units
- Shunt reactor
- Shunt Reactor with tap changer and tertiary winding (optional)
- Transformer-feeder application or Feeder-transformer (optional)
- Double bank transformers (optional).

In three-winding transformer applications, the third winding, namely the tertiary winding, will only supply substation auxiliaries. However in some Transmission applications, the tertiary winding is connected to a reactor unit for voltage control and the reactor capacity can be up to 45MVAr [23].

2.10.8.1 Station Transformer

This differential protection scheme is designed to cater for the protection and control of station-transformer configurations. It is intended to be a cost effective scheme which includes the minimum protection functions which Eskom would be comfortable with under these conditions of application. This is a two winding transformer scheme with differential protection and back-up protection [23].

2.10.8.2 Mobile Transformer

This scheme is designed to cater for the protection and control of mobile substations and smaller HV transformers (< 40MVA). It is intended to be a cost effective scheme which includes the minimum protection functions which Eskom would be comfortable with under these conditions of application [23].

The transformer protection scheme shall include the following: differential, three phase HV O/C, HV and MV REF (High Impedance), HV and MV E/F (IDMTL or DTL) and OLTC O/C blocking. If critical alarms are not acknowledged (e.g. Buchholz, Oil level, protection not healthy, and DC fail), the scheme should initiate a trip of both HV and MV TRFR breakers (Master trip) after a set time delay [23].

2.10.8.3 Distance Protection

A distance protection relay is a non-unit form of primary protection with integrated back up protection which, when combined with some form of signalling, may perform as a unit protection [8].

There are four types of shunt fault for which a distance protection relay must operate [8]:

- A single phase to earth fault A-E, B-E or C-E
- A phase to phase fault A-B, B-C or C-A
- A double phase to earth fault A-B-E, B-C-E or C-A-E, and
- A three phases fault A-B-C

Types of fault not normally considered when applying distance protection include ‘cross country’ faults, and a combination of series and shunt faults; for example a conductor breaking and falling on the ground on the load side of a protected line. This is because a distance protection relay cannot be expected to measure these faults correctly. Supplied with secondary current and voltage, a distance protection relay is calibrated in secondary ohms to measure the positive sequence line impedance. Each type of fault is considered separately since a single voltage and current cannot be chosen to cover all four different types of shunt fault [8]

2.10.8.4 Distance Relays

Distance relays have a balance between current and voltage, expressed in terms of impedance. When a line is protected against short circuits, the relation between the voltage at the relay´s location and the fault current flowing to the short circuit is defined by impedance. This impedance is proportional to the physical distance from the relay to the short circuit. Therefore, these relays achieve selectivity on the basis of impedance rather than current. If there is any abnormal situation, as for example more short circuit current flowing to the fault than which it is expected, the balance between the voltage at the relay´s location and the increased short circuit current will correspond to a impedance that does no longer represents the line distance between the relay´s location and the fault location and therefore relay will trip [9].

Distance relays are not so much influenced by changes in short circuit magnitude as for instance over-current relays are, and hence, are preferred to over-current relays as they are less affected by modifications in generation capacity and system topology. Distance relay setting is constant for a wide range of changes external to the protected line and should be used when over-current relay is slow or is not selective [9].

2.10.8.5 Differential Relays

A simple form of unit protection can be achieved by comparing the currents entering the protected zone with those leaving it. The difference between these currents is, ideally, zero, with no in-zone fault and non-zero with an in-zone fault. This is known as the Merz-Price principle. Circulating current differential protection refers to the fact that under normal load or through-fault conditions the current transformer (CT) secondary currents circulate in what is known as the balance loop. The protection relay is shunt-connected across this loop (see Figure 2-2) and since it is operated by the difference of the currents entering and leaving the protected zone it is termed a differential relay [8].

Differential relays may have several configurations based on the equipment that they protect and almost any type of relay can be made to operate as a differential relay, if it is connected in a determined manner [24]. In Figure 2-2a simple differential relay connection is shown.

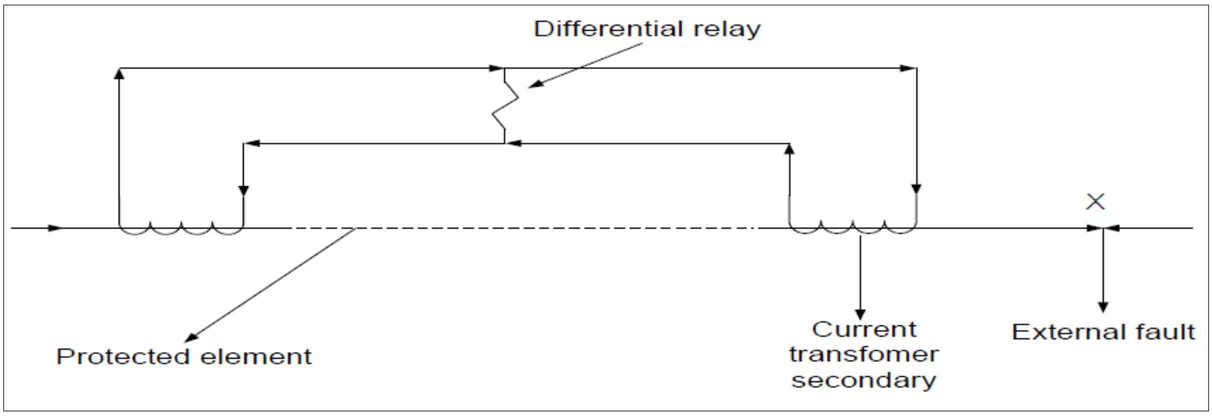


Figure 2-2: Differential behaviour for an external relay **[24]**

The protected element (dashed line) may be a line, a winding of a generator, etc. Current transformers are connected at both ends of the protected element. In addition, the current transformer secondaries are interconnected and an over-current relay is installed across the current transformer secondary circuit. If a fault occurs at X and the two current transformers have the same ratios, the currents will flow as indicated by the arrows (see Figure 4) and no current will be seen by the differential relay [24].

2.10.8.6 Switched and Non Switched Relays

A distance relay requires six different pairs of input quantities for six types of basic shunt fault. The input quantities can either be switched to a single measuring unit in a switched distance relay or measured directly in a non-switched relay [8].

2.10.8.7 Switched Relays

Current and voltage quantities are switched to a single measuring circuit by separate starting units connected in each of the phases. Zone timers increase the relay measurement range by incremental steps for faults outside of the Zone 1 reach [8].

2.10.8.8 Non Switched Relays

Non-Switched relays, or complete schemes, have separate measuring circuits for each of the six types of shunt fault. The measuring elements are permanently connected to measure input currents and voltages for each respective zone. For example, eighteen measuring circuits are provided in a three-zone relay scheme [8].

2.10.8.9 CT Ratio

Factors to be considered when selecting a CT ratio are:

- The maximum line conductor current rating;
- The relay setting range for secondary impedance settings;
- CT saturation.

2.10.8.10 Overcurrent Protection [25]

Protection against excess current was naturally the earliest protective system to evolve. Correct current relay application requires knowledge of the fault current that can flow in each part of the network. Since large scale tests are normally impracticable, system analysis must be used.

2.11 Relay Setting Calculation Information [8]

A list of information for relay-setting calculations is shown below:

- Single line diagram of the power system involved showing the type and rating of protective devices and their associated current transformers.
- The feeder positive sequence impedance in primary ohms.
- The feeder zero sequence impedance in primary ohms.
- The impedance in ohms of adjacent feeders in primary ohms.
- The position, rating and impedance of any transformer(s) connected to the system within the distance protection reach.
- Details of tee off connections on the protected feeder.
- The feeder conductor maximum current rating.
- Maximum and minimum fault currents in the feeder.
- Minimum voltages for faults and normal operating conditions.
- Operation times of adjacent network protection.
- CT and VT ratio and performance curve of the CTs

The relay settings are first determined so as to give the shortest operating times at the maximum fault levels and the checked to see if operation will also be satisfactory at the minimum fault current expected.

2.11.1 Relay characteristic angles [8]

Impedance starter and impedance measurement characteristic angles are within available relay setting ranges set as close as possible to the line angle but not greater than the line angle. To provide additional resistive coverage on short lines, the relay characteristic angle of a mho relay may be set less than the actual line angle. The zone reaches of the relay must then be adjusted to compensate for a lower relay characteristic angle.

2.11.2 Overcurrent Relay Ratings [8]

The voltage rating of the overcurrent protective device must be at least equal to or greater than the circuit voltage. The overcurrent protective device rating can be higher than the system voltage but never lower.

The ampere rating of an overcurrent protecting device normally should not exceed the current carrying capacity of the conductors. As a general rule, the ampere rating of a overcurrent protecting device is selected at 125% of the continuous load current

2.11.3 Overcurrent starters [8]

Two distinct types of overcurrent starter are:

- The plain overcurrent starter, and
- The voltage controlled overcurrent starter

A current starter must also not pick up on inrush current for current supervised switch-on-to-fault protection schemes as this may result in an unnecessary circuit lockout.

Overcurrent starters in a switched distance scheme are set [21]

- To pick up above 1.2 times the maximum current rating of the protected line.
- To less than 0.7 times the minimum fault current for faults covered in the Zone 3 reach.
- To not operate on sound phase current (fault plus load current).
- To not operate on inrush current at circuit restoration.

2.12 Fault Level Philosophy

The National Power System is an interconnected grid, the selection of power system equipment at the Transmission level and the Generation level has a bearing on the fault level at the Distribution level.

During planning with regards to fault level, the engineers need to plan not to subject any equipment to a fault level higher than the manufacturers rating of the equipment. This is to ensure that no equipment is stressed beyond its limit. The philosophy aligns itself with the philosophy of safety to the equipment and safety to personnel. The same rationale applies to the use of preferred transformers [19]

It must be ensured that adequate network fault levels are maintained to ensure adequate power quality. Furthermore, sufficient fault levels are required for the correct operation of protective devices to safeguard against electrical faults. Too low a fault level will create grading difficulties for the protection engineer as the differentiation between fault current and load current may be too close to each other.

Fault level is also important to maintain network stability as it reflects the extent to which the system impedance can absorb a disturbance without resulting in an undesirable oscillation. The fault level of a network becomes an important factor when considering power quality aspects of harmonics and flicker especially when considering the effect of the installation of a capacitor bank and the small Hydro systems on the distribution network [26]

Fault level studies should be performed before the connection of the generator. IEC 60909-0 stipulates that for the calculation of maximum busbar short-circuit currents, 'it seems adequate to choose a voltage amplification factor of 1.1 considering that the highest voltage in a normal undisturbed HV system does not differ, on average, by more than approximately 10% from nominal system voltage'. With this in mind, and assuming that the system impedance remains reasonably constant, one can calculate the maximum short-circuit currents by multiplying the actual current values by the factor (1.1) actual per unit (pu) [19]

Two types of fault levels that should be studied:

- Single-phase to ground faults.
- Three-phase faults.

The fault level is sensitive to the future location of other generation, and the future is uncertain and difficult to predict. Since the future fault level could increase significantly, the generation developer must also ensure that their generating plant is rated as per Table 2-5. This will ensure that the developer's generation plant will be adequately rated if the fault level at the POC increases up to the limit in Table 3. It must be understood that Table 2-5 is a design requirement. The actual fault level (as required for protection studies and settings) may be significantly lower and will change as fault levels in the network change [19]

The minimum fault level that the generating plant protection equipment must be designed for should not be less than the fault levels stated in Table 2-5 if new networks are added, or existing equipment upgraded, the equipment specified should be rated to at least the rating specified in Table 2-5

Table 2-5 : Minimum equipment fault level ratings [19]

Equipment voltage level	Short-circuit rating at POC
11 kV	25 kA
22 kV	25 kA
33 kV	25 kA
66 kV	25 kA
88kV	40kA
132kV	40kA

2.13 Fault Level Increase after the Connection of Generator

Connecting a generator to a utility network has the effect of increasing the fault levels in the network close to the point of generator connection. This may result in the violation of equipment fault levels ratings. Due to the operation of a generating plant, the network's short-circuit current is increased by the generating plant's short-circuit current, particularly in the vicinity of the network connection point [14] .Therefore, information about the anticipated short-circuit currents of the generating plant at the Point of Connection (POC) must be provided in the application form (application from the IPP developer). Short-circuit studies should be done to analyse the effect of the generators on the fault levels. No generator should be connected to the network if this connection will result in fault levels exceeding 90% of equipment fault level ratings. Short-circuit or fault studies are conducted to determine the magnitude of currents flowing through the electrical system during faults. Short-circuit studies ensure that the wide range of electrical equipment used to generate, transmit, and distribute electrical power is sufficiently sized to interrupt or withstand short-circuit current. Short-circuit studies are required to identify the maximum fault currents that will flow in the network under faulted conditions. The maximum fault current is required to determine whether the existing equipment is adequately rated for the fault level [13].

2.14 Fault Level Limits

According to Eskom standard [44] in order to determine a generating plant's short-circuit current contribution, the following rough values can be assumed:

To determine a generating plant's short-circuit current contribution, the following rough values can be assumed [19]

- For synchronous generators – eight times the rated current;
- For asynchronous generators and double-fed asynchronous generators – three to five times the rated current;
- For generators with inverters – 1.2 times the rated current.

2.15 Synchronous machines fault contribution

The fault contribution from a synchronous machine (generator and/or motor) depends on the size, output voltage and impedance of the generator. The fault contribution from the synchronous generator, at the generator terminals, can be calculated with the following formula [19]:

Equation 2-1: Fault current contribution

$$I_K = \frac{C \times S_G}{\sqrt{3} \times \left|R_g + jX''_d\right| \times V_G}$$

Where:

I_K = Fault current contribution from the generator (kA)
C = Voltage factor. For all distribution networks above 1 kV, the voltage factor is 1.1.
S_G = MVA rating of generator (e.g 10MW)
X''_d = Sub-transient reactance of generator (pu)
R_g = Generator stator resistance (pu)
V_G = Output voltage of the generator (kV)

The fault current contribution from asynchronous generators behaves similar to that of synchronous machines during the sub-transient phase. After the sub-transient phase, the fault current contribution from an asynchronous generator decays rapidly. The sub-transient phase is the phase during the first few cycles after a fault. Typically, this ranges from one cycle to 10 cycles. This is due to the lack of an excitation winding [20].

NOTE: The above equation calculates the fault level contribution of the generator at the generator terminals.

The typical fault current rating of isolators on 11 kV and 22 kV feeders are approximately 7.5 kA. Thus in medium voltage distribution networks, a fault contribution of < 6 kA at 11 kV or 22 kV should not result in a technical problem [19].

Equation 2-2: Fault Levels

$$Fault\ Level\ (MVA) = \sqrt{3}\ \times V_{Nom} \times I_f$$

Where:

V_{Nom} = the nominal voltage (kV),
I_f = the current drawn by a three-phase fault at the point of interest (kA).

To mitigate for high network fault levels, upgrade existing network and change equipment ratings. Increase impedance and use high impedance transformers.

2.16 Mitigation of high network fault levels

The following options can be used to mitigate high network fault levels [14]:

- Upgrade existing equipment. Replace inadequately rated equipment with equipment with a higher fault level rating.
- Create normally open points (network splitting). Change the network configuration such that the impedance (between the generation and equipment with inadequate fault level rating) is increased and the fault level reduced.
- Increase the impedance between the generation and equipment with inadequate fault level rating.
- Series reactors are usually used in conjunction with standard impedance transformers.
- Use high-impedance transformers as an alternative to the combination of standard impedance transformers and series reactors.
- Use extremely fast-acting fuses or super-conductive switches to interrupt fault current extremely quickly, thereby preventing equipment damage.
- Change the earthing configuration and ground impedances of generators and transformers. This will affect the zero sequence impedance, and hence the single-phase fault current.
- Add extra impedance into the zero sequence networks, by connecting a y-wound transformer’s neutral via a resistor to ground, thereby reducing the single-phase fault level.

2.17 Quality of Supply

The main purpose of this section is to discuss the basic understanding of power quality in relation to the hydro generation. A major issue related to interconnection of embedded resources onto the power grid is the potential impact on the quality of power provided to other customers connected to the grid. Renewable Sources such small Hydro electrics, etc. are intermittent in nature.

While feeding the customer loads reliability and quality of the supply are of importance. Induction generators connected to the local grid may lead to severe power quality problems such as flicker, and voltage dips [26].

Further, unbalancing of the supply system may distort the supply voltage at the point of common coupling (PCC). In this paper the power quality issues related to the embedded generation have been analysed.

The behaviour of the grid with connection/disconnection of the induction generator (islanding), unbalancing will be demonstrated in DigSilent PowerFactory.

2.18 Voltage Unbalance

Voltage unbalance is present in a three phase system when the magnitudes of the phase voltages or the relative phase displacements of the phases (or both) are not equal. The unbalanced voltages can be represented by the sum of three sets of symmetrical vectors, namely [36]:

- The positive sequence set, consisting of three vectors all equal in magnitude and symmetrically spaced, at 120 ° intervals, in time phase, their phase order being equal to the phase order of the system-generated voltages.
- The negative sequence set, consisting of three vectors all equal in magnitude and symmetrically spaced, at 120 ° intervals, in time-phase, their phase order being the reverse of the positive sequence phase. Voltage unbalance (UB) is usually expressed as a percentage, given by: UB = Vn/Vp, where Vn is the negative sequence voltage, in volts; and Vp is the positive sequence voltage, in volts [36].

2.19 Compatibility Level

Quality of Supply (QOS) is described by a particular set of electromagnetic compatibility levels and these compatibility levels are used to set minimum standards. It follows that the compatibility level should be so chosen that the equipment connected to the supply network has a high probability of operating correctly, and that the supply network has a high probability of operating within the required limits [41].

The maximum compatibility level of voltage unbalance as specified in NRS048-2 is 2%. In networks supplying predominantly single phase loads the compatibility level for voltage unbalance is 3%. Predominantly single phase loading is defined when both of the following criteria are met [41]:

- The size (maximum demand in MVA) of loads connected between phases or between phase and ground represent more than 60% of the maximum loading (maximum demand in MVA) on the feeder under consideration, and
- The single-phase load represents more than 60% of the energy (kWh) supplied for the 12 month period (As per NRS048-2 [41]).

Indicative planning limits for voltage unbalance are provided in Table 2-6 below for each and every system voltage levels.

Table 2-6: Indicative planning levels for voltage unbalance [32]

System voltage	Voltage unbalance planning limit
EHV	0.8%
HV	1.4%
MV	1.8% (predominantly single phase loads 2.7%)
LV	2.0% (predominantly single phase loads 3.0%)

Referring to Table 2-6, this means that the voltage unbalance in the MV network (including the unbalance in the upstream HV and EHV networks) should be planned to be less than 1.8% and 2% in networks supplying predominantly three phase and single phase loads respectively. When planning a MV network the planner needs to take into consideration the likely levels of voltage unbalance from the HV and EHV networks when determining acceptable levels of MV network induced voltage unbalance [41].

2.20 Impact of Distributed Generation

If the distributed generators are correctly installed at the optimal location and if units are correctly coordinated, they will have positive impact on the unbalanced distribution system. Main use of DG is for generation back up. Another advantage of DG is injection of excess power into unbalanced distribution network when the DG capacity is higher than the local loads.

Distributed generators in unbalanced distribution systems perform the task like load voltage stabilization, uninterruptable power supply, reactive power support for power factor correction, balance the source voltages in case of unbalanced load system and active power support. For the radial analysis of the unbalanced distribution systems, DGs can be modelled as negative loads. That means negative active and reactive power injection independent of the system voltage. Distribution systems are also regulated through tap changing transformers by using voltage regulators and capacitors in MV feeders [20]

2.21 Power quality (QOS) issues

Embedded generation will influence the power quality of distribution networks. The usual causes of concern are transient network voltage disturbance, referred to as 'flicker' because of its effect on lighting, and harmonic distortion of the voltage waveform. Voltage flicker may be caused either by the connection and disconnection of generators or by transient torque pulsations from the prime mover being translated in to network voltage variations. Harmonic distortion of the network voltage is generally caused by the power electronic interfaces which are being used increasingly for the connection of embedded generators, although directly connected generators may also have an effect [20].Lot of research work has been done on distribution systems reconfiguration but not on DG impact on unbalanced distribution network reconfiguration.

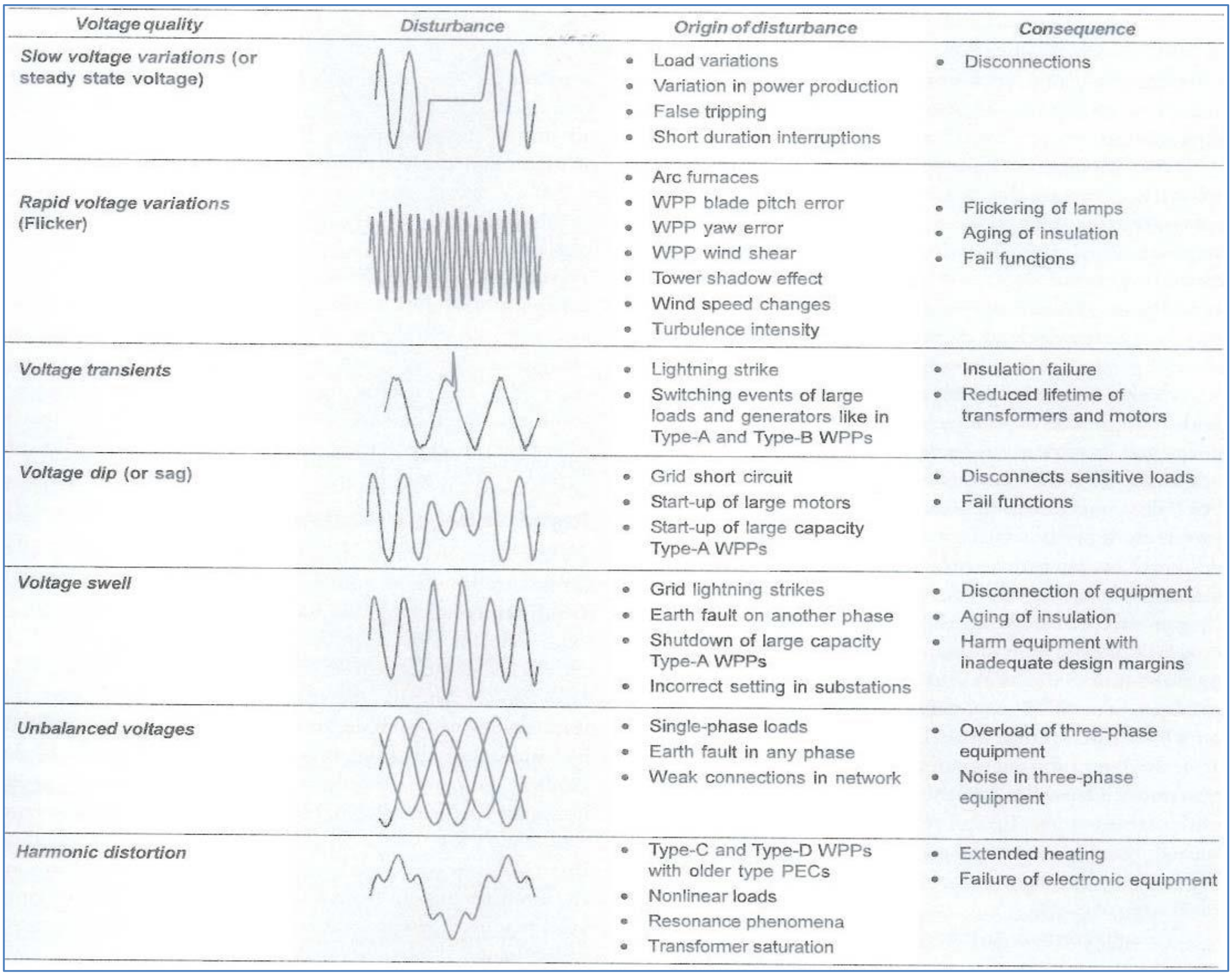
Standards are in place to control the connection of loads likely to degrade the power quality of the distribution network, and these are also applied to Hydro generation. The prediction voltage flickers from operating embedded generation plant remains more difficult and either data is required from installations already in service or very detailed simulation modelling of the entire generator system is necessary. Surprisingly, the connection of rotating embedded generators may then act to improve the power quality of the network by increasing the fault level and so reducing the transient voltage variations. Embedded generation may also balance the voltage of unbalanced network but then additional negative phase sequence current flow can lead to the possibility of overheating of the generator. Convertors, for stand alone, shunt connection are now being offered for power quality improvement of industrial or commercial loads and it is likely that some type of embedded generation plant offer active power quality improvement facilities in the future [20].

The major concern when connecting a significant amount of generators to the grid includes the following phenomena [14] (refer to Figure 2-3):

- Transient voltage variations (voltage dips or sags): Voltage dips and sags refer to the same phenomenon. Voltage sag refers to the remaining or residual voltage, i.e. the voltage decreases to the sag value. Voltage dip refers to the difference between the nominal or declared voltage and the residual voltage. The high demand for reactive power further depresses the network voltage. Depending on the severity, this can lead to voltage instability or, in the worst scenario, voltage collapse. Synchronous generators and inverter-based generation connections are able to compensate for dips and sags; as a result, this phenomenon is not an issue.

- Rapid voltage changes (flicker): Voltage flicker describes the effect of variations in the network voltage, which may be caused either by variable generation or by varying loads. Voltage flicker can be a result of step changes in generation output, which results in a voltage change at the Point of Common Coupling (PCC) or along the feeder. Step voltage changes may be caused by inrush currents, which occur when transformers and/or induction generators are energized from the network. A sudden voltage reduction can be experienced when a generator is disconnected. The voltage flicker results in the flickering of lighting loads, which may be noticeable and irritating to the customers.
- Harmonics: In general, there are two ways in which harmonics can be generated by generators:
  - due to saturation in electrical machines, and
  - due to harmonic injection by power electronic equipment

  Harmonic voltage distortions will lead to increased losses in the generators and may also disturb the control systems and harmonic current performance of power electronic converters [14] .



Voltage quality	Disturbance	Origin of disturbance	Consequence
Slow voltage variations (or steady state voltage)		• Load variations • Variation in power production • False tripping • Short duration interruptions	• Disconnections
Rapid voltage variations (Flicker)		• Arc furnaces • WPP blade pitch error • WPP yaw error • WPP wind shear • Tower shadow effect • Wind speed changes • Turbulence intensity	• Flickering of lamps • Aging of insulation • Fail functions
Voltage transients		• Lightning strike • Switching events of large loads and generators like in Type-A and Type-B WPPs	• Insulation failure • Reduced lifetime of transformers and motors
Voltage dip (or sag)		• Grid short circuit • Start-up of large motors • Start-up of large capacity Type-A WPPs	• Disconnects sensitive loads • Fail functions
Voltage swell		• Grid lightning strikes • Earth fault on another phase • Shutdown of large capacity Type-A WPPs • Incorrect setting in substations	• Disconnection of equipment • Aging of insulation • Harm equipment with inadequate design margins
Unbalanced voltages		• Single-phase loads • Earth fault in any phase • Weak connections in network	• Overload of three-phase equipment • Noise in three-phase equipment
Harmonic distortion		• Type-C and Type-D WPPs with older type PECs • Nonlinear loads • Resonance phenomena • Transformer saturation	• Extended heating • Failure of electronic equipment

Figure 2-3: Typical power quality issues associated with different generators **[14]**

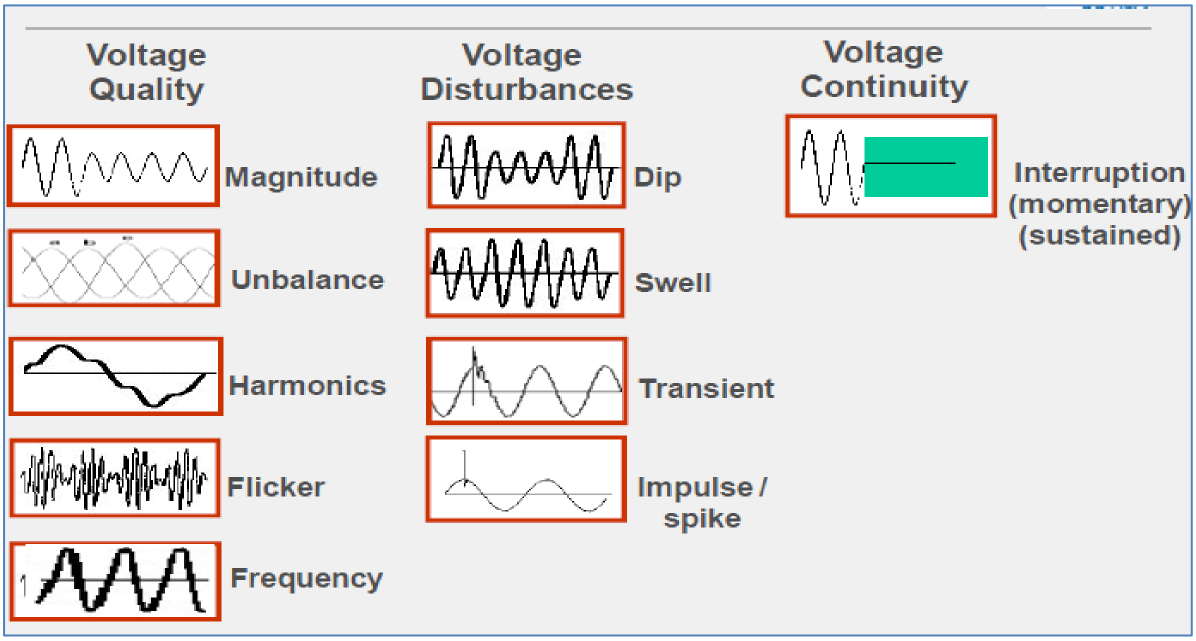


Figure 2-4: Harmonic Emissions **[20]**.

It can be noted that Harmonic emissions could be limited by making use of harmonic filtering techniques. These filters should also be checked against the existing network harmonics, as well as potential resonance conditions that may arise due to the installation of capacitance in conjunction with the generating plant. It is crucial that the potential to overload these capacitors and harmonic filters due to existing harmonic distortion be prevented. Another mitigation option is to connect the generating plant at a higher voltage level or curtail generation output.

2.22 MV Load Balancing

MV voltage unbalance is predominantly caused by unbalanced loads and the connection of unbalanced technology to the three phase Delta MV networks [44]:

- Single phase and dual phase MV/LV transformers are connected between two MV phases (AB, BC or CA).
- Phase to phase MV lines are connected between two MV phases (AB, BC or CA).

In order to minimise voltage unbalance the phase connection of single phase transformers, dual phase transformers and phase to phase tee-offs must be optimised. The phasing typically needs to be rotated so that the load is shared as equally as possible across all three phases in the three phase MV Delta backbone. From a practical connection perspective it is often easier to connect between the outer two phases of three phase delta structures. This typically results in two of the MV phases loaded significantly more than the third phase. This may result in unacceptable levels of MV voltage unbalance [44].

2.23 LV Load Balancing

LV service cable phase connections may have various configurations and decisions regarding how many phases to take from each node or pole and how to arrange subsequent connections to minimize voltage drop must be made. One of the largest contributing factors to voltage drop in LV networks is the presence of neutral currents due to unbalanced loading conditions. Not much can be done about the behaviour of consumers and technical unbalance minimization techniques must be provided. It is important to maintain reasonably balanced loading on each of the available phase conductors of each LV feeder. The reason is that large imbalance results in substantial neutral currents, which increase the voltage drop of the heaviest loaded phase [44].

It is important to achieve balanced loading on each of the three phases to:

- Minimize neutral currents, which will increase the voltage drop of the heaviest loaded phase.
- Reduce the negative phase sequence voltages.

Electrification projects are often designed to cater for single-phase service cable take-off points via pole-top boxes or equivalent. This is the simplest method of servicing individual households.

Table 2-7: One phase per node (RWB-RWB) [44]

Node	Red (R)	White (W)	Blue (B)
A	4	0	0
B	0	4	0
C	0	0	4
D	4	0	0
E	0	4	0
F	0	0	4

The recommended connection strategy is that of an oscillating phase connection strategy as it produces the smallest voltage drop. Each LV distributor begins by using a different phase and then oscillating down the length of the LV feeder. The following phasing system uses 4 service connections per node (pole or kiosk). The oscillating phase connection taking two phases out per node produces the following connection arrangement:

- RR-WW
- BB-BB
- WW-RR
- RR-WW
- BB-BB
- WW-RR

Table 2-8: Two phases per node oscillating [48]

Node	Red (R)	White (W)	Blue (B)
A	2	2	0
B	0	0	4
C	2	2	0
D	2	2	0
E	0	0	4
F	2	2	0

There are several formulas to calculate voltage unbalance [48]:

Equation 2-3: Voltage Unbalance formula 1

$$V_{Unbalance} = \left|\frac{V_{Negative\ sequence}}{V_{Positive\ Sequence}}\right| \times 100\%$$

Or

Equation 2-4: Voltage Unbalance formula 2

$$V_{Unbalance} = \frac{(V_{Max} - V_{Min})}{V_{Ave}}$$

Or

Equation 2-5: Voltage Unbalance formula 3

$$\mathrm{V_{Unbalance}} = \frac{\text{Maximum measured V from Avarage}}{\mathrm{V_{Ave}}} \times 100\%$$

Equation 2-6: Voltage Unbalance Equation formula 4

$$\mathrm{V_{Unbalance}} = \frac{(|\mathrm{V_a} - \mathrm{V_{ave}}| + |\mathrm{V_b} - \mathrm{V_{ave}}| + |\mathrm{V_c} - \mathrm{V_{ave}}|)}{2 \times \mathrm{V_{ave}}} \times 100\%$$

The above equations will be used to perform the hand calculation in order to verify the simulated DigSilent PowerFactory results.

It has been noted that, the splitting of the networks will assist with alleviating low voltages experienced at the end of the networks. It would also assist in reducing the unbalance. Balancing of phases on all the 22kV feeders is required. Dual phase spurs greater than 400kVA should be upgraded to three phase before any balancing can be done.

2.24 FACT Devices

This is where the Flexible AC Transmission Systems (FACTS) technology comes into effect with relatively low investment, compared to new transmission or generation facilities. Flexible AC transmission system (FACTS) devices use power electronics components to maintain controllability and capability of electrical power system.

FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the voltage stability and steady state and transient stabilities of a complete power system. The paper aims demonstrate the benefit of using the STACOM over SVC in order to address power quality on the system. The simulation results demonstrate the effectiveness of the STACOM on transient stability of the system. Keywords: FACTS, SVC, Transient stability and STATCOM.

2.25 STATCOM

A STATCOM (Static Compensator) is a power electronic device comprised of power inverters to inject reactive current into a power system for the purpose of controlling system voltage or power factor. The Figure 2-5 shows a high level schematic for a typical STACOM. The supply voltage could be AC/DC and the inverters comprises of thyristors (for fast switching), capacitors (to hold DC charge) and inductance for AC smoothing filter components). From the inverters there is a step up transformer that connects to the system where voltage and power factor is controlled [27].

A large penetration of wind generation into the power system will mean that poor power quality and poor stability margins cannot be tolerated from wind farms. This requires that methods to improve power qualify and stability for such systems be found. The static compensator (STATCOM) with hybrid battery energy storage (BES) has great potential to fulfil this role, though considerable advances in the control of this system are still to be made. From an economic point of view, rating the STATCOM for steady-state power-quality improvement duty is appropriate. Rating the STATCOM to absorb large amounts of additional power in excess of its transient overload capability during network faults is inappropriate. A hybrid of BES and braking resistor is therefore proposed. A new hybrid STATCOM-BES control technique is developed and discussed in the context of improving the stability and power quality to fixed speed, and induction generator. The variation of the network voltage, active and reactive power with the fluctuation of the wind generation is studied. A wind generation system with a STATCOM battery energy storage unit and the new control was simulated and the results demonstrate that both power quality and the stability margin can be improved significantly for wind farms [27].

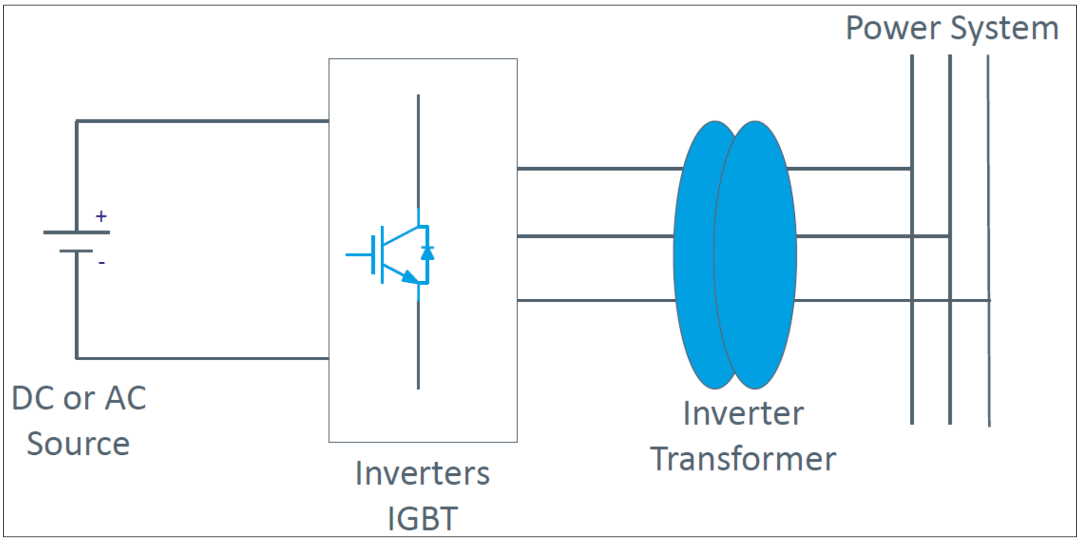


Figure 2-5: STATCOM configuration [23]

2.26 STATCOM Applications

The following are useful application for a STATCOM in modern utility [27]

- Helping utilities recover from system voltage collapse events and increase power transfers
- Helping wind, hydro plants and solar farms meet a variety of Grid Codes requirements worldwide
- Helping industries improve their power quality by significantly reducing their electric outage costs

2.27 STATIC VAR COMPENSATOR (SVC) [27]

Static VAR Compensator (SVC) is a first generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors). SVCs have been used for high performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control. TSR is effectively an infinitely variable reactor but has drawback of creating high harmonics [26].

The Static VAR Compensator (SVC) is one of the shunt connected FACTS devices, which is based on power electronics. It helps in voltage regulation, reactive power control and improving the transient stability of the system. The voltage regulation by SVC is done, by controlling the amount of reactive power injected into or absorbed from the power system. [27], [28].

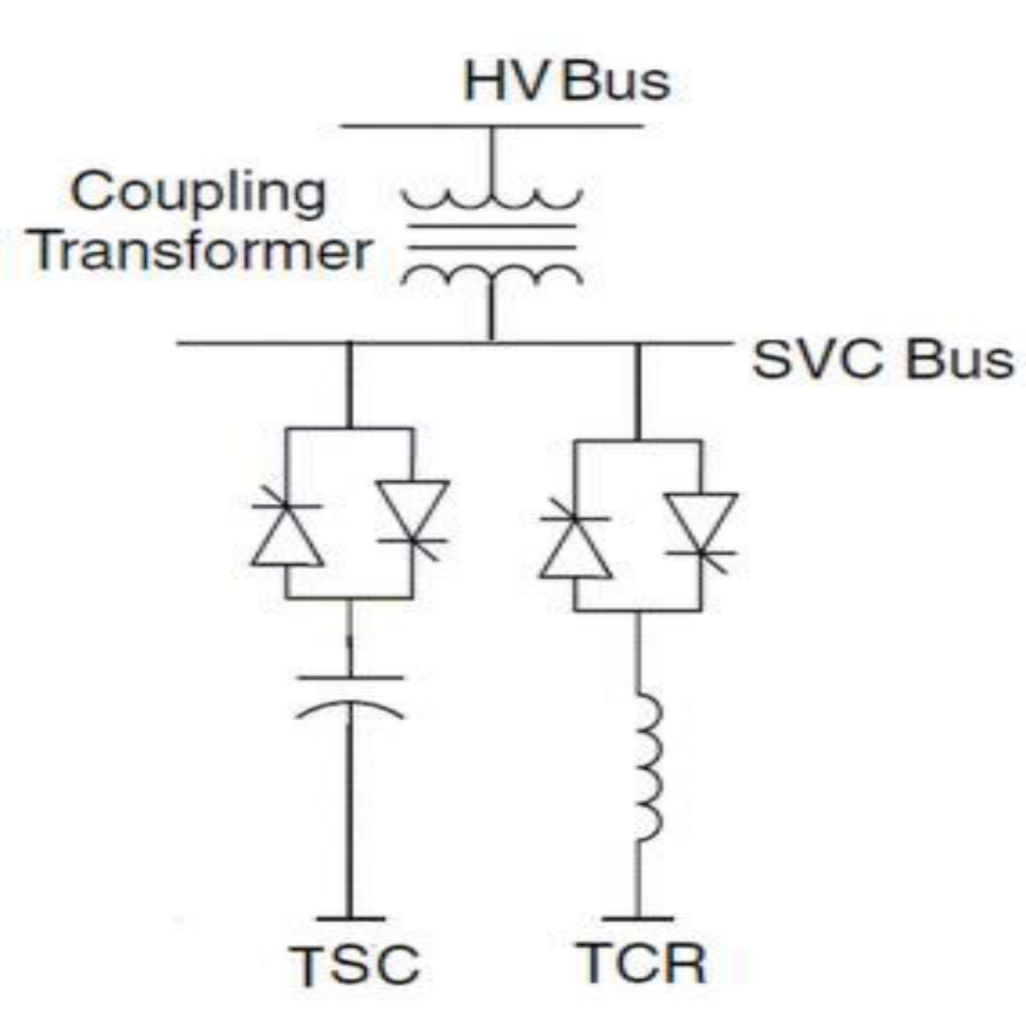


Figure 2-6: Configuration of SVC **[28]**, **[27]**

There are two basic types of SVCs, each having a different combination of the components namely [28], [27]:

1. SVC of the TCR-FC type
    - As its name indicates, the SVC of the TCR-FC type consists of a TCR, which absorbs reactive power from the ac power system to which the SVC is connected, and several FCs, which supply reactive power to the system connected to the SVC.

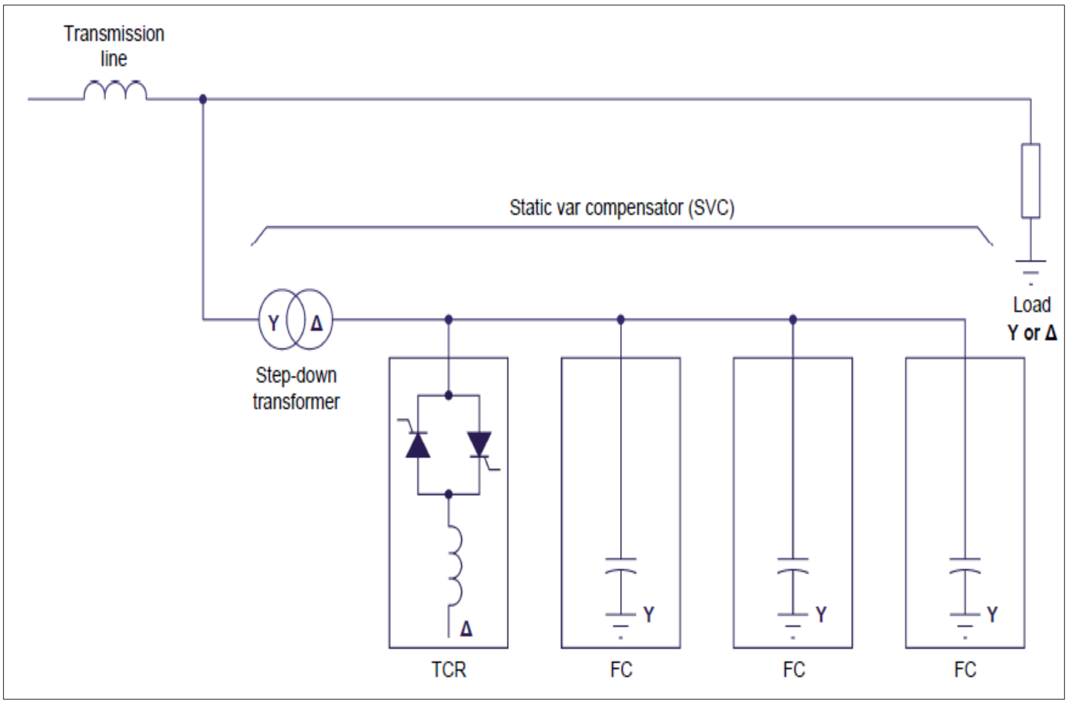


Figure 2-7: SVC of the TCR-FC type, **[27]**

2. SVC of the TCR-TSC type
   - As its name indicates, the SVC of the TCR-TSC type consists of a TCR, which absorbs reactive power from the ac power system connected to the SVC, and several TSCs, which supply reactive power to the ac power system connected to the SVC.

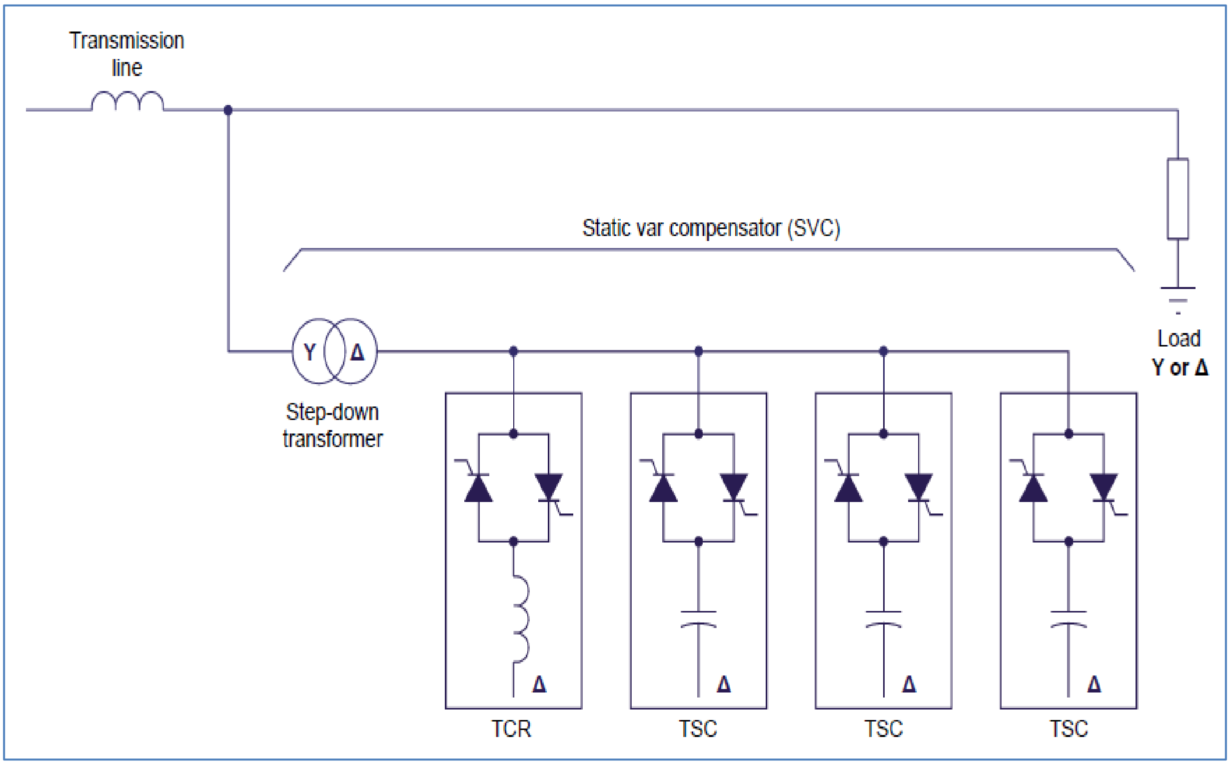


Figure 2-8: SVC of the TCR-FC type **[27]**

The table below displays the advantages and the benefit of using STATCOM over SVCs.

Table 2-9: Advantages of STATCOM over SVC **[27]**

Description	SVC	STATCOM
Response time	Greater or equal to 10ms. Control option twice per 20ms cycle.	Less than 5ms from capacitive to inductive. Fast response causes valve elements to be triggered on and off at typically 10 kHz frequency.
Maintainability	More LV plant equipment, stringing and busbars particularly capacitor banks/ filters. Each fixed capacitor/ filter bank requires its own breaker, isolator, reactors, CTs post insulators, stringing cabling and protection.	NO filters banks, reactors. NO associated breakers and isolators, safety earthing, lifting equipment, vermin proofing, and protection, capacitor oil spill/containment, fire risks, hot spots, Infra-Red (IR) scanning and weed control.
Losses	High losses due to TCR operation when output is close to zero. High losses mean more cooling power, pumps, fans and air-conditioning therefore more vibration and wear and tear at zero output. With indirect TCR control, SVC losses are inversely related to output.	Low losses when operating close to zero MVAR output. With typical intermittent utilization consuming about 1/3rd of the SVC losses. High losses only when output is high.
Harmonic filtering	Produces powerful harmonics and requires filter banks for typically; 2nd, 3rd, 5th, 7th, 11th and 13th harmonics. Internal filter banks rendered ineffective by the transformer impedance for cleaning up network harmonics.	Due to high pulsing frequency, and multi-level technology producing insignificant high frequency harmonics, requiring no filtering. Very suitable for impact load compensation and active harmonic filtering.
Life cycle cost	High because of many LV plant components with specific failure modes. Capitalized losses are high. Requires more man power for maintenance.	Low due to modular power electronics with standard components. No condition monitoring or maintenance foreseen on key components which are power electronics. Key power electronic components and power modules are repairable in factory.
Reliability Availability and Maintainability (RAM)	Both have similar electronics in control, protection computers. RAM expected to be negatively impacted due to many LV components requiring condition monitoring and maintenance. Time-based maintenance will degrade availability and human interaction will degrade reliability. More maintenance of cooling heat exchangers and air conditioner expected due to higher duty.	Slightly more electronics per module but operating in air-conditioned container. Total RAM expected to be better than SVC because of overall few LV components requiring inspection and maintenance. Short duration outages due to low time-based maintenance and inspection requirements on power electronics.

Description	SVC	STATCOM
Mobility	The design requires extensive studies to match it to the specific network. Due to outdoor equipment on foundations with cabling, relocation would require civil work which would be expensive and time consuming. The relocation process can be expected to take longer than installing a new SVC	No system studies required for a specific network as it is not sensitive to the system parameters. Easy relocation would be a major advantage.
Technology	Although SVCs are still used worldwide, they are based on old technology which is slowly being phased out with much more robust semi-conductors.	STATCOMs are based on new technology and are replacing the SVCs.
Capability	Has overload capabilities	No Overload Capability
Performance	Q = V2*X, impedance controlling device. Reactive power is dependent on the square of the voltage.	Q = I*V, current controlling device. Reactive power is linearly dependent on voltage

2.28 Voltage Regulation

The introduction of embedded generation presents a new set of conditions to networks both with respect to the direction of real and reactive power flows, but also with the quantity of power needed to be transported. Modern distribution systems were designed to accept bulk power at the grid supply points and to distribute it to customers. Thus the flow of both real power (P) and reactive power (Q) was always from the higher to the lower voltage levels. With the significant penetration of embedded generation the power flow may become reversed and the distribution network is no longer a passive circuit supplying loads but an active system with power flows and voltages determined by the generation as well as the loads [19].

The principle of voltage regulation in electrical systems is understood in its simplest form by considering two nodes that are interconnected by a conductor of given impedance $(R + jX)$, and across which real (P1) and reactive (Q1) power is transferred (refer to Figure 2-9 below) [22]. Operating the generator at a leading power factor (absorbing reactive power) acts to reduce the voltage rise but at the expense of increased network losses.

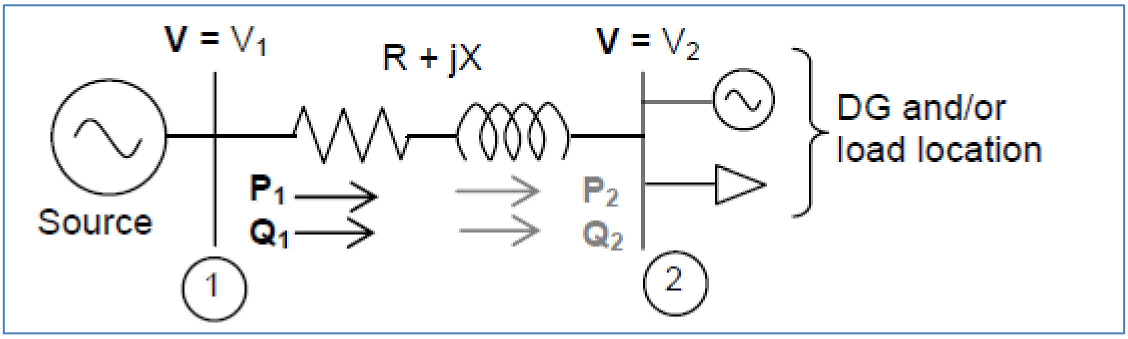


Figure 2-9:Simple network model to understand voltage regulation on a radial network **[22]**

Note: P1 and Q1 are positive when flowing away from bus 1, whilst P2 and Q2 are referenced as positive into bus 2.

In Figure 2-9, power flow across the branch impedance is expressed in terms of both sending-end (P1, Q1) and receiving-end (P2, Q2) quantities. The reactive power drawn by the generator is effective in reducing the voltage rise, but higher real power losses are incurred in the circuit. Power flow in radial circuit can be explained through the figure shown in Figure 2-9 [22].

Over-voltages due to reverse power flow: If the downstream DG output exceeds the downstream feeder load, there is an increase in feeder voltage with increasing distance. If the substation end voltage is held to near the maximum allowable value, voltages downstream on the feeder can exceed the acceptable range. The load tap changers (LTCs) and static voltage regulators (SVRs) are used to control voltages. As a result, LTC or SVR can be set such that a good voltage profile may not be obtained. Figure 2-10 illustrates one voltage regulation problem that can arise when the total DG capacity on a feeder becomes significant. This problem is a consequence of the requirement to disconnect all DG when a fault occurs. Figure 2-10 (a) shows the voltage profile along the feeder prior to the fault occurring. The intent of the voltage regulation scheme is to keep the voltage magnitude between the two limits shown. In this case, the DG helps keep the voltage above the minimum and, in fact, is large enough to give a slight voltage rise toward the end of the feeder [19]

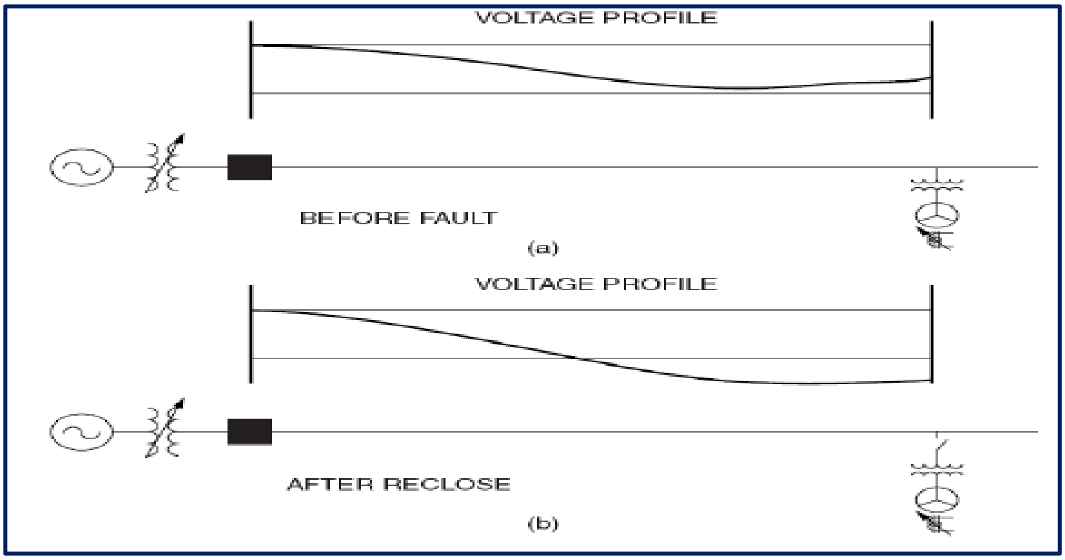


Figure 2-10: Voltage profile change when DG is forced off to clear faults **[19]**

Khan [19] has argued that when the fault occurs, the DG disconnects and may remain disconnected for up to 5 min. The breaker recloses within a few seconds, resulting in the condition shown in Figure 2-10. The load is now too great for the feeder and the present settings of the voltage regulation devices. Therefore, the voltage at the end of the feeder sags below the minimum and will remain low until voltage regulation equipment can react. This can be the better part of a minute or longer, which increases the risk of damage to load equipment due to excessively low voltages [19]

Solutions include:

- Requiring customer load to disconnect with the DG. This may not be practical for widespread residential and small commercial loads. Also, it is difficult to make this transition seamless and the load may suffer downtime anyway, negating positive reliability benefits of DG [19].
- Installing more voltage regulators, each with the ability to bypass the normal time delay of 30 to 45s and begin changing taps immediately. This will minimize the inconvenience to other customers [19]
- Allow DG to reconnect more quickly than the standard 5-min disconnect time. This would be done more safely by using direct communications between the DG and utility system control [19].
- Limit the amount of DG on the feeder [19]

Table 6 below shows the overview of some common benefits of Distributed Generation:

Table 2-10: Theoretical benefits of distributed generation **[28]**, **[26]**

Reliability and Security Benefits	Economic Benefits	Emission Benefits	Power Quality Benefits
• Increased security for critical loads • Relieved transmission and distribution congestion • Reduced impacts from physical or cyber attacks • Increased generation diversity	• Reduces costs associated with power losses • Deferred investments for generation, transmission and distribution upgrades • Lower operating costs due to peak shaving • Reduced land use for generation	• Reduced line losses • Reduced pollutant emissions	• Voltage profile improvement • Reduced flicker • Reduced harmonic distortion • Support voltage stability

However, connection of DG has drawbacks such as follows: [26]

- Many DGs are connected to the grid via power converters, which injects harmonics into the system.
- The connection of DG might cause over-voltage, fluctuation and unbalance of the system voltage if coordination with the utility supply is not properly achieved.
- Depending on the network configuration, the penetration level and the nature of the DG technology, the power injection of DG may increase the power losses in the distribution system.
- Short circuit levels are changed when a DG is connected to the network. Therefore, relay settings should be changed and if there is a disconnection of DG, relay should be changed back to its previous state

2.29 Statutory Voltage Regulation Limits

Voltage regulation limits for LV networks in South Africa are defined in the South African Electricity Act (Act 41 of 1987) and NRS048-2. The standard for new customers is 400/230V (three-phase/single-phase) with an allowable variation of ±10%. Prior to 1990, however, the Electricity Act specified limits of 380/220V ±5%, although according to Dr Carter-Brown, Eskom designed and contracted to 380/220V ±7.5% in supply agreements [22].

In Eskom, the voltage regulation limit for direct supplies to customers at medium and high voltages is normally contracted as a default value of ±7.5%, although Carter-Brown stipulates that the actual voltage must fall within +5%, -7.5% under normal network conditions. In the absence of a contractual agreement, NRS048-2 stipulates that the maximum voltage regulation range for MV and HV supplies is limited to ±5% [22].

The above discussion might lead to a conclusion that, in terms of voltage regulation, the maximum permissible penetration of distributed generation onto a distribution network must, in the worst case, rise to a maximum of 105% of nominal. Indeed, this is true of HV networks, and would be true of MV systems were it not for the newly-adopted planning strategy in Eskom Distribution regarding the apportionment of voltage drops between MV and LV networks. It will be seen presently that in certain

DG applications, the maximum prescribed voltage at MV-connected DG locations may be less than 105% [22].

2.30 Voltage Rise

The majority of rural distribution networks in South Africa are constrained by voltage related issues rather than capacity, waveform quality or electrical loss considerations. The magnitudes of loads (i.e. load per customer) on rural networks in South Africa are also low. This is evidenced by individual customers commonly being supplied through relatively small (16-200kVA) distribution transformers [22].

The distributed nature of network load dictates that rural distribution feeders in South Africa are long, with typical lengths ranging between 20km and 100km. Long feeders are prone to voltage-drop problems on account of their high resistance, and conductor sizing is thus usually based on the limitation of this effect rather than on capacity or loss considerations. Nevertheless, the economics of these lightly loaded networks is such that relatively high resistance ACSR “Hare” or “Mink” conductors are commonly applied at voltages up to 66kV. This discussion has serious implications for generation in South Africa [22].Voltage rise problems must be expected with increased penetrations of DG on local distribution networks. Further, given that local networks are significantly more sparsely and lightly loaded than typical systems in other countries, it is to be expected that the voltage rise problem will be more severe in South Africa than elsewhere.

There are a number of factors that are expected to be of primary importance when considering the voltage rise effect on distribution networks with generators connected [22]. These are:

- Factors affecting source voltage:
  - Presence and method of control of source transformer OLTC and/or voltage regulator/s
  - Source impedance (magnitude and angle)
  - Substation HV and MV busbar loads (magnitude and angle)
- Factors pertaining to the DG:
  - Location relative to the source substation
  - Power generated (magnitude and power factor)
- Factors relating to the DG feeder:
  - Network voltage level
  - Conductor type or types used
  - Locations of specific loads
  - Magnitude and power factor of load; and
- Load type

It can thus be concluded that the factors that were identified above as influencing the voltage rise phenomenon in active networks will give rise to voltage drop effects in passive systems. The Distribution MV/LV transformers are operated on fixed tap, it has been noted that this voltage rise could have a direct impact on customers.

For many years, voltage control in distribution networks has been achieved predominantly through the use of On-Load Tap Changing (OLTC) of the substation-installed power transformers. In more recent times, line-installed voltage regulators are also being used to support the voltage on distribution networks at times of heavy loading. It is common for controlled busbar/node voltages to be maintained at values above nominal - typically 103% - so as to ensure adequate regulation at the most remote end of the feeder. Higher set point voltages (up to 104%) are also commonly applied in South Africa [22].

Voltage rise is typically the main constraint for the connection of generators to LV and MV networks. A simple algebraic method can be used as a guide to determine the maximum rating of generation that can be connected at a particular location before the upper voltage limit on the MV network is reached [29]:

Equation 2-7: Maximum rating/export of the generator

$$P_G = \frac{V_{std} \times V_{std} - V_{setpoint}}{r \times d} + \left[S_{min} \times \left(1 \times \frac{d}{2 \times L}\right) \times (\cos\emptyset + \sin\emptyset)\right] - \left(\frac{x}{r} \times Q_{EG}\right)$$

Where (refer to Figure 2-11):

P_G = Maximum exported generation power [MW]

V_{std} = Upper voltage regulation limit on the network (usually 1.05 pu) [pu]

$V_{setpoint}$ = OLTC set point voltage (usually 1.03 pu) [pu]

r + jx = Impedance per km of the line connecting the generator and the source busbars [Ω/km]

d = Distance of the EG from the source substation [km]

L = Backbone length of the feeder [km]

S_{min} = Minimum feeder load apparent power [MVA]

Cosø = power factor of feeder minimum load

Sinø = $\sqrt{1 - cos^2\emptyset}$

Q_{EG} = Reactive power exported by the generator into the network [MVar] = 0. Assume the generator will operate at unity power factor.

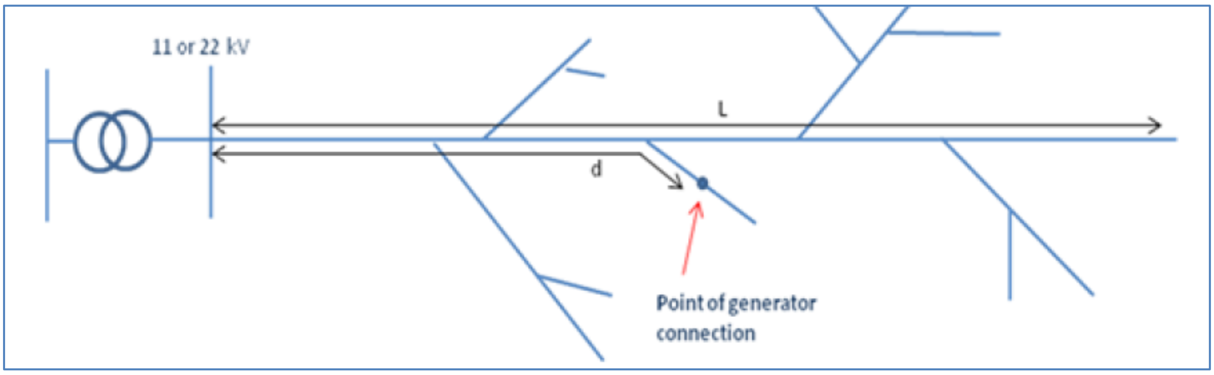


Figure 2-11: Typical diagram of a medium voltage distribution feeder **[29]**

2.31 Mitigation of the voltage rise effect [22]

There are a number of mitigations to this problem. These include:

- Reducing the sending-end substation voltage,
- Having the DG operate at a leading power factor,
- Installing a voltage regulator on the DG feeder,
- Upgrading the feeder to a conductor of larger cross-section, or
- Constraining the generator.

2.32 Voltage regulation after the connection of generator [14]

The options for the mitigation of the voltage rise phenomenon are:

- Achieving reactive power compensation by altering the generator control mode. This may result in the generator absorbing reactive power under specific operating conditions and thereby reducing the voltage rise in the network.
- Coordinating voltage control through optimized on-load tap changing voltage control settings on
- Constraining the generator(s) so that the real power output is kept below the level at which problems arise.
- Traditional network upgrade options, such as upgrading conductor sizes, constructing additional lines and upgrading to a higher voltage (e.g. 88 kV to 132 kV; 11 kV to 22 kV).
- Installing voltage regulators (only applicable to medium voltage).

From the above section, it can be concluded that the voltage can have the biggest impact when generators are connected to an LV or MV network. There can be a drastic voltage rise when a generator is connected to an LV or MV network. This is also applicable to HV, if the generator is big enough.

2.33 Rapid Voltage Change [22]

Rapid Voltage Change (RVC) is a phenomenon in which there are changes in voltages noticeable by other customers at the Point of Connection (POC). These voltage changes can be caused by changes in generation output.

In the event of disconnection of one generating plant or of several plants simultaneously at one network connection point, the voltage change at every point in the network is limited to $\Delta U_{max} \leq 3\%$ under system healthy conditions. For more stable generating plants, such as a Combined Heat and Power (CHP) unit, Hydro generation, cogeneration or Concentrated Solar Power (CSP) plant (which seldom trips), an RVC limit value of 5% is specified, because rapid output changes and tripping of plant occurs infrequently.

As a function of the network fault level (MVA) SkV of the utility network at the point of generation connection (value derived from power factor during load flow simulation) and the rated apparent power SrE of a generating unit, a sudden voltage change caused by a generation connection can be estimated at:

Equation 2-8: Maximum Change

$$\Delta U_{MAX}(\%) = \frac{S_{rE}(MVA)}{S_{kV}(MVA)} \times 100$$

The maximum change in LV voltage (due to voltage drop/rise in the MV/LV transformer and LV feeders) due to embedded generators is limited to 3%. This is a common international practice where the generation is variable. This will ensure that voltage changes due to short term variations in generation output are within acceptable limits, e.g. every time there on/off generators, the LV voltages should not vary by more than 3% (as generator output changes) [22].

The total generation connected to an MV feeder is limited to 15% of the MV feeder maximum loading. This value is informed by practices in the United States and Europe, and is based on the ratio of maximum to minimum feeder loading for typical consumer load profiles. A limit of 15% will ensure a low probability of reverse power flow into the MV feeder source, thereby preventing voltage rise in the MV feeder and reducing the possibility of an island for operation of MV switches and [22].

2.34 Transient Stability of Power System

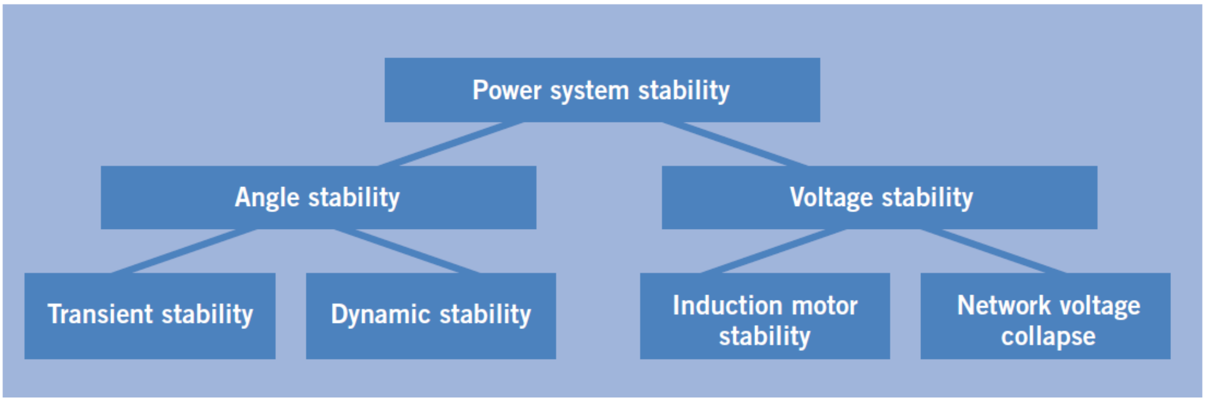


Figure 2-12: Elementary forms of stability **[26]**

Transient stability is the ability of power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on distribution facilities, loss of generation, or loss of large load. In order for the system of synchronous generators to remain stable, the electromagnetic and mechanical torque of each synchronous machine needs to be restored or preserved. In the case of instability the rotor angles of the generators will increase to such a point where synchronism is lost [26].

2.35 Angle Stability

Transient (Angle) stability is the ability of the power system to maintain synchronous operation when subjected to a severe transient disturbance [5] there may be sudden disturbance due to:

- Faults on transmission circuits, transformers, buses.
- Switching operation
- Loss of generation
- Loss of loads

In large power systems, transient instability may not always occur as "**first swing**" instability. There could be as a result of superposition of several swing modes causing large excursions of rotor angle beyond the first swing. Study period of interest in transient stability studies is usually limited to 3 to 5 seconds following the disturbance, may extend up to about 10 seconds for very large systems with dominant inter-area swing modes. Swing Curves are used to determine the stability of the system. If the rotor angle δ reaches a maximum and then decreases, then it shows that the system has transient stability. On the other hand if the rotor angle δ increases indefinitely, then the system is unstable [5]

A ***swing curve*** is the plot of torque angle δ vs time t.

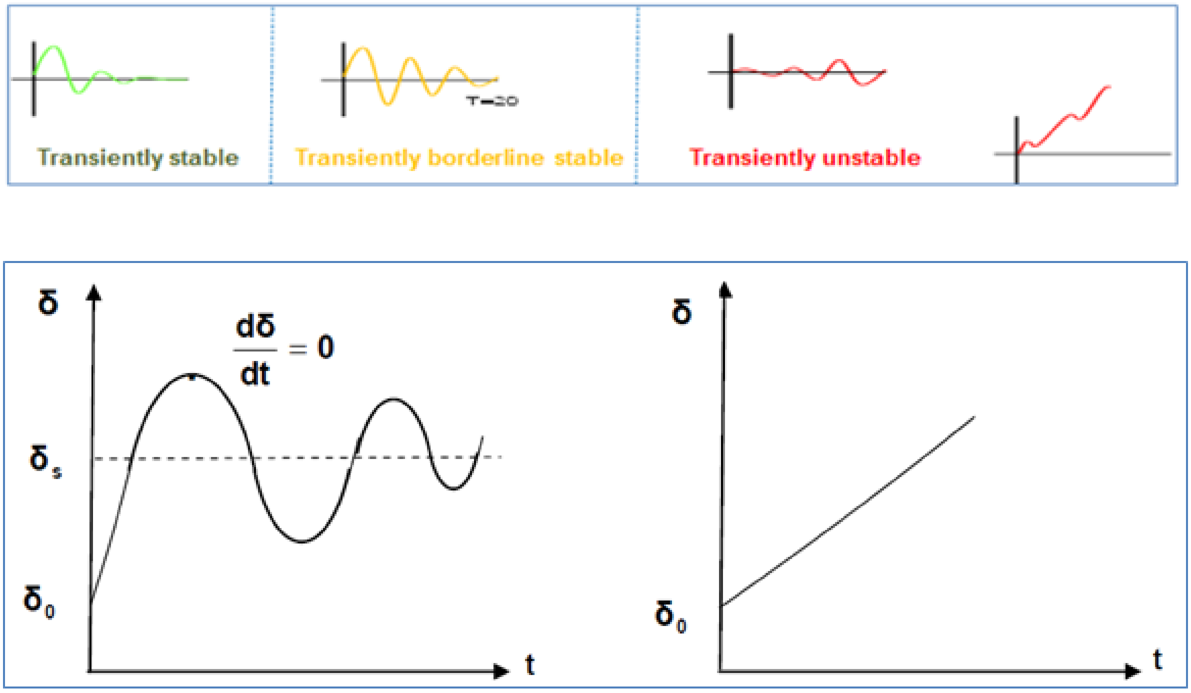


Figure 2-13: Swing Curves **[30]**

Literature is available analysing the effect of hydro power DG on the transient and voltage stability of the system. Most of the literature shows that the presence of small hydro generators on distribution level will have a positive effect on the transient stability of the system. In a study by Londero et al [2009], it was shown that operating hydro power DG at the end of a distribution network, the voltage profile, voltage stability margin and the transient stability of the system was improved [26]

Even though literature is available regarding the transient ability of networks operating solely with hydro power, it will be presumed that the answer to the transient response of a hydropower system has not been answered and this will be tested in the practical simulation study.

The power system stability phenomenon can be divided into three subcategories namely, rotor angle or transient stability, voltage stability and frequency stability. For this study the transient and voltage stability of the generators and the network will be investigated. The effect of DG on the transient and voltage stability is well documented and can be considered as one of the key areas of concern for DG interconnection, especially when the penetration level of the DG increases [5].

The rotor inertia also plays a role when considering the rotor speed stability of the Hydro generators. The larger the inertia the greater the critical fault-clearing time and consequently the more stable the Hydro plant will be. For small rotor inertia, the rotor will speed up more during a fault and the stability margin is reduced [22].Solanki [5] states that the steady-state stability limit of induction generators can limit their connection to weak distribution networks and this is due to very high source impedance and low network short-circuit levels, reducing their peak torque to such an extent that they cannot operate at rated output. By controlling the active power output of the machine during contingencies the rotor speed stability can be improved [5].

2.36 Distributed generation

Much distributed generation (i.e. rotating generators connected to the distribution system) is unlikely to be stable after network faults due to its low inertia and the long protection clearing times of distribution networks. Distributed generators take a voltage and frequency reference from the power system and are not intended to operate in islanded mode. Distributed generators are fitted with Loss of Mains protection to detect islanding as operation is not permitted without a connection to the normally operating power system. Traditionally distributed generators have not been expected to support the power system in the event of disturbances in frequency and voltage but to trip as soon as a network disturbance is detected [5].

Generator transient instability is not normally an issue with generators connected to a distribution system. However, generators connected to long lines, subject to long protection clearance times, could experience transient instability. Multiple generator installations could be particularly prone to instability. Generating plants could have a significant impact on stability following a network fault. Induction generators absorb higher reactive power when voltage is low. Increased reactive power consumption can lead to voltage instability if the network is weak. In general, when speaking of transient stability, one refers to the synchronous machine rotor angle. In most instances, machine size is the deciding factor, leading to transient stability analysis. For example, if transmission planning is to connect a 1 100 MW generating plant, the machine could lose stability for a 100ms fault on the transmission line [22].

2.37 Factors Influencing Transient Stability [5]

- How heavily the generator is initially loaded.
- The generator output during the fault. This depends on the fault location and type.
- The fault clearing time.
- The post-fault transmission system reactance.
- The generator reactance. A lower reactance increases peak power and reduces initial rotor angle.
- The generator inertia. The higher the inertia, the slower the rate of change angle. This reduces the kinetic energy gained during fault, i.e. area A1 is reduced.
- The generator internal voltage magnitude (El). This depends on the field excitation.
- The infinite bus voltage magnitude (EB).

2.38 Causes of Voltage Collapse [5]

- The load on the transmission lines is too high.
- The voltage sources are too far from the load centre.
- The source voltages are too low.
- Large distances between generation and load.

- ULTC action during low voltage conditions.
- Poor co-ordination between various control and protective systems.
- Insufficient load reactive compensation.

2.39 Prevention of Voltage Collapse: [5]

- application of reactive power compensating devices
- control of network voltage and generator reactive o/p
- co-ordination of protection / controls
- control of transformer tap changers
- under voltage load shedding
- stability margin
- spinning reserve
- operators' action

2.40 Transient Stability is improved by the following: Decrease mechanical power [5]:

- Decrease the total reactance between the load and generator (i.e. more lines)
- Increase the load (this provides 'braking' force)
- Increase inertia (higher inertia means less angle deviation during fault)
- Increase excitation voltage (i.e. export more Q)

2.41 Structure of Power System Model [28]:

2.41.1 Components:

- Synchronous generators, and the associated excitation systems and prime movers
- Interconnecting transmission network including static loads
- Induction and synchronous motor loads
- Other devices such as HVDC converters and SVCs

2.41.2 Monitored Information [28]:

- Basic stability information
- Bus voltages
- Line flows

From the discussion in this Chapter (2) it was displayed what the possible effects are regarding network stability, when small hydro is connected to unbalanced distribution network. The factors that influence the system stability were also discussed. The most likely parameters were also discussed and conclusions can therefore be made as to which network and DG parameters need to be taken into consideration for this study. The stability studies look at how a power system operates during disturbances. A common objective is to see how long a protection device can take to clear a fault before the generator (and possibly the surrounding power system) becomes unstable.

2.42 Evaluation of Possible Alternatives to Supply the new Bulhoek S/S Load

The source to feed the new Bulhoek substation will need to be evaluated. The main challenge is the possible existence of power quality violations on the proposed existing network. This has already been looked at; the detailed study will be discussed in the design and data collection chapter. Additionally the refurbishment need of the current Bulhoek substation would necessitate the moving of Bulhoek substation to a new location. It is almost impossible to accommodate future IPPs (including Teebus small Hydro) at the existing Bulhoek substation. The only viable alternative is to feed the new Bulhoek substation from one of the two existing traction lines (a full detailed study will need to be done in future). The Bulhoek s/s 5MVA transformer nameplate has already been reached. There are also accessibility problems to the substation as well as to the MV feeders. Power System Reliability

Reliability of the electric power system is defined by its ability to secure the supply of electricity of acceptable quality to the customers. The reliability of sub-systems, constituting the electric power system, i.e. generation, transmission, distribution, can be analysed separately. So, the reliability of the fulfilment of single function: generation, transmission, distribution and supply to the particular customers are considered. Three hierarchical levels can be also distinguished in the system [29].

2.43 Factors influencing MV feeder reliability [46]

MV distribution network reliability is determined by the number of faults that occur on the distribution network and the impact of the outage(s) on the connected customers. The number of faults expected to occur on the distribution network, as well as the customers impacted, are determined by the exposure. The exposure is dependent on the number of customers interrupted by a fault and the probability of a fault occurring, while the probability of a fault occurring depends on the total volume of equipment that the customers are connected/exposed to. The MV distribution line length is the main contributor to network faults. The voltage regulation on an MV distribution network depends on the amount of load transferred as well as the impedance of the line. In the electrification context, the amount of load is determined by the number of customers as well as the average load requirement of each customer, while the impedance is mainly determined by the line length and conductor type. It is evident that the expected reliability and the voltage regulation on the network are related by the feeder length and number of customers connected to the network. The voltage regulation policy/standard therefore implies a certain base level of exposure and network reliability. The impact of fault occurrences can be further limited by the careful use and placement of protection devices. In an overhead MV distribution network the protection devices to be used are fuses and reclosers. These devices are used to clear and isolate the faulted network with minimum customer impact, as well as to restore supply to as many customers as possible [46].

2.44 Network Performance/Reliability Indices [46]

To correctly evaluate the past performance of a network, it is recommended that the following indices are used [46]:

System Average Interruption Duration Index (SAIDI): This indicates the duration of a sustained interruption the average customer would experience per annum.

Equation 2-9: SAIDI

$$SAIDI = \frac{\text{Sum of system interruption duration p.a}}{Total\ number\ of\ sustained\ system\ interruption\ p.a}$$

System Average Interruption Frequency Index (SAIFI): This indicates how often the average customer connected would experience a sustained interruption per annum.

Equation 2-10: SAIFI

$$SAIFI = \frac{Total\ number\ of\ system\ interruptions\ p.a}{Total\ number\ of\ system\ affected\ p.a}$$

Customer Average Interruption Duration Index (CAIDI): This is the average interruption duration for those customers interrupted. It is determined by dividing the sum of all customer interruption duration by the number of sustained customer interruptions for the year.

Equation 2-11: CAIDI

$$CAIDI = \frac{\text{Sum of system interruption duration p.a}}{Total\ number\ of\ sustained\ system\ interruption\ p.a}$$

Customer Average Interruption Frequency Index (CAIFI): This is the average number of interruptions per customers interrupted. It is determined by dividing the number of customer interruptions observed in a period by the number of customers affected. The customers affected are counted only once regardless of the number of interruptions that each may have experienced during the year.

Equation 2-12: CAIFI

$$CAIFI = \frac{Total\ number\ of\ system\ interruptions\ p.a}{Total\ number\ of\ system\ affected\ p.a}$$

Supply Loss Index (SLI): This is the total MVA hour loss during the month due to negotiated, notified, emergency and fault outages during the month divided by the System Supply Capacity. SLI is a measure of the unavailability of supply (hours).

Equation 2-13: SLI

$$SLI = \frac{Negotiated + Notified + Emergency + Fault\ MVA\ hrs\ Lost}{System\ Supply\ Capacity}$$

Faults/100 km: This is an index used to reference the performance of different lines and represents the faults occurring per 100 km of line. This is usually represented over a 12 month moving average.

Equation 2-14: Faults/100km

$$Faults/100kms = \frac{Total\ faults\ incidents\ x\ 100}{Total\ line\ length}$$

Hrs/Incident: This represents the average outage duration per incident during the month. It indicates the average amount of time taken to locate and repair the fault and restore supply.

Equation 2-15: Hrs/Incident

$$Hrs/incident = \frac{Total\ outage\ duration\ for\ faults}{Total\ no.of\ incidents}$$

SAIDI indicates the total duration of interruptions an average customer is exposed to for a predefined period; whereas SAIFI signifies how often an average customer is subjected to sustained interruptions over a predefined time interval. CAIDI indicates the average time required to restore the services [46].

Reliability indices form a significant part of the system as they provide information about the network performance by measuring the rate of interruptions that the customers experience. Most of all, the benefit to cost analysis indicates that the best alternative is based on the initial capital outlay and benefit achieved with the configuration alternatives.

2.45 Review of International and South African Grid Codes that relate to the connection of DG [50]

The South African grid and distribution codes explain the minimum technical requirements for all grid connected generators. The South African distribution network code also mandates each distributor to have an interconnection standard specifying the technical criteria for the connection of an embedded generator.

The generator must adhere to the minimum requirements, South African grid code – the network code [50] and RSA renewable generation grid code in order to connect to the Eskom network. In order to operate a generator in parallel with the utility network, the generator is required (by the grid code) to have a grid connection agreement. This grid connection agreement is a separate agreement from the commercial agreement. The commercial agreements will address energy tariffs for generation exported into the utility network and wheeling agreements for customers selling the generated power to Eskom or another party.

It is a grid code requirement that all grid-connected generators must have certain capabilities, e.g. the generator must be able to provide the active power and reactive power (PQ) capability as required by the codes.

Conventional induction generators, as used in wind power applications, consume reactive power. It will most often be required by the network operator that some form of reactive power compensation be added to the wind farm to assist in reactive power and voltage control. Specified ranges of reactive power and power factor are given by various grid codes and it is expected that the wind farm power stations be able to operate at any point within the defined limits. Most countries specify a power factor operation range between 0.9 lagging, where reactive power is delivered to the system, and 0.95 leading, where reactive power is drawn from the [31].

Table 2-11: Power Factor Requirement per Country **[31]**

Country	Comment
Germany	Active power capacity < 100MW: 0.95 lagging to 0.95 leading
	Active power capacity > 100MW: power factor is voltage dependent
Ireland	0.95 lagging for production between 100% to 20%
	0.95 leading for production between 100% to 50%
Denmark	Based on $\frac{Q}{P_{rated}}$
Queensland	>0.8 to unity – not
South Australia	0.8 lagging to 0.8 leading but depends on the voltage and demand
South Africa	Active power capacity < 20MW: 0.975 lagging to 0.975 leading for all operating conditions
	Active power capacity > 20MW: 0.95 lagging to 0.95 leading for all operating conditions

As shown in Table 2-11 the South African grid code states that for independent Power Producers (IPPs) facilities with a capacity less than 20MW, the active power output should be 0.975 lagging to 0.975 leading under all operating conditions. For IPPs energy facilities greater that 20MW, the reactive power limit should be 0.95 lagging or leading for all operating conditions [50].

When DG is connected to the network the voltage profile of the power system in the interconnected area will change. The voltage will mostly increase at the connection point and this increase is a function of the weakness (or short-circuit power) of the network and of the values of the active and reactive power flows [7].

The IEEE, in the Interconnection Standard for DG, specifies that the distributed generation shall not actively regulate the voltage at the interconnection point IEEE [7] The IEEE also specifies that if the terminal voltage falls below certain threshold values, the DG shall cease to energize power system in the indicated time.

Some grid codes specify different reactive power requirements for different voltage conditions. The reason for this is explained by the fact that a high reactive power production induces higher voltages which is undesired if the initial voltage is high already whereby power factor control can assist in voltage control [31].

The South African grid code also specifies that the wind farm should have a closed loop voltage regulation system that controls the terminal voltage between 90% and 110% of the nominal voltage of the network to which it connects. This requirement is in the same range as other international grid codes, although most network operators specify different voltage operating ranges to the wind farm for different voltage levels and allow operation outside of the specified voltage ranges for short periods of time [50].

2.46 Fault Ride through Requirements

If the penetration level of DG reach a certain level, disconnection of the generators during network faults could result in network instability. Grid codes have therefore been reviewed and fault ride through capabilities are specified for generators. Fault ride through, or low voltage ride through, of wind power plants needs to be implemented so that the generators can contribute during short circuit conditions and in the network recovery after the fault clearing [31].

Figure 2-14 illustrates the fault ride through (or low voltage ride through) requirements for some grid codes, indicating the minimum voltage that the generators should be able to withstand during fault conditions. The wind generators should remain connected for the indicated voltage dips on any or all of the phases.

Some grid codes specify a specific voltage restoration rate after a fault occurred. The British code requires 90% restoration after 0.5s while the German code requires restoration with a minimum rate of 20% of the nominal output power reaching 100% recovery after 5s. The less stringent requirement of the German code compared to the British code can be attributed to the strong interconnected German grid compared to the relatively weak British system where the need for active power restoration to the pre-fault values is more crucial for system stability [31].

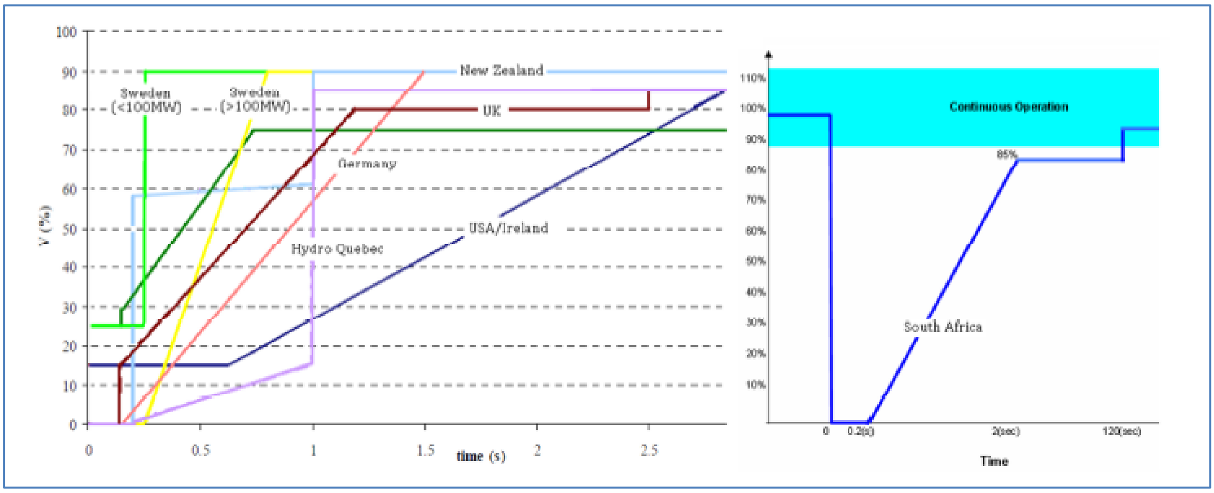


Figure 2-14: LVRT Requirements of various Grid Codes **[22]**

The fault recovery slope, as shown in the figures above, should depend on the strength of the interconnection point to the network and the reactive power support. Van Zyl [22] states that stronger power systems can allow a much steeper recovery and minimize the ride through requirements. In this study it is shown that as the short circuit ratio decreases, the speed of recovery is slower and it is suggested that in weaker systems the LVRT should have a slower rate of recovery [22].

Germany requires that the voltage be supported with additional reactive power during a voltage dip and that additional reactive power be consumed when a voltage rise occurs. If a fault is recognised, reactive support should take place within 20ms and the reactive current must be at least 0.2pu of the rated reactive current per 1pu of the voltage dip except for a dead band between 0.9 and 1.1pu of the voltage [22].

The South African Grid Code also states that for fault recovery during the voltage dip, the generation plant must provide voltage support through reactive power supply. In the case where the generator disconnects, as per Figure 2-14 the generator must reconnect within 1 second after a voltage recovery of at least 0.9pu [22].

The South African Grid Code has also made no distinction between the connections of large amounts of IPPs connected to the high voltage transmission network and possible smaller amounts of wind power that could be connected to the distribution network. Other countries like Germany and Denmark have had to adapt their Grid Code requirements in order to specify conditions specific to lower and higher voltage conditions [5]. It could be proposed that it might be necessary for South Africa to follow suit.

2.47 Conclusion

From the above Chapters, it can be concluded that the presence of small hydro generators on the distribution level will have a positive effect on the transient stability of the system.

It is important to note that the generation supplies loads that would otherwise be supplied by the utility network. From a voltage change perspective, it does not matter how much of the generation is consumed locally or fed back into the network. When the generation output changes, the loading in the utility network changes accordingly, as the utility network supplies loads that would have been supplied by the embedded generator. Hence voltage change magnitudes (due to changes in generation output) are dependent on the generation size, and not on the net export magnitude into the utility network.

Islanding of the DG is not allowed in South Africa. In cases where the Hydro plant connects to a distribution network with low voltage problems or where voltage support becomes a problem during periods of high load demand, the generation could be used to assist in reactive power generation for voltage regulation.

From the literature review it can also be concluded that not all the answers regarding the connection of distributed generation has been addressed completely. International research and Grid Code specifications are focussed on networks with strong interconnection and voltage support and these conditions might not be true for the South African grid.

The impact of generators connected to the grid depends on how the generating plant is designed, and how the design is influenced by the South African Grid Code requirements. Hence the impact will depend on the Grid Codes. More stringent Codes results in generators having less network impacts. In this way, most generators support the grid, rather than create problems for the grid. The minimum technical requirements for the generating plant are specified in the relevant codes.

Connecting generators to a utility network have huge impact on the performance and operation of the network. The impact of the generators depends on the characteristics of the generator, the size of the generator and the location where the generator is connected (a strong or a weak network).

Although it is unlikely that the existing hydropower potential in South Africa will be ever fully exploited, small decentralized hydro power stations could play a role in supplying electricity to Rural Areas. In a number of cases the basic infrastructure is already in place and the low ecological impact as well as the economic effects due to the possible large contribution of the South African industry would be speaking in favour of the development of the small hydro potential.

Chapter 3. DATA COLLECTION

3.1 Introduction

This section focuses on the collection of data related to sub-transmission networks in the defined study area. The gathered data includes Eskom distribution networks and substations, loading data, train schedules, potential IPPs and small Hydro Plant around Teebus area, protection schemes used, future network expansion plans, network performance (refurbishment plans, equipment age and faults stats), quality of supply issues, area development and future electrification plans. The standard distribution voltages used on the paper are 132kV, 22kV, 11kV and LV service voltage of 400V three phase and 230V single phase. Where data is unavailable (in cases where power quality recorders are not installed), an assumption is drawn for the purpose of continuity and project progress. This will be explained where applicable.

3.2 Network Data Collection

Various software tools were used to capture the data from Eskom distribution Network:

- Smallworld (TIPS) is widely used by Eskom to represent the true geographical overview of the network (incl. HV, MV and LV networks). Smallworld also assist the user to be able to gather the type of conductors, transformers, technology etc. and number of customers connected to that particular feeder.
- MV-90 (Remote Statistical Metering System). It is the loading information recorded by measurement devices for the purpose of billing the customers and load forecasting. The information in the system relates to kW and kVAr. MV-90 uses the statistical meters at the each substation for load measurements and load forecasting purposes.
- Power Geo-Load Forecast, known as Power GLF has been designed for this purpose which assist in utilizing the philosophies of load forecasting to develop a load forecast for an aggregated area (high or medium voltage network) or at a micro level (section of medium voltage or LV network). Knowing where the load or generation will materialize is vitally important. Knowing when the load will materialize and knowing how much of load will materialize are the three critical aspects to a load forecast.
- SCADA stands for Supervisory Control and Data Acquisition system. It is used primary to monitor and control the network by system control and network optimisation. The information in the system includes everything that is measured such as voltage, power, current, frequency, tap position, oil temperature, breaker status, protection status etc. SCADA is located at the central corporate workstation which provides the ability to access remote devices in substation in a secure, controlled and managed fashion. Typical devices include substation relays, remote Terminal Units (RTUs), Direct Current (DC) chargers and other intelligent electronic devices.
- UDW is Utility Data Warehouse that stores the long term data of the SCADA system. Its function is limited to extracting data. It does not have any graphs or analysis function.

Figure 3-1: Metering and protection data capturing SOURCE [51]

- Reni is a tool that is used to store all the single line diagram of the substations, MV networks and LV networks in Eskom database.

3.3 Network Information

The Teebus area is located ±15km away from Bulhoek substation and it falls within the Eastern Cape boarders on the Northern side. The 66kV line feeding Bulhoek 66/22kV, 5MVA substation is within the Free State Operating Unit (FSOU). Bulhoek substation is situated in the Eastern Cape and supplies two MV feeders, namely: Middleburg and Steynsburg 22kV feeders with approximately 900 agricultural and 1100 residential customers. The 22kV network stretches from Bulhoek substation towards the Teebus area where potential small hydro electrics are situated.

The majority of the Bulhoek customers are industrial and agricultural (farmers - irrigation to feed livestock) customers, therefore, possibility of voltage unbalance on the distribution networks relatively exist. Voltage unbalance would be worsened by integrating a single phase generator, i.e. distributed generation based on small hydro power units, and moreover voltage unbalance is caused by the 132kV infeed from the traction system (alternative 2). The voltage unbalance becomes more noticeable as more and more single phase DG units are introduced into the distribution system. The Bulhoek substation and the 66kV line are due for refurbishment.

3.4 Teebus and Orange Fish Tunnel Information

Teebus area in the Eastern Cape was identified in the world small hydropower development report 2013 as one of the potential areas to source power to remote rural electrification using hydropower system. Various power generation sources have been investigated as part of Eskom's drive to increase national electricity supply. These include construction of new plant, as well as the upgrading of existing assets.

The Orange River Tunnel shown in Figure 3-2 below was completed in 1975 and the key infrastructure that artificially transfer water from Gariep dam into the Eastern Cape (Teebus spruit and Sunday River). The Teebus site has an existing underground structure that is designed to allow only two Hydro powered turbine generator sets.

The main purpose of the Tunnel is to transfer water to Eastern Cape for irrigation, urban and industrial purposes. However, there is considerable additional hydro power potential to the existing underground structure. According to the feasibility/preliminary study conducted by Eskom, there is an indication that there is sufficient water to support 10MW (2x5.64MW) of base load. This is based on the water transfer head between Gariep and Teebus site and prevailing tunnel conditions. In the first phase the hydrological assessments should be completed to determine if the intention to add the additional units to the schemes is still feasible. The waterways are existing and all the major infrastructure investments have been done long ago.

An application by Project Development Department, Eskom Holdings SOC Limited was received by Eskom Eastern Cape to connect the Hydro Power plant (10MW) to the Eskom MV network. The Teebus Hydro Power Plant has been given a bid to be connected through Renewables Energy Independent Purchase Programme (REIPPP). The proposed generation facility would comprise of two 5.68MW generators. The Teebus Hydro Power Plant is located at the outfall of the Orange Fish Tunnel (Figure 3-2 below) that transfers water from Gariep Dam to Sundays River System.

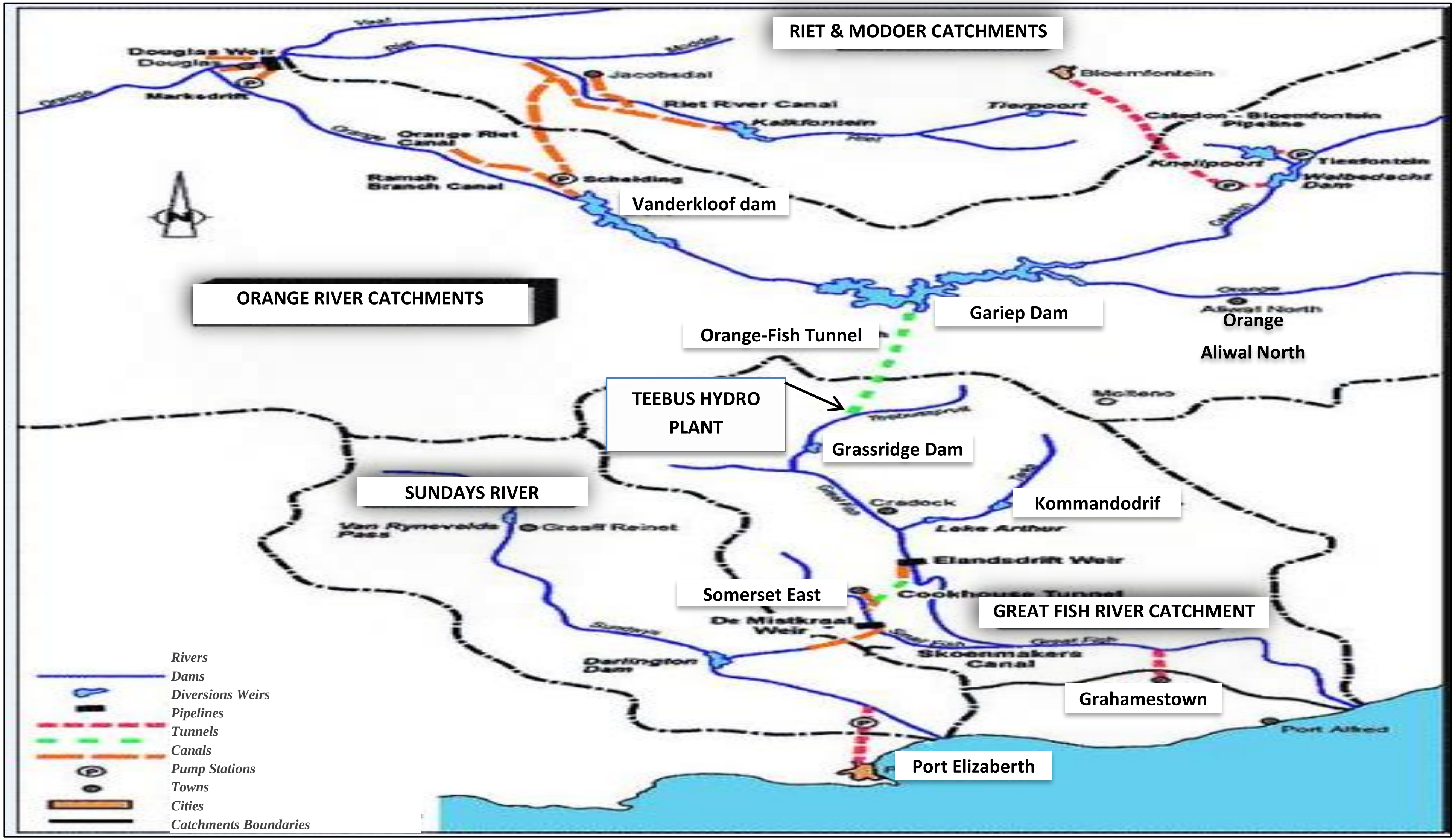


Figure 3-2: Orange River Catchment and Teebus Plant [44]

3.5 Bulhoek/Middleburg 22kV Line

Bulhoek/Middelburg 22kV feeder mainline (backbone) conductor is Mink (see Appendix A for conductor parameters) and it interconnects with Middelburg/Bulhoek, Bulhoek/Steynsburg and Tsolwana/Bulhoek Middelburg Tee 22kV feeders via normally open points at structures BUL MID 324, KN-2, BLOM-219, TSO-BM-656 and TSO-M-654.

This is the C3 network class (93% voltage level limits), the MV source voltages are set at 103% and the minimum measured voltage is 94% (and simulated) of nominal voltage. According to the loading data (March 2014 to June 2014), provided by metering department (Eskom), the current peak load is 4.02MVA, with the Homier Munic load at 0.88MVA. This line supplies power to about 264 customers which consists of 13 LPU (Large Power users) customers. There is also an existing voltage regulator (three canned-closed delta) installed at structure BUL_MID_181 and a 400kVAR capacitor bank installed at structure HOF49_243 to boost the voltages. The line length is approximately 207km long. This feeder supplies predominantly agricultural load. These types of customers are supplied via a LV and have maximum demand of more than 100kVA (as are typically required for large three phase motors).

The Figure 3-4 below demonstrates the load measurements of the Bulhoek/Steynsburg 22kV feeder in 2014.

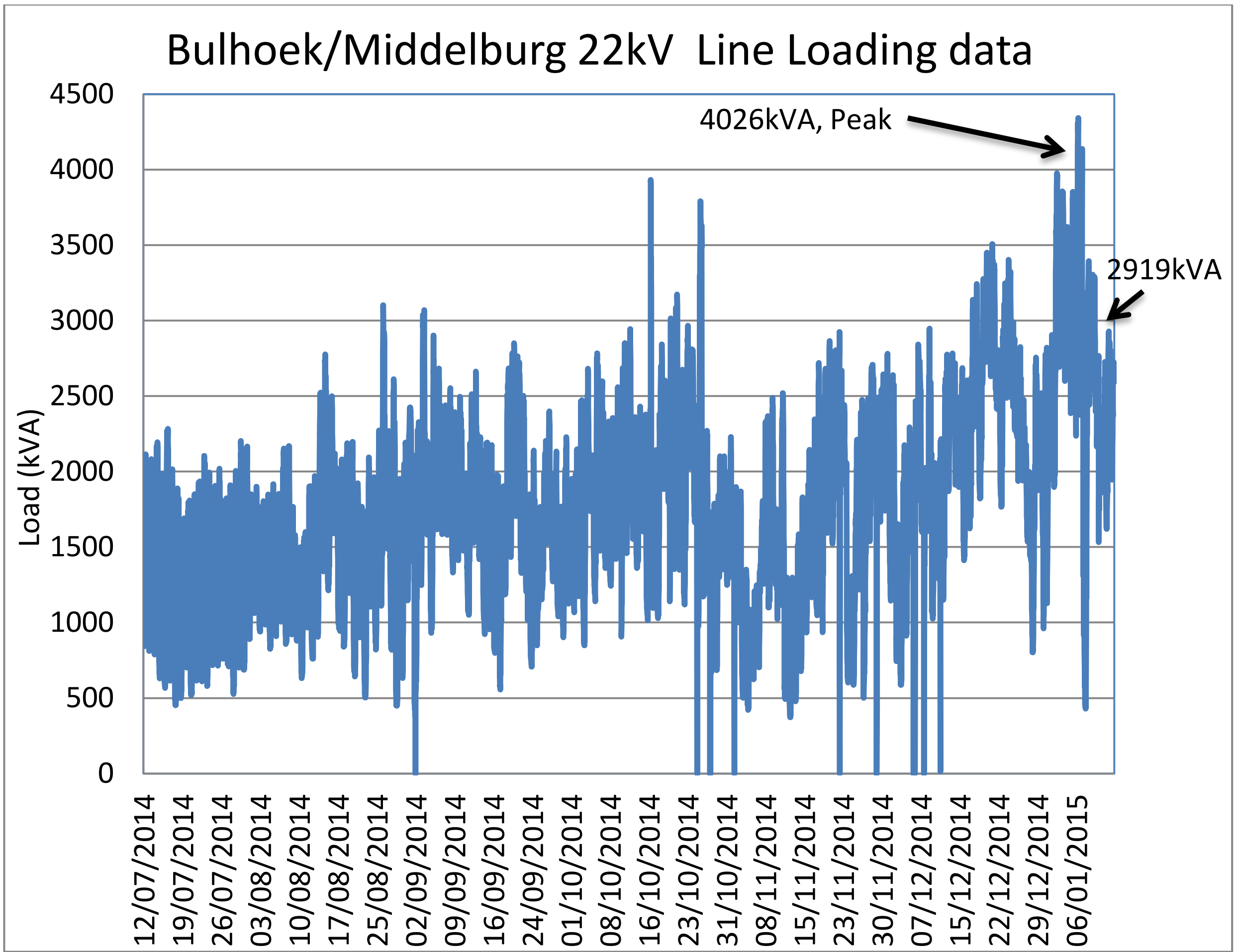


Figure 3-3: Load measurements for Bulhoek/Middleburg 22kV line

The Figure 3-4 below show the voltage records for Bulhoek/Middleburg 22kv line, it can be noted that the lowest voltage of 94.3 is experience during peak between 18:00 and 20:00

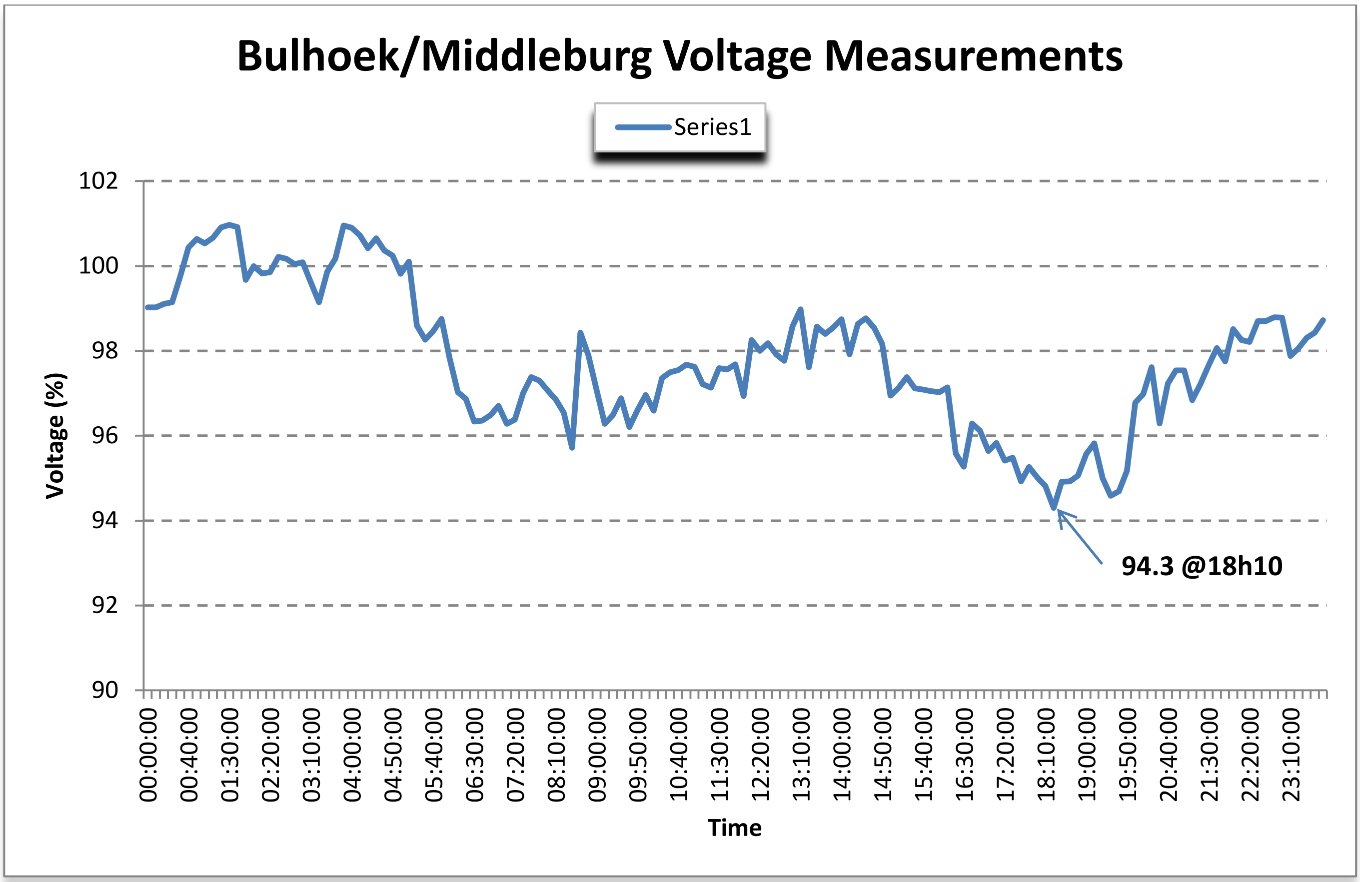


Figure 3-4: Voltage measurements for Bulhoek/Middleburg 22kV line

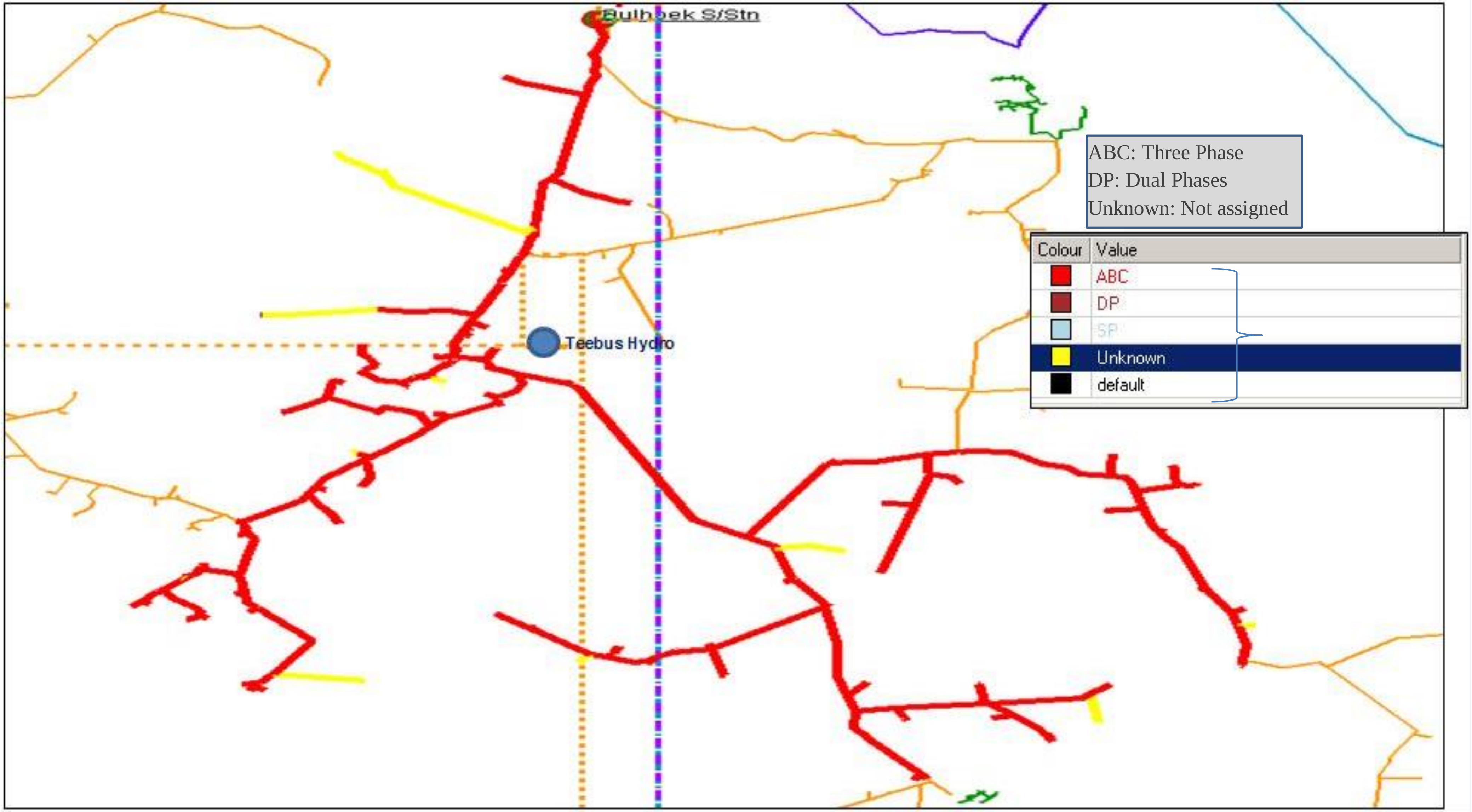


Figure 3-5: Existing overview phasing on Bulhoek/Middleburg 22kV line

3.6 Bulhoek/Steynsburg 22kV Line

Bulhoek/Steynsburg 22kV feeder mainline is constructed with mink (see Appendix A for conductor parameters) conductor. This is the C3 network class (93% minimum voltage levels) with voltages at 98% of nominal. The total line length is approximately 95km. According to the loading data provided by metering department, the current peak load is 1.9MVA, with the Steynsburg Munic load at 0.69MVA and between 12 July 2014 and 13 January 2015, the line loading has been below 2MVA. The line supplies farming community (34 customers) and Steynsburg 22/11kV 5MVA substation that feeds Steynsburg Munic and Khayamnandi (1909 electrification customers). Most electrification customers are fed via a 11kV system as it can be seen on the Figure 3-8 below. The Large Power User on this feeder is Department of Water Affairs with a Notified Maximum Demand (NMD) of 500kVA.

The

Figure *3-8* below depicts the phase information for Bulhoek/Steynsburg 22kV feeder captured from Smallworld. The

Figure *3-8* also shows that some of the single phase customers are connected on the red and white phases and some parts of the network is unknown. This causes voltage unbalance on the network which at this stage exceeds the limit as set by NRS048.

The Figure 3-6 below demonstrates the load measurements of the Bulhoek/Steynsburg 22kV feeder in 2014.

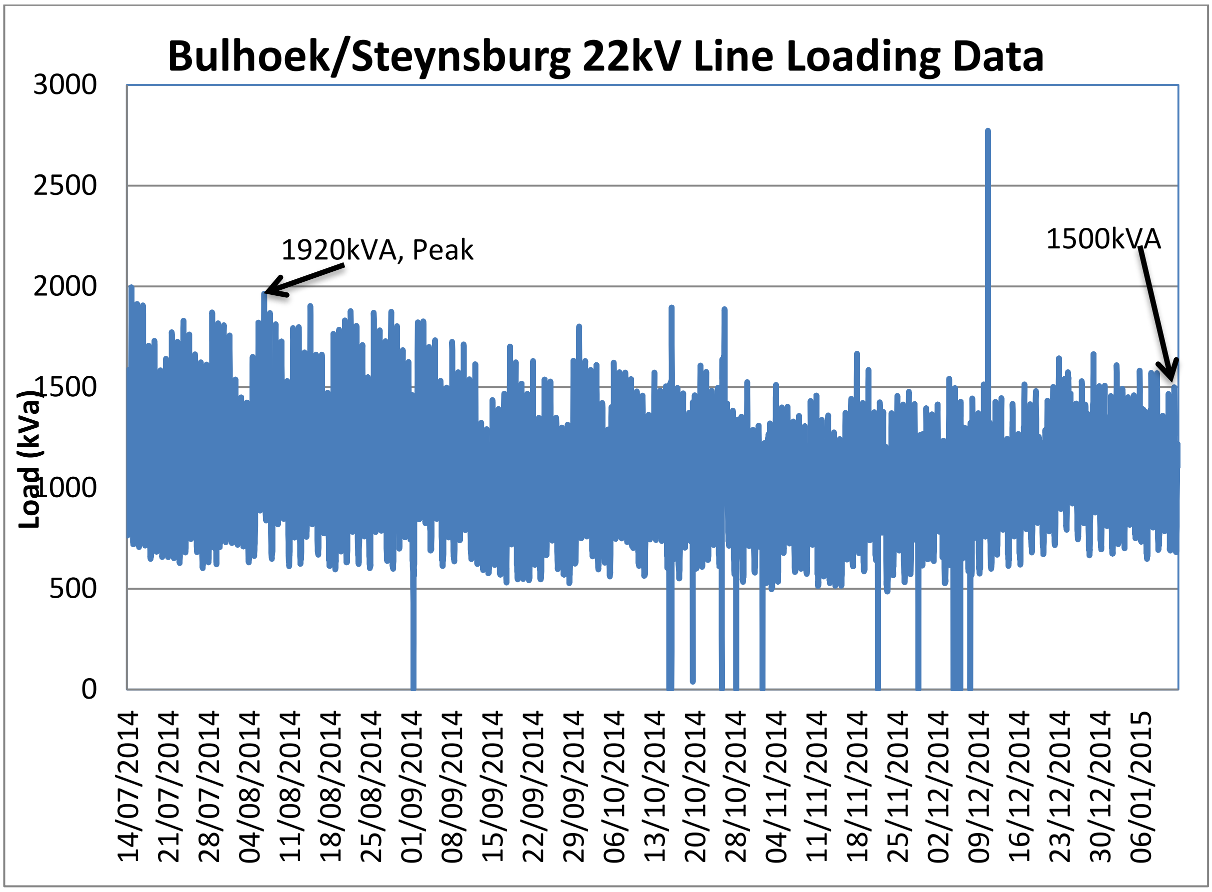


Figure 3-6: Load measurements for Bulhoek/Steynsburg 22kV line

The Figure 3-7 and Figure 3-9 below shows the voltage records for Bulhoek/Middleburg 22kv line, it can be noted that the lowest voltage of 98.94 and 94.3 are experience during peak at 19:00 respectively.

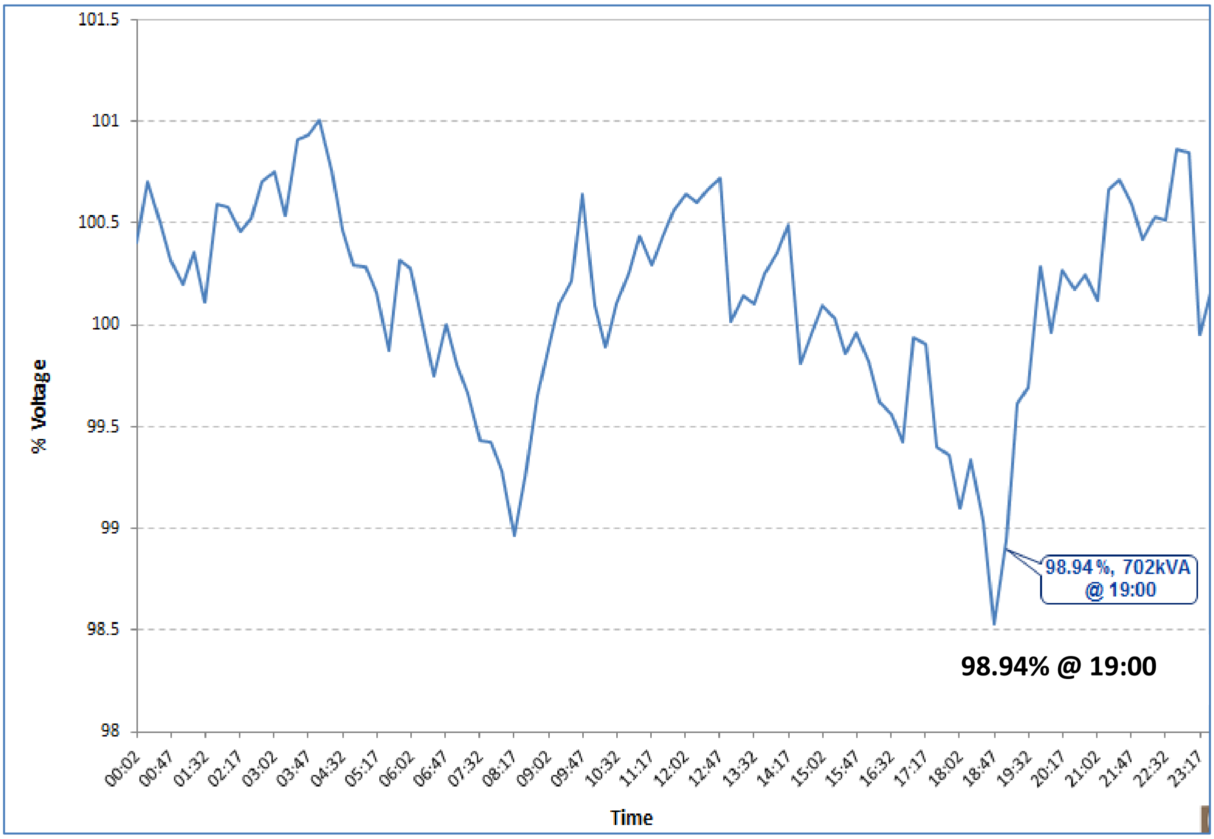


Figure 3-7: Voltage measurements for Bulhoek/Steynsburg 22kV line

Figure 3-8: Existing overview phasing of Bulhoek/Steynsburg 22kV line

3.7 Customer Base

Table 3-1 below provides information on the LPUs with a NMD of 200kVA and above within the study area. LPUs are all the customers with the NMD greater than 200kVA; the table does not include the prepaid/small power user's customers. The loading data available is for the 2015 calendar year and on the table below only the peak load is recorded. The largest customers in terms of load consumption in this area are the local municipalities that fall within the study area.

Table 3-1: Number of customers and feeders from Bulhoek s/s

Substation Name	Feeder	Number of Customers	Line Length (km)	Main Line Conductor Rating (MVA, 50^0 C TT)	Network Class	Load (MVA)
Bulhoek (66/22kV, 5MVA)	Middleburg 22kV	264	208	10.7[2]	C3	4.2
	Steynsburg 22kV	30	96	10.7[3]	C3	2.2

Table 3-2: Large Power Users Loading Information

Substation Name	Customer Description	Point of Supply Description	Customer Account No	NMD (kVA)	2015 Peak (kVA)
Bulhoek	Van der Kel Boerdery	HOF33	EL-9887746678	200	104
	Southey JOH	TS9	EL-8055297068	200	100
	Lord Robert Andrew 36	TS36	EL-9605391931	315	281
	UKhahlamba municipality	KKGR002	EL-6263012376	315	190
Steynsburg	Gariep Steynsburg municipality	OBS33	EL-7601398095	800	826

The Figure 3-10 shows the load at the Bulhoek substation. The load has been below 5MVA for the past three years according to the measurements from metering Department. There were indications of spikes on regular basis on the Bulhoek 22kV feeders. These spikes were caused by faults that were experienced on these lines. With developments expected in the area, the load is estimated to not grow to more than 5MVA (Maximum transformer capacity) for the next 10 years.

[2] 10.7MVA is the normal thermal rating for the Hare conductor, more details are found in Appendix E
[3] 10.7MVA is the normal thermal rating for the Hare conductor, more details are found in Appendix E

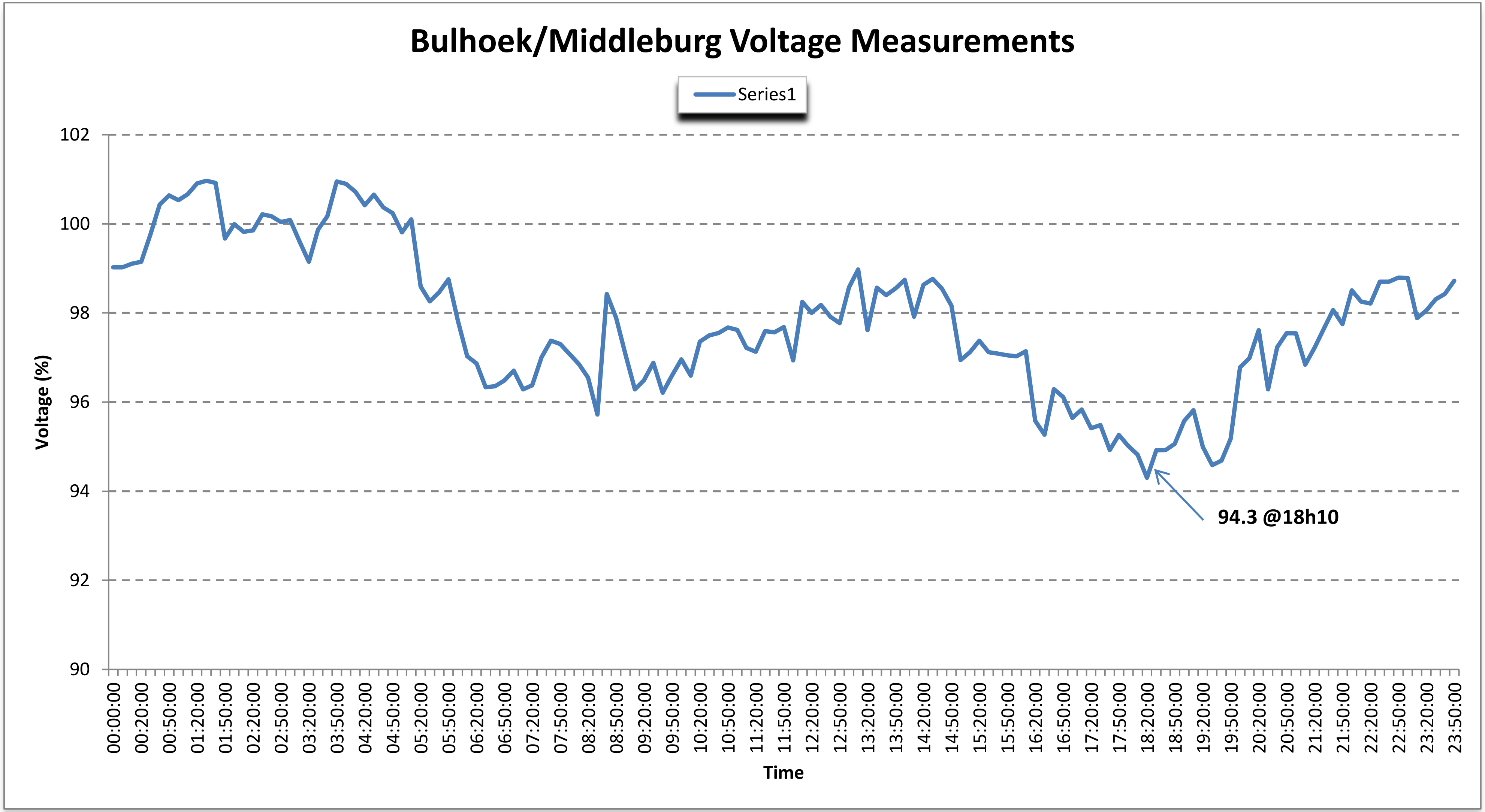


Figure 3-9: Bulhoek/Steynsburg 22kV line voltage measurements

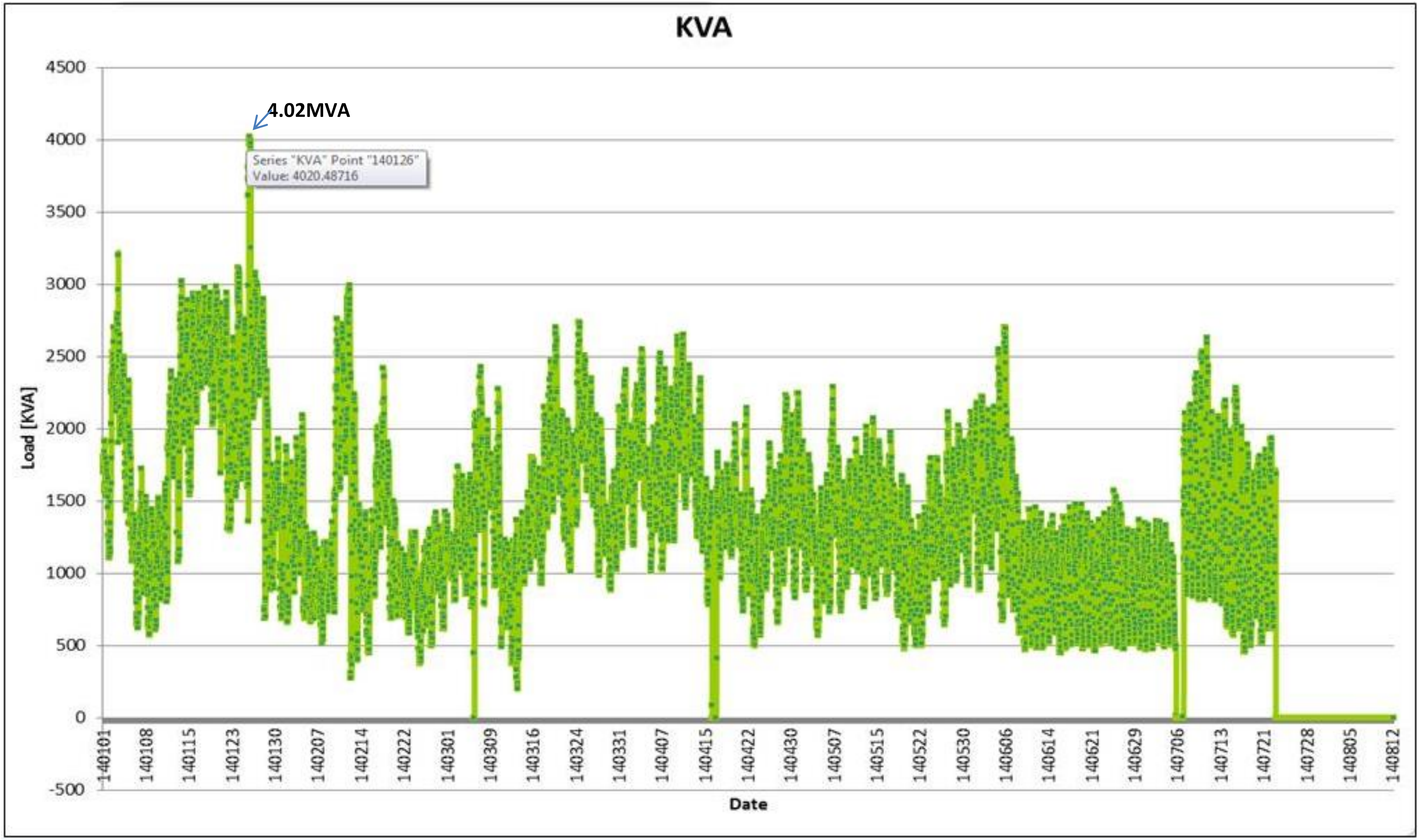


Figure 3-10: Bulhoek Transformer loading data

The following section details the quality of supply (QOS) parameters seen at Bulhoek 22kV busbar.

From the collected measurements, it is evident that unbalance connection (load balancing) has a major effect on the technical performance of MV networks supplying unbalanced technologies such as phase to phase tee-offs. The voltage unbalance is being partially caused by the connection of the electrification customers, the phases that are normally overloaded during the electrification projects are blue and red phases (two outer phases - CA) as most single phase household connect to dual phases spur lines. Proper balancing can significantly reduce the level of voltage unbalance. This was witnessed at the Steynsburg 11kV Munic feeder that supplies Khayamnandi electrification. The following Figure 3-11 depicts the original technological overview of how the network should be configured.

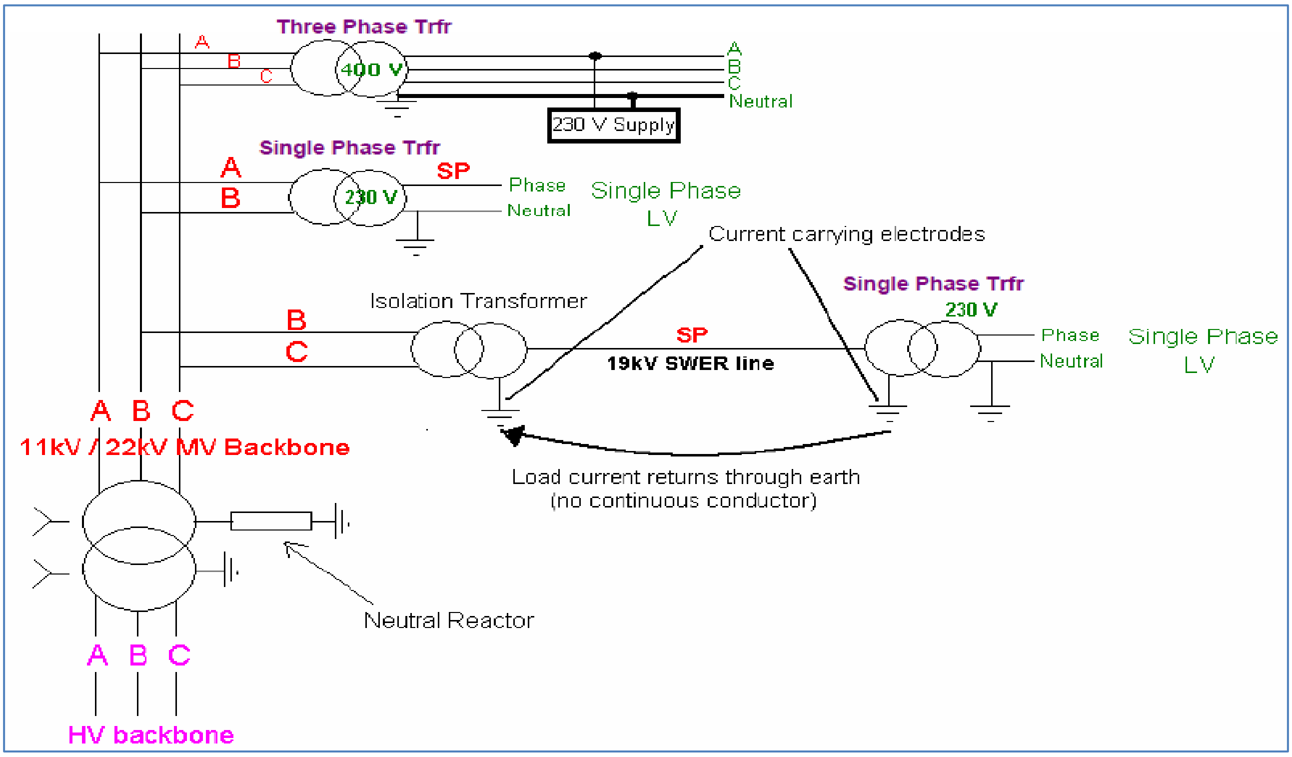


Figure 3-11: Single phase LV Technology sourced from a MV system [46]

3.8 Single Phase

Single phase LV technology is derived from a MV system in one of the following ways:

- By using only 2 phases of the 3 phases in a three phase MV delta system and transforming the voltage through a step-down transformer to provide the single phase LV system.
- By using a 19kV SWER network and transforming it through a step down transformer to the single phase LV system.
- By connecting between phase and neutral of a three phase Star or dual phase LV network, which are in turn connected to the MV system via a three phase and dual phase transformer respectively.

A single phase LV system has two wires (one for the neutral and one for the phase conductor). The phasing of the LV technology will be SP if it is the combination of two primary system phases. When sourced from a three phase Star system the phasing will be A, B or C.

3.9 Load Forecast Philosophy

The single biggest drive for new or existing network is new load, load expected, and future socio economic activity in the study area. Hence, knowing the drivers for expanding load is critical to the any network. These drivers may manifest as Political or economic drivers. Load forecasting at a macro level is done to derive the long term requirements of a power system. Similarly, forecasting the load at a micro level is performed to underpin the requirement for medium term development of the network. Without proper load forecasting one cannot plan adequate future networks.

There are three main principles behind load forecasting. Knowing where the load or generation will materialize. Knowing when the load will materialize and knowing how much of load will materialize are the three critical aspects to a load forecast. Understanding the three critical load forecasting factors to develop future scenarios for developing the strategy build of the distribution power system. Both methods must employ a sensitivity analysis to determine the risk of uncertainty within the forecast. The sensitivity of the preferred network alternative to meet the forecast needs to be assessed to determine if different forecast scenarios result in different network solutions. Special attention needs to be paid to forecasts where different forecast scenarios have different preferred network solutions. A consequence of geographical based load forecasting is the definition of load zones that may be subjected to criteria such as reliability, losses, feeder length (minimizing exposure) and the number of transformers to define the load zone for a particular urban (and rural) area of supply. A load forecasting tool known as Power GLF has been designed for this purpose which assist in utilizing the philosophies of load forecasting to develop a load forecast for an aggregated area (high or medium voltage network) or at a micro level (section of medium voltage or LV network). Power GLF tool was used in this paper for forecasting studies.

3.9.1 Base Spatial Model

The large power users are forecasted depending on the customer class they belong to and the growth curve emulating the type of load. Two types of forecast methods were used to determine the load growth of the LPUs, namely fixed percentage and spatial load growth methods. The LPU's NMD and historical loading were used as an indication of their possible maximum saturation load.

Developments should be forecasted using information contained in the Forecast Baseline Report (Town Planning information). However, for this load forecast the baseline reports was not available and so development information was provided by the Town and Regional Planner by means of a spreadsheet. For developments where insufficient information was available to do a load forecast, benchmarking was used to forecast the load of the development.

The base year for the forecast is 2014. Historical loading data was obtained from MV90 tool. The base load was compared to the previous Graaff Reinet NDP and Network Master Plans load forecasts.

3.9.2 Impact of Assumptions on the forecast

- Subclass for electrification
  - To emulate the demand behaviour, a subclass that represents the type of the domestic dwelling was chosen to ensure that the quality of the electrification load model representation is achieved. The forecast method used in the subclass is in terms of number of households connected.
- Spatial forecast for LPU's
  - As per DGL 34-1284 Geo-based Load Forecast Standard, load subclasses have been derived for specific LPU's using historical data for those loads. LPU's growths were forecasted using a fixed or spatial load forecast method.
- Base loading
  - Statistical metering (mainly from MV90) was used as base load data (2014 measured load). In areas where there was no metering data available the loading of the load object was assumed using benchmarking of typical similar known loads.

3.9.3 Load Forecast Summary

- The load forecast is one of the most important aspects of planning.
- If the load forecast is incorrect you will not be able to correctly plan for the future.
- Gather existing and historical load information (kW, kVAr, PF, LF, load profiles, peak load and minimum load, types of customers, seasonal load variations, etc.)
- Determine what is happening in the area and what developments are planned for the future. (Communicate or liaise with the area Customer Services for large customers details and most importantly site should be visited.

3.9.4 Customer Load Types on the Existing Distribution Network

The majority of customers around the Teebus area are agricultural consumers. Figure 3-12, Figure 3-13, Figure 3-14 and Figure 3-15 show the load types that falls under the agriculture and these load types are subdivided into the following subclasses:

- Dry land crops and animal - Farming mostly of animals including dairy farming and animal breeding
- Mixed - Growing of crops combined with animals
- Irrigation – Farming of mostly crops, market garden and horticulture.

It is evident on the figures below that the agricultural load peaks during the day in summer period.

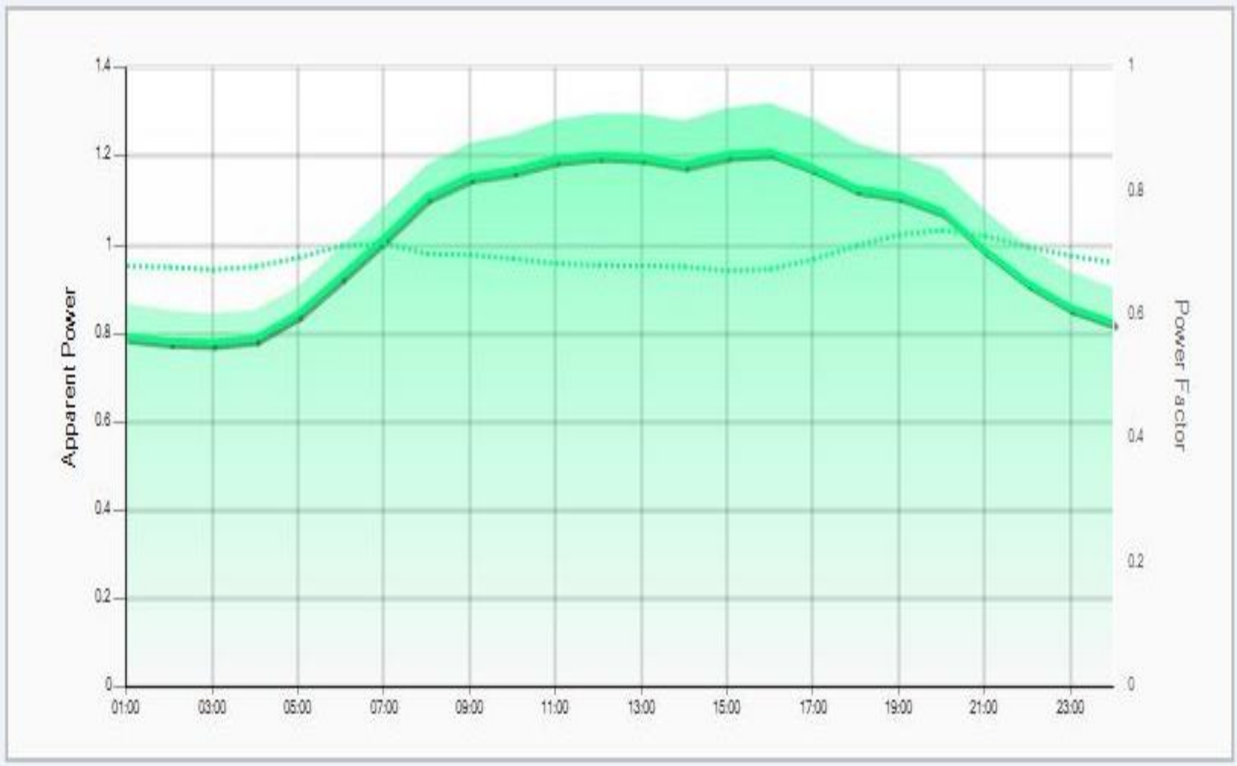


Figure 3-12: 1A Dry lands crops and Animal standard load profile-PowerGLF

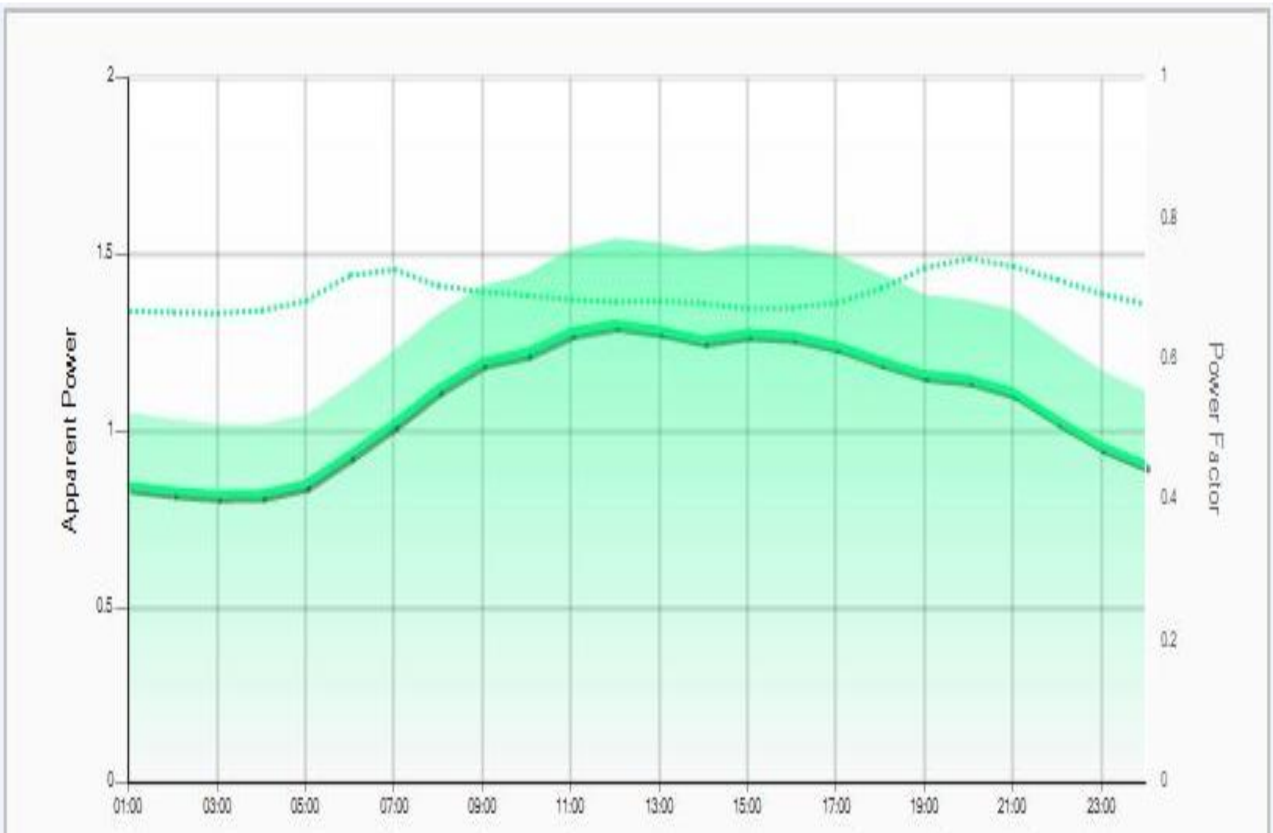


Figure 3-13: 1C Mixed standard load profile - PowerGLF

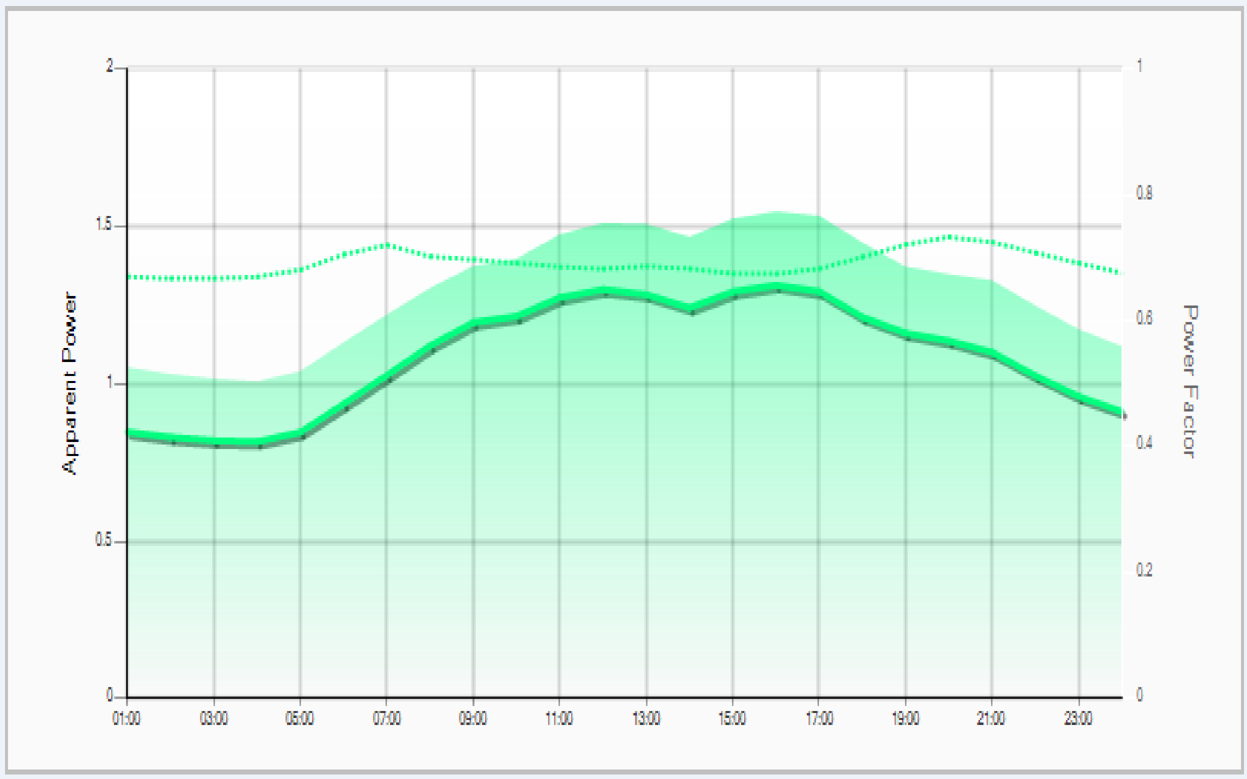


Figure 3-14: 1B Irrigation standard load profile- PowerGLF

Figure 3-15 below shows the rural residential type of load profile. This is referring to all customers that receive income between R1 800 - R3 200 per month. Typical dwellings range from shacks to newer government subsidy houses (RDP style). Generally the household size is less than $40m^2$. The load peaks between 05:00 and 09:00am and in the afternoon between 18:00 and 21:00.

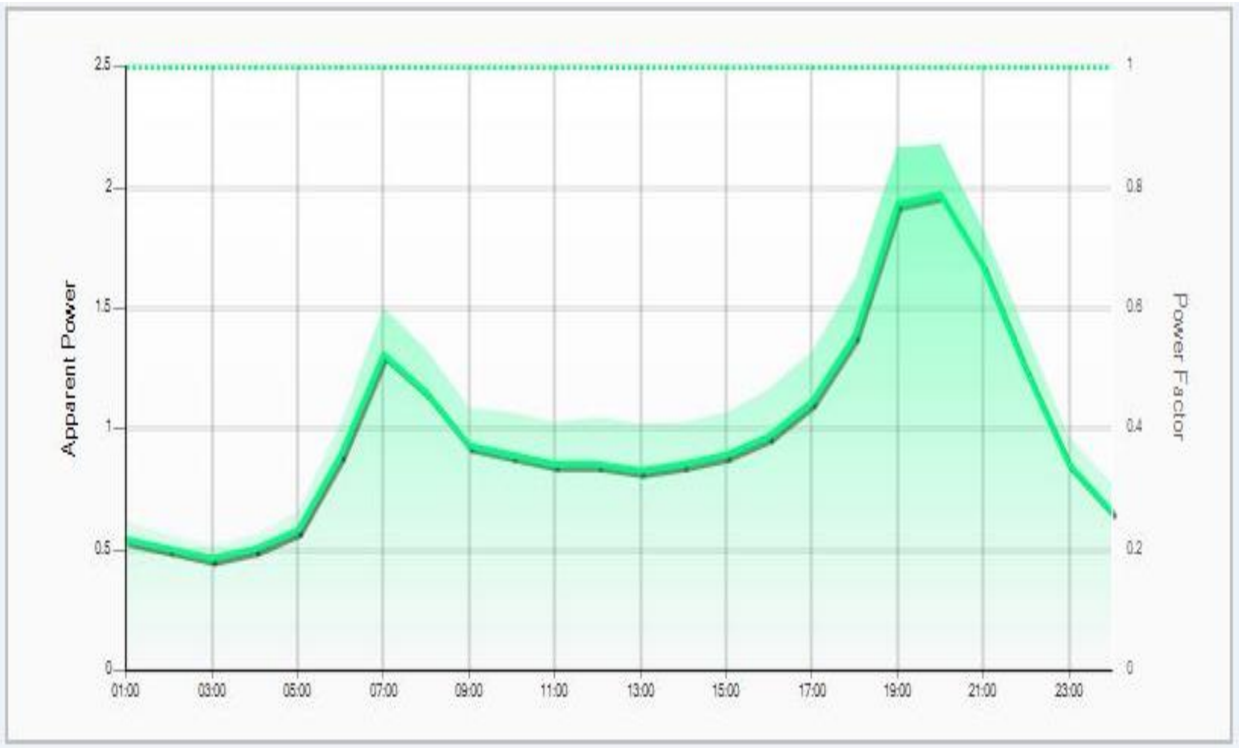


Figure 3-15: Rural Residential standard load profile-PowerGLF

The Figure 3-16 below shows the load profiles with the agricultural load (customers) being the most dominating in the Teebus area. It can also be noted from the PowerGLF profile that the peak for agricultural load is seen during the day and in summer. These graphs represent the actual load profiles on site.

The Figure 3-16 shows a quick screen shot taken from PowerGLF tool. This also depicts (see Figure 3-17) the most likely load forecast for Bulhoek substation load forecast.

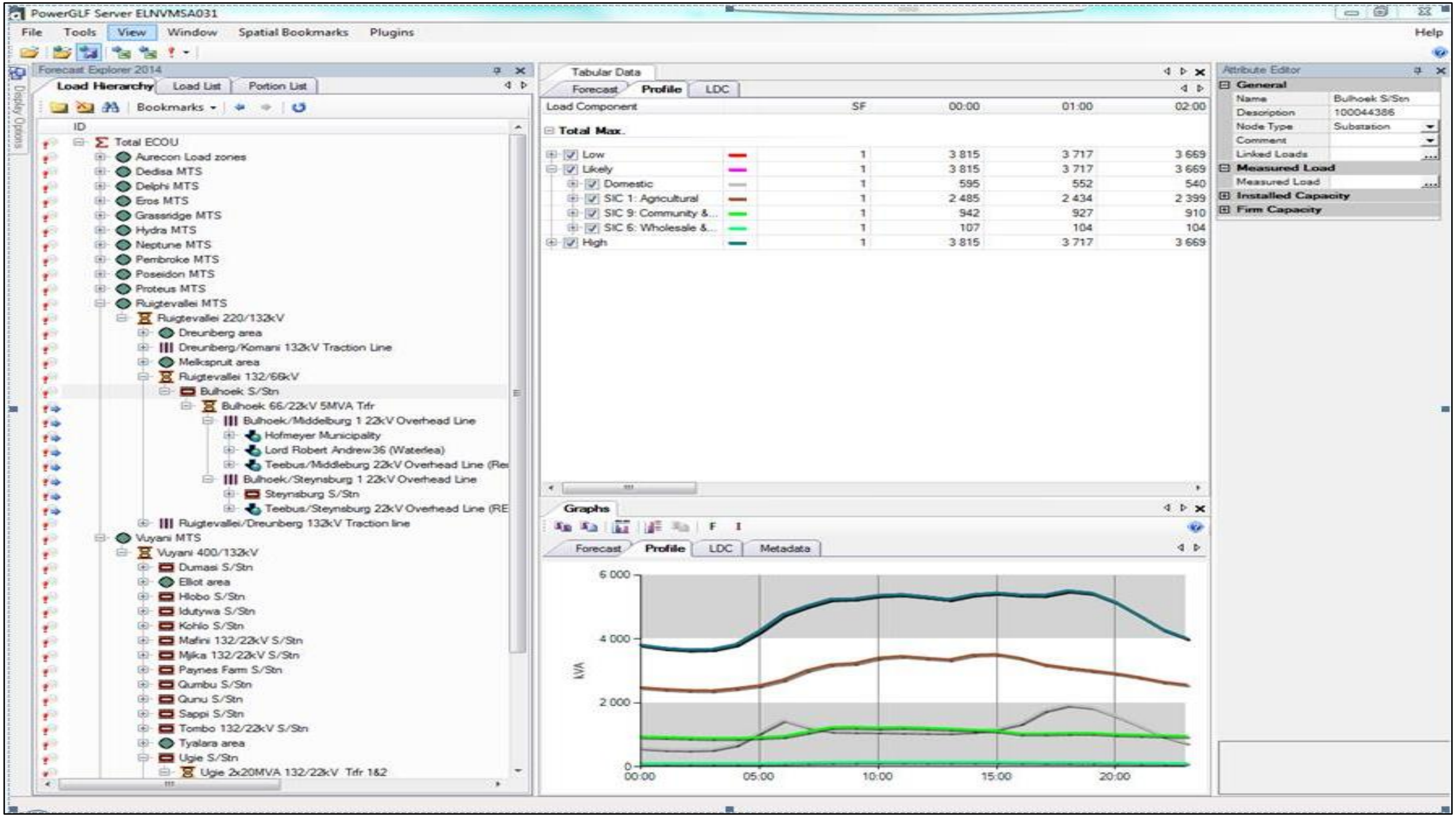


Figure 3-16: Load profiles modelled in PowerGLF

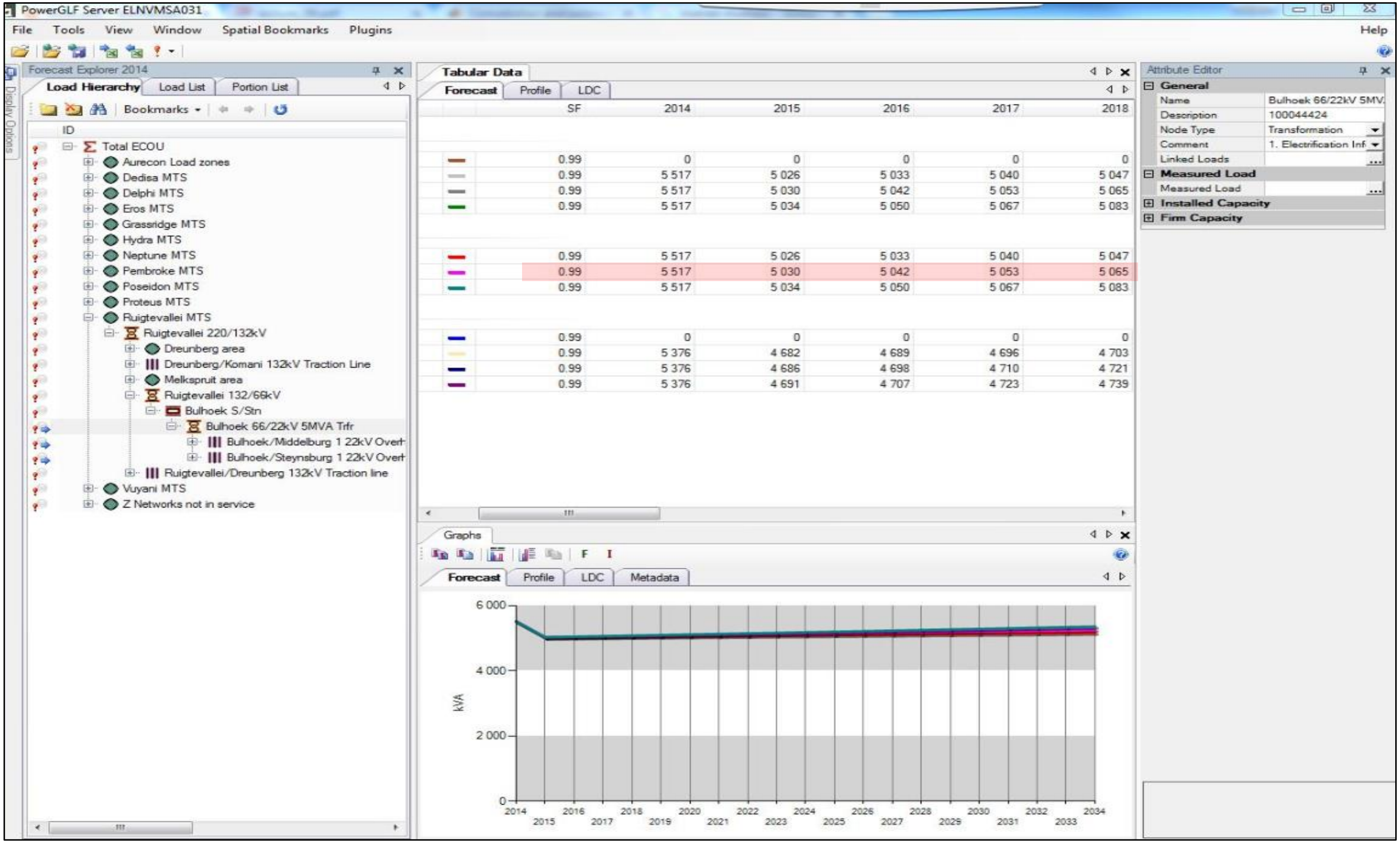


Figure 3-17: Load forecast taken from PowerGLF

3.9.5 Substation Load Forecast

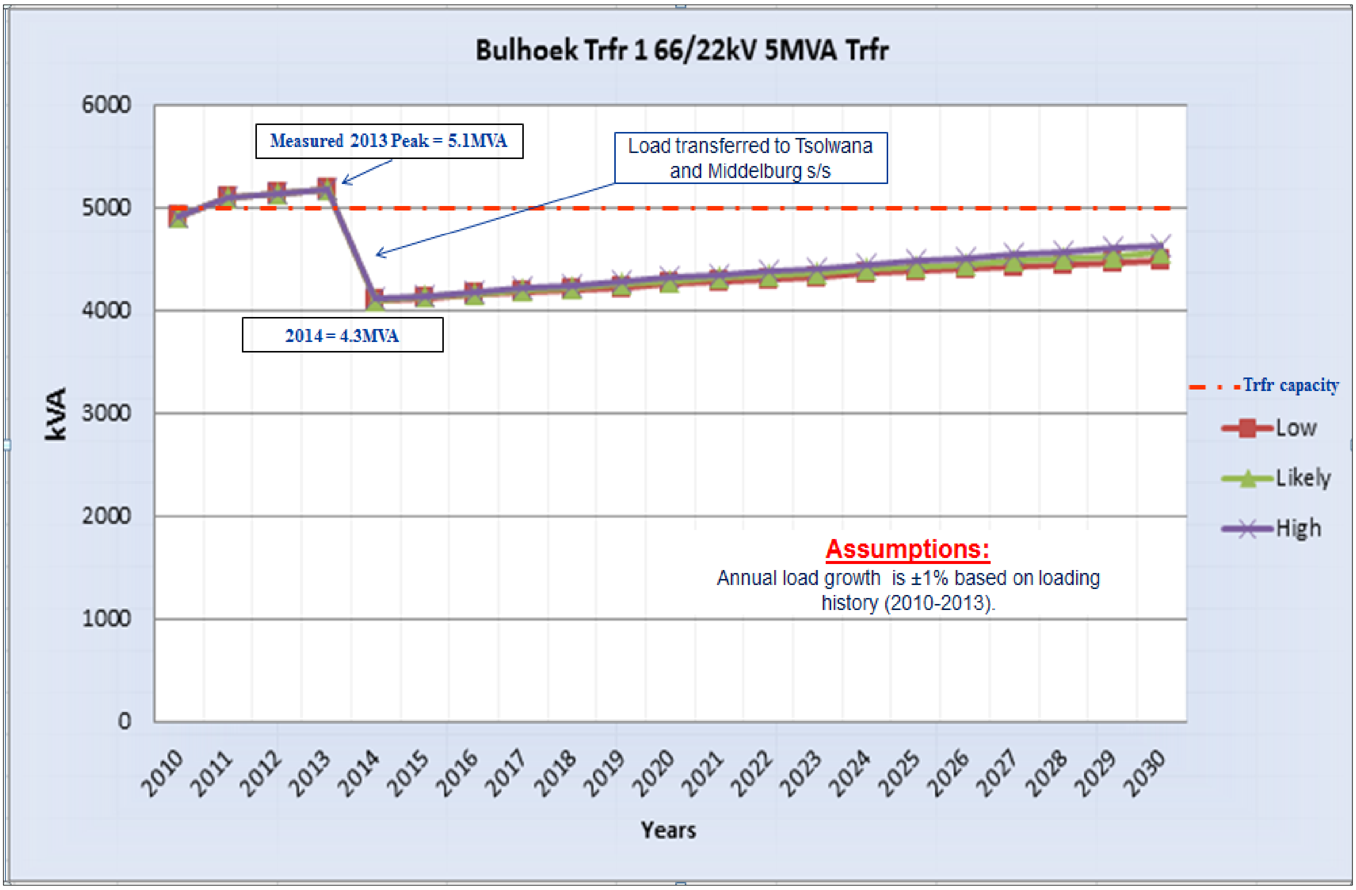


Figure 3-18: Bulhoek s/s Load Forecast

The load forecast is extracted from the Geo-Based Load Forecast (PowerGLF) tool. The Figure 3-18 above shows the future load prediction for the 22kV feeders fed from Bulhoek s/s. The measured load (5.1MVA) in 2013 went above the transformer capacity and was reduced to 4.3MVA by shifting the load to the neighbouring MV feeders (Middleburg/Bulhoek 22kV feeder). The predicted load forecast shows that the load will not exceed the trfr limit for the next 20 years. The average load growth rate per annum for this feeder is approximately 1% based on the historical data and there are no known significant developments in the area. The measurement is taken from the most likely scenario as this is the most predicted growth. The connection of the small Hydro electrics will benefit largely the upstream network and the over-voltages on the MV network would be tested in the analysis. The future load growth in the area and the connection of small hydro generators will influence the selection the transformer sizes.

3.9.6 Future Load Forecast

The future load growth development envisaged for the municipality is mostly household developments in the form of low housing and also gap households. The rest of the municipalities that fall within the study area have no developments that were established which will contribute to the load growth. There is a number of IPPs that have applied for connection in the area. These small hydro generations are all intending to export power to Bulhoek substation. The detailed study will be done to check the Bulhoek substation capabilities.

Table 3-3: Inxuba Yethemba Municipality Developments

Load Driver	**Quantity**	**Load (MVA)**
Cradock Mall	1	1
Lingelihle middle income housing	250	0.52
Michaudal high income housing	140	0.29
Oukop low income housing	2250	1.28
Total MVA Contribution		3.09
Future Hydro Generation		
Navitas Power		10MW
Gaia Power		4.4MW
Future Wind Generation		
Inno Wind		Capacity not confirmed yet
Wind Current SA		Capacity not confirmed yet

3.10 Network Performance Data

The investigation was carried out to determine the root cause of the poor performance on the MV network with respect to failure rates and SAIDI contribution. Most part of the network was built from 1979 and has their backbone built with a Steel A-frame with porcelain post insulators. Two-phase customer spurs of the latter are built with upright and side porcelain post insulators with no cross-arm.

- **Detailed investigations have shown some of the following defects on the Badsfontein/Bulhoek 66kV line:**
  - Vibration dampers and earth wire are loose and some removed
  - Strain cross arms are broken and bad soil erosion around the structures.
  - Ground is being washed away around some poles
  - Poles are skew and have loose tension stays.
  - Sloping arms are cracked and there are loose nuts
  - Pollution and rust on disc insulators.
  - The shield wire on this line is badly corroded.

It was found that when the Badsfontein/Bulhoek 66kV line fails it is a struggle to operate via the two control systems. This causes time delays and affects the performance. It was also found out that existing MV feeders do not have bypass facilities on the therefore, no load transfer is possible. The

Table ***3-4*** shows a summary of the long duration faults that occurred on the Badsfontein 66kV line.

Table 3-4: Faults and duration of the faults occurred on Badsfontein 66kV line

Line	**Date**	**Fault Type**	**Duration**	**Hours Lost**
Badsfontein /Bulhoek 66kV	07/02/2008	Conductor broken	10hrs	10hrs
	12/09/2008	Conductor broken	10hrs	10hrs
	02/09/2012	Equipment maintenance	11hrs (planned)	11hrs
BA-BU-135 (Line isolator)	07/03/2011	OLTC- Faulty	70hrs (Alarm)	70hrs

Table 3-5: Outages and faults occurred at the Bulhoek substation

Substation/Line	Date	Fault Type	Hours Lost
Bulhoek Substation	27/10/2013	Equipment maintenance	15hrs (planned)
Bulhoek Substation	27/09/2011	Equipment maintenance	8hrs
Bulhoek substation Trfr 66kV (Notified)	27/09/2011	Conductor Failure	73hrs
Bulhoek substation Trfr 22kV Bkr (Notified)	22/12/2012	Trfr OLTC locked out	45hrs
Bulhoek/Middelburg 22kV (Fault)	05/09/2012	Protection scheme problem (secondary plant)	786hrs(≈ 1month)

Table ***3-5*** above depicts the faults and the duration that the equipment was out for at the Bulhoek substation. There were a total of fourteen conductor failures on the Bulhoek/Middleburg 22kV network. Seven of these conductors failed during clear weather conditions, two failed during overcast, one failed during storm, three during windy conditions and one failed during rainy conditions. The more detailed data is listed in Appendix E.

3.11 Protection Philosophy Data:

There are type of technology protection used by Eskom Distribution, generally referred to as phase 1, 2, and 3.

- Phase 1 relays – Old electromechanical relays with moving parts. These have dominated the protection field for a long time, but are gradually being phased out.
- Phase 2 relays – introduction and use of static relays an offshoot of semiconductor devices. Advantages of lower weight, non-moving parts, reduced wear and tear.
- Phase 3 relays – Reliability of electronic components major problem with Phase 2 relays. E.g. Siemens 7SL27, SEL -351S. This led to advent of digital or microprocessor based relays.

The difference is basically based on the speed, functionality, flexibility and reliability. A single digital relay can provide the same functionality of eight or more phase 1 relays, at the same price as one electro-mechanical relay. At Bulhoek substation the protection schemes have recently been changed to phase three technology. The future is tending towards digitised substations with all relays communicating back a central location (East London, Sunilaws Office Park).

Table 3-6: Stages of technological development

Period	Technology	Example		
		Rural Feeder Relay	Impedance Relay	Recloser
Phase 1	Electro-Mechanical Relay	CDG	LZ32	OYT
Phase 2	Electronic	GAD	7SL27	ESR
Phase 3	Digital	DPU2000, SEL 351S	SEL 321	NULEC

3.12 Protection Coordination

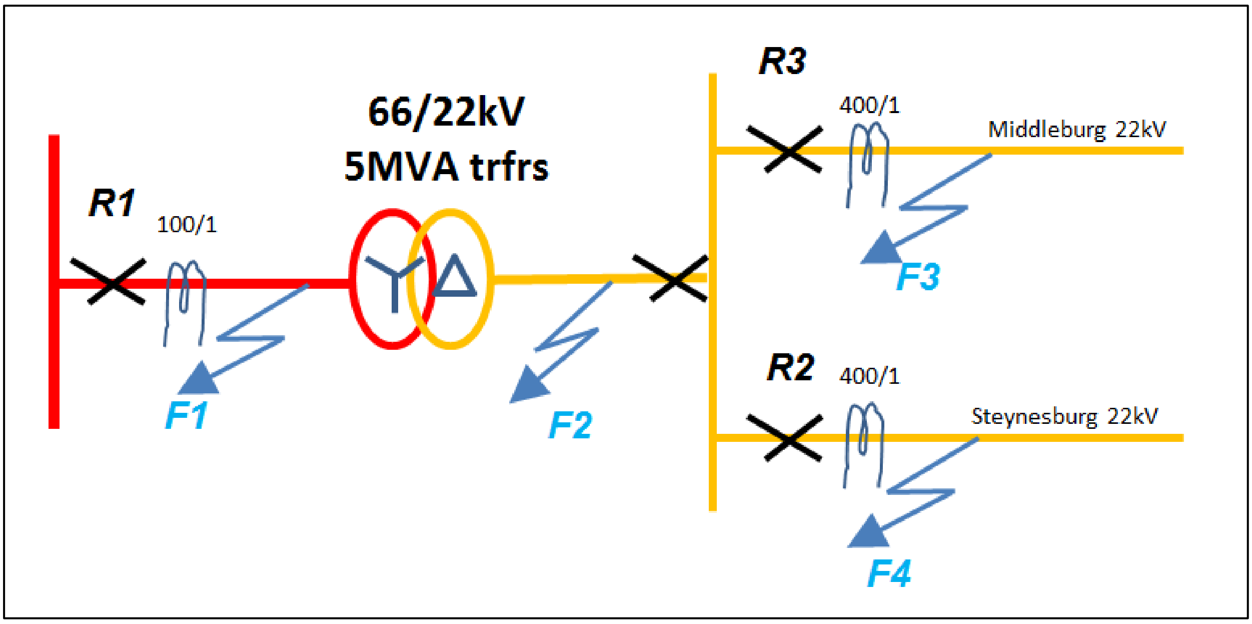


Figure 3-19: Existing protection coordination

Data required for the coordination study [8]**:**

- Single Line diagram
- System voltage levels
- Incoming power supply data
    - Impedance and MVA data
    - X/R ratio
    - Existing protection including relay device numbers and settings, CT ratios and time-current characteristic curves
- Data on system under study
    - Generator ratings and impedance data
    - Motor ratings and impedance data

- Protective devices ratings including momentary and interrupting duty as applicable
- Time-current characteristic curves for protective devices
- CT ratios, excitation curves and winding resistance
- Thermal (I^2t) curves for cables and rotating machines.
- Conductor sizes and approximate lengths

- Short circuit and current data
  - Maximum and minimum momentary (5cycles and above) short circuit currents at major buses.
  - Maximum load currents
  - Motor starting currents
  - Transformer protection points

3.13 Coordination procedure [20]:

The following procedure should be followed when conducting a coordination study:

- Select a convenient voltage base and convert all ampere values to this common base. Normally, the lowest system voltage will be chosen, but this may not always be the case.
- Indicate short-circuit currents on the horizontal axis of the log-log graph.
- Indicate largest (or worst case) load on the horizontal axis. Safety factor for CT saturate- 0.22 seconds
- Specify protection points. These include ration and setting errors.
- Indicate protective relay pick-up ranges.
- Starting with the largest (or worst case) load at the lowest voltage level, plot the curve for this device on the extreme left side of the log-log graph. Although the maximum short-circuit current on the system will establish the upper limit of curves plotted to the right of the first and succeeding devices, the number of curves plotted on a single sheet should be limited to about five to avoid confusion.
- Using the overlay principle, trace the curves for all protective devices on a composite graph, selecting ratings or settings that will provide overcurrent protection and ensure no overlapping of curves
- Coordination time intervals. When plotting coordination curves, certain time intervals must be maintained between the curves of various protective devices in order to ensure correct sequential operation of the devices. These intervals are required because relays have over travel and curve tolerances, certain fuses have damage characteristics, and circuit breakers have certain speeds of operation. Sometimes these intervals are called margins.
- When coordinating inverse time overcurrent relays, the time interval is usually 0.3 - 0.4 seconds. This interval is measured between relays in series either at the instantaneous setting of the load side feeder circuit breaker relay or the maximum short-circuit current, which can flow through both devices simultaneously, whichever is the lower value of current. The interval consists of the following components:

List of indices required to analyse protection philosophy;

- Incidents per device
- Outage duration linked to the device
- Number of customers affected per device
- Customers affected per incident for each device
- Hours lost per incident for each device

Knowledge of the existing protection philosophy is vital to get the correct analysis of the distribution network (as listed above).

3.14 Reclosers and Voltage regulators on the Bulhoek/Middelburg 22kV feeder

- 4 x Automatic Re-closers (ARC) relay (location)
  - BUL-MID 224
  - HOF34-2
  - TSO-BM-T-790
  - BLOM-2
- 4 x Automatic sectionalising devices
- 1 x Closed delta 200A Voltage regulator (located at structure BUL-MID-181)
- Expulsion fuses, extensively used in Eskom
- MV/LV transformers operates on fixed tap, this voltage rise could have a direct impact on customers.
- Fault path indicators (FPI)

The Bulhoek/Middleburg 22kV feeder has four reclosers according to the information gathered using a single line diagram. The network is then demarcated into 5 recloser zones as follows:

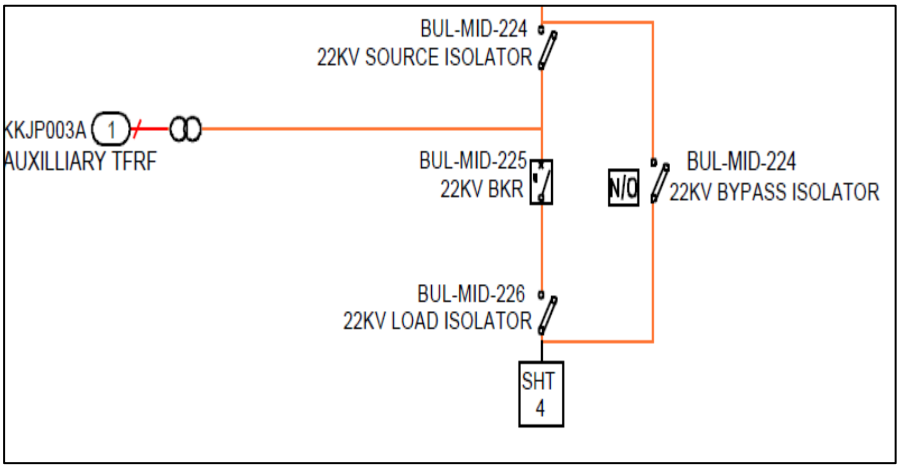


Figure 3-20: Recloser configuration

Table 3-7: Breakers zone and customer zonal protection

Breaker Zone	Make	Telemetered	Zonal customer base	Zonal Trfr KVA base	Line length (km)
Z1 (Fdr Bkr)	EIB	YES	11	150	15
Z2 (KKJP003A)	NULEC	YES	40	80	7
Z3 (HOF34-2)	NULEC	YES	35	37	56
Z31 (TSO-BM-T-790)		NO	6	26	13

The line needs minimum of 4 up to a maximum of 7 reclosers based on line length of the existing feeder and kVA ratios of the transformers. The line currently has 4 automatic reclosers. The network portion beyond recloser HOF 34-2 needs an additional recloser.

3.15 Fault Path Indicators

The line needs a minimum number of 4 FPIs based on number of currently installed reclosers. The reclosers and the FPIs need to be placed in strategic positions and as optimally as possible. The line currently has one FPI installed at structure TSO-BM-T 770. Three additional FPIs are required. The FPIs are very useful devices during fault finding exercise there installed on the distribution networks usually pole-mounted at between 1.8m and 2m below the lowest conductor or phase segregated units installed on the conductor. The must be installed at the visible vicinity preferable visible from the road.

3.16 Fuses

The types of fuses used in Eskom Distribution network are expulsion fuses and cut-out base. The Fusing will be reviewed based on MV Protection Philosophy Eskom Standard and the changes where necessary will be noted from the protection optimisation exercise. The Bulhoek/Middleburg 22kV feeder consists of the following (K-type) fuses:

Table 3-8: Number of fuses on Bulhoek Middleburg 22kV feeder

Rating (A)	Type	Number
10	K	6
20	K	32
30	K	17

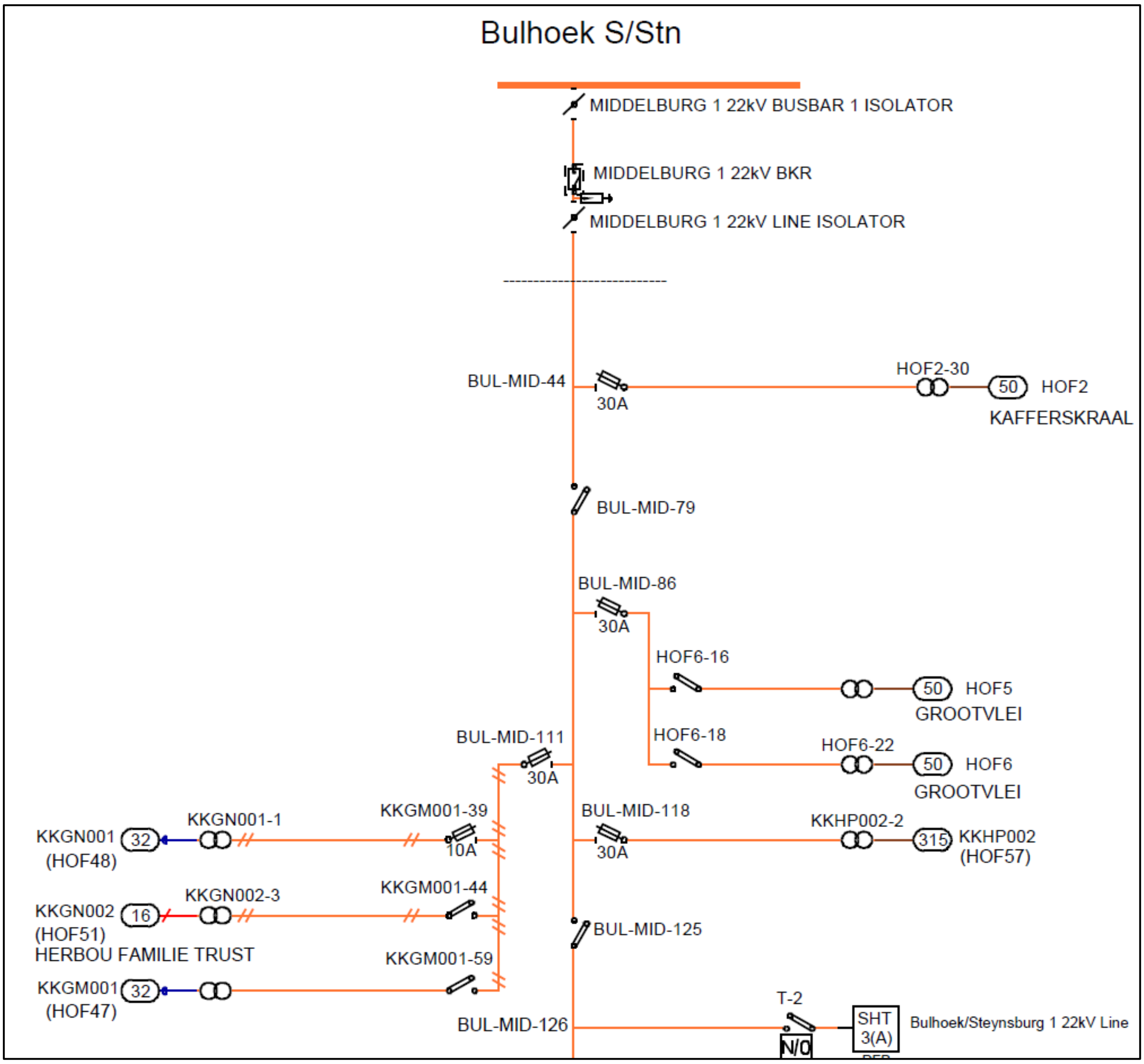


Figure 3-21: Single Line Diagram showing fuses

The above Figure 3-21 is a Bulhoek/Middleburg 22kV single line diagram (SLD) feeder depicting the expulsion fuses installed. The placement of the fuses in this case will not be affected by adding the generation onto the distribution network.

The following chart shows the events occurrence per month of year 2013/14.

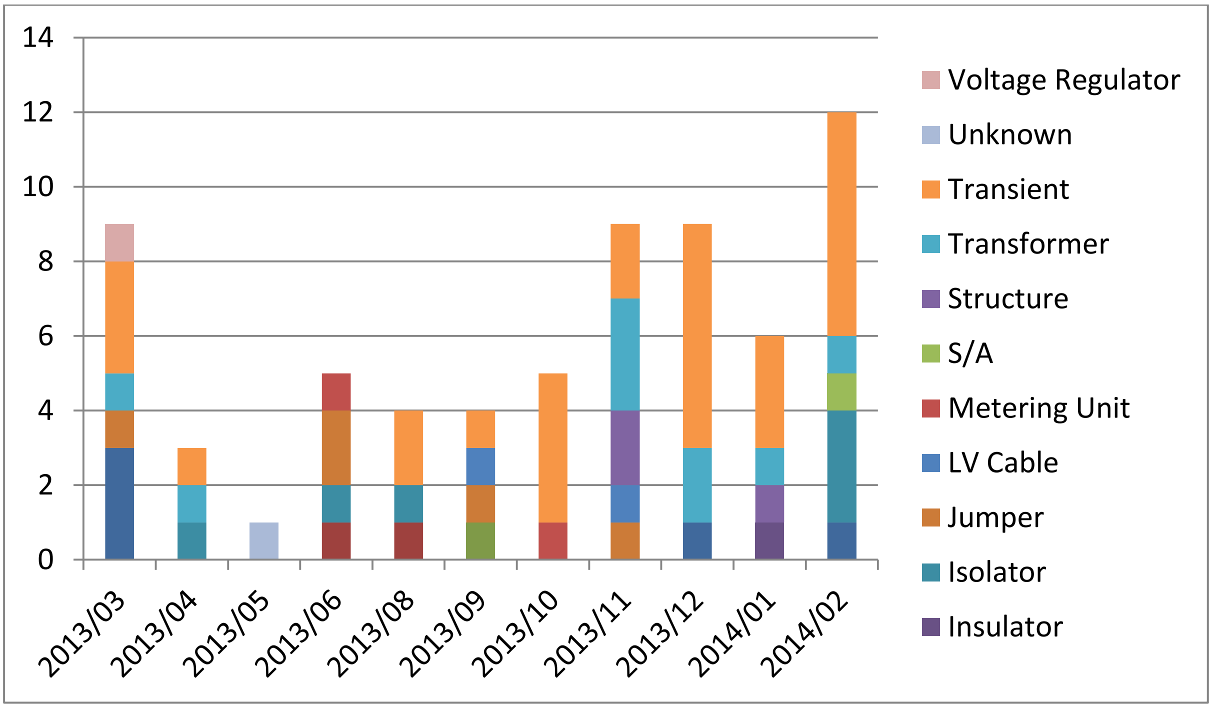


Figure 3-22: Events per month

The above chart shows that most events occurred during the summer months in 2014. Also the transient's events which are line breakers locking out with no permanent fault found are occurring almost throughout the year but predominantly during the summer months.

3.17 Quality of Supply

The main objective of this section is to monitor the full spectrum of deviation in quality of supply at the Bulhoek substation. The aim is also to ensure that excessively high levels of deviation are identified, action plans put in place so that they can be appropriately managed. The data was downloaded from the quality of supply recorders at Bulhoek substation. Note that the data also does not include the traction voltage unbalance.

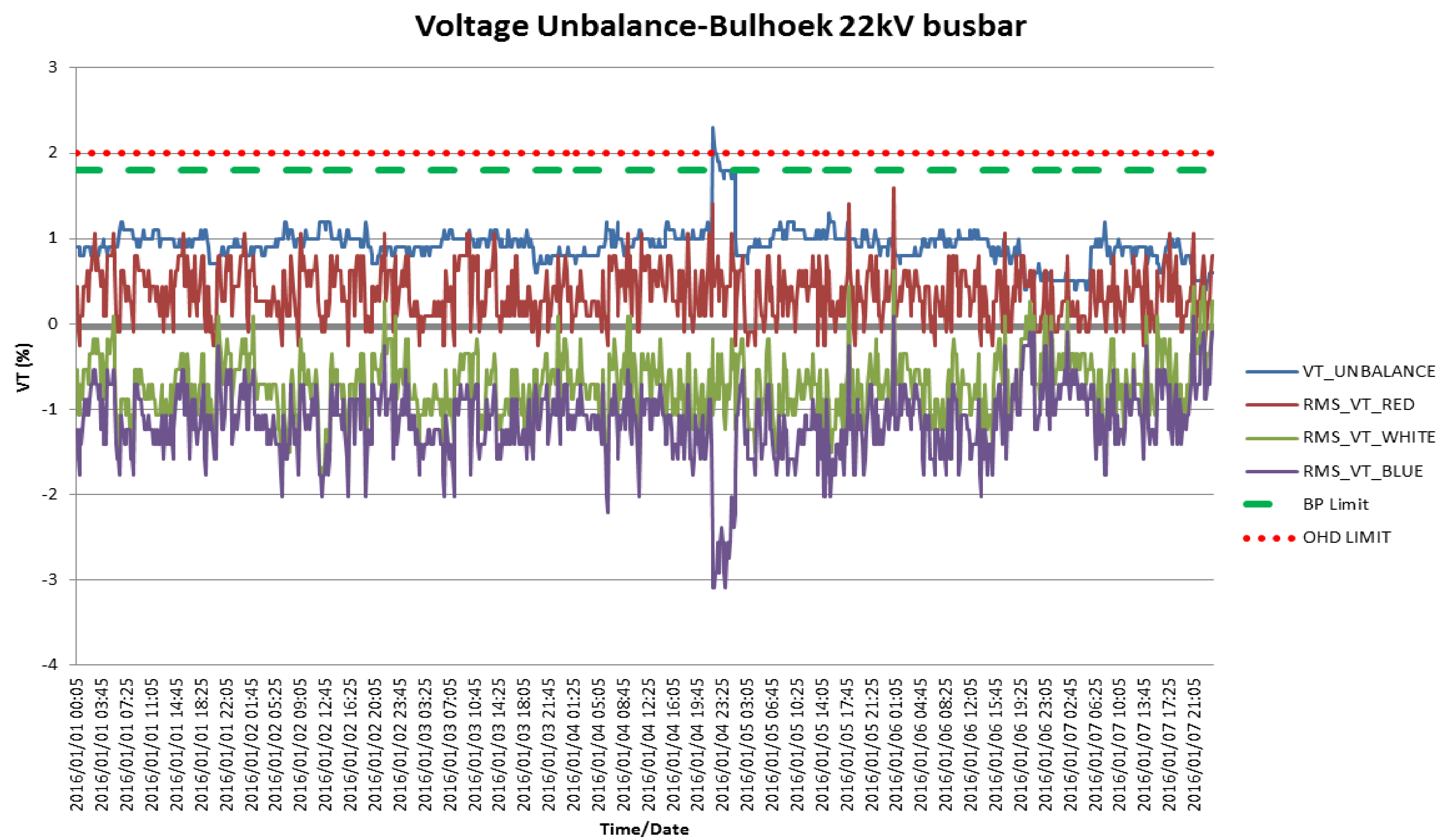


Figure 3-23: Bulhoek 22kV Voltage unbalance - RMS Values

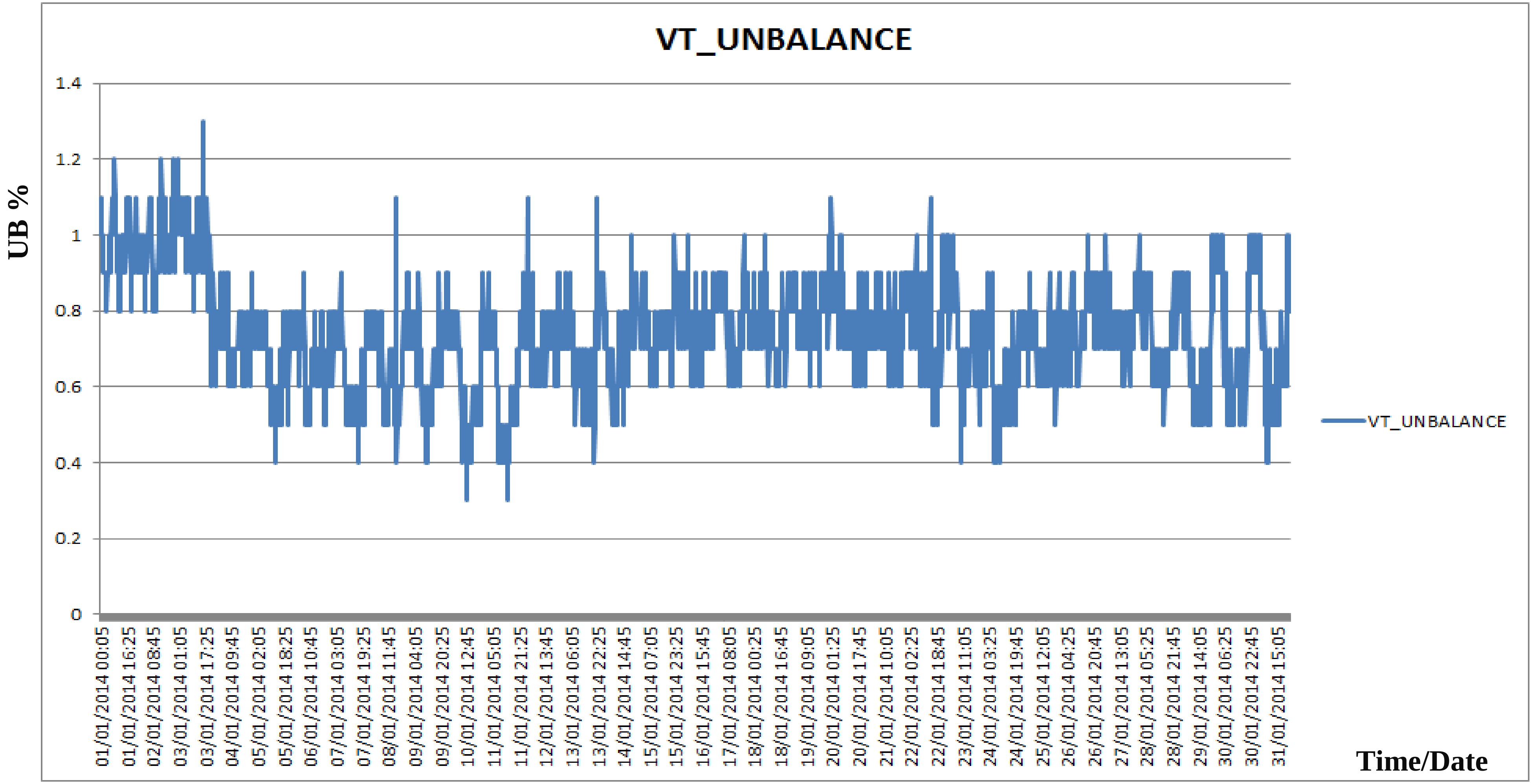


Figure 3-24: Bulhoek/Middleburg 22kV feeder 2014 data

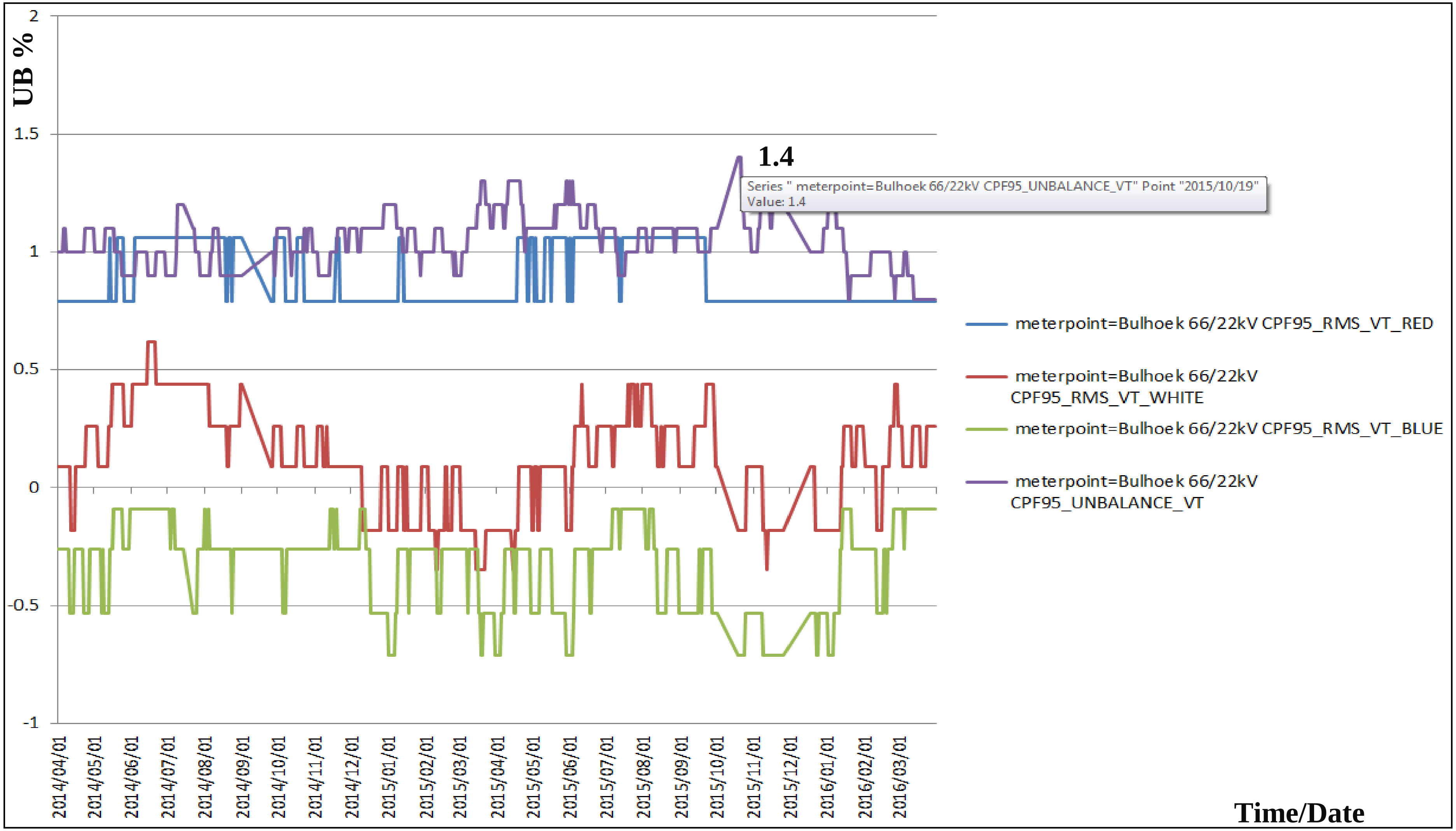


Figure 3-25: Bulhoek/Middleburg22kV voltage unbalance - CPF 95 values 2015 data

Figure 3-23, Figure 3-24 and Figure 3-25 show the measured trended values recorded by a power quality (PQ) recorder at the Bulhoek 22kV busbar for approximately a year. These compatibility values shown on Figure 3-25 are minimum and maximum RMS values. The voltage profiles indicate that Eskom currently does not comply with the +-5% or with the +-7.5% standard limit prescribed by the NRS 048-02, the exceedances that happened on 04 January 2016. This trended values do not necessary mean the voltage unbalance limits are exceeded. The trended values (RMS) are not used only for reporting purposes but the CPF 95 values, where the 5% of the data has been filtered. Cumulated Probability Function (CPF 95) is shown in Figure 3-24 and Figure 3-25. Based on the graphs above, it is found that the voltage unbalance is within the limits set by the National Electrical Regulator. The actual analysis will be discussed in depth under the analysis section. It should be noted that the red and the blue phases are significantly loaded. It can be seen that the winter demand also possibly results in lowering the voltages. The white phase is shown to be relatively lightly loaded throughout the year.

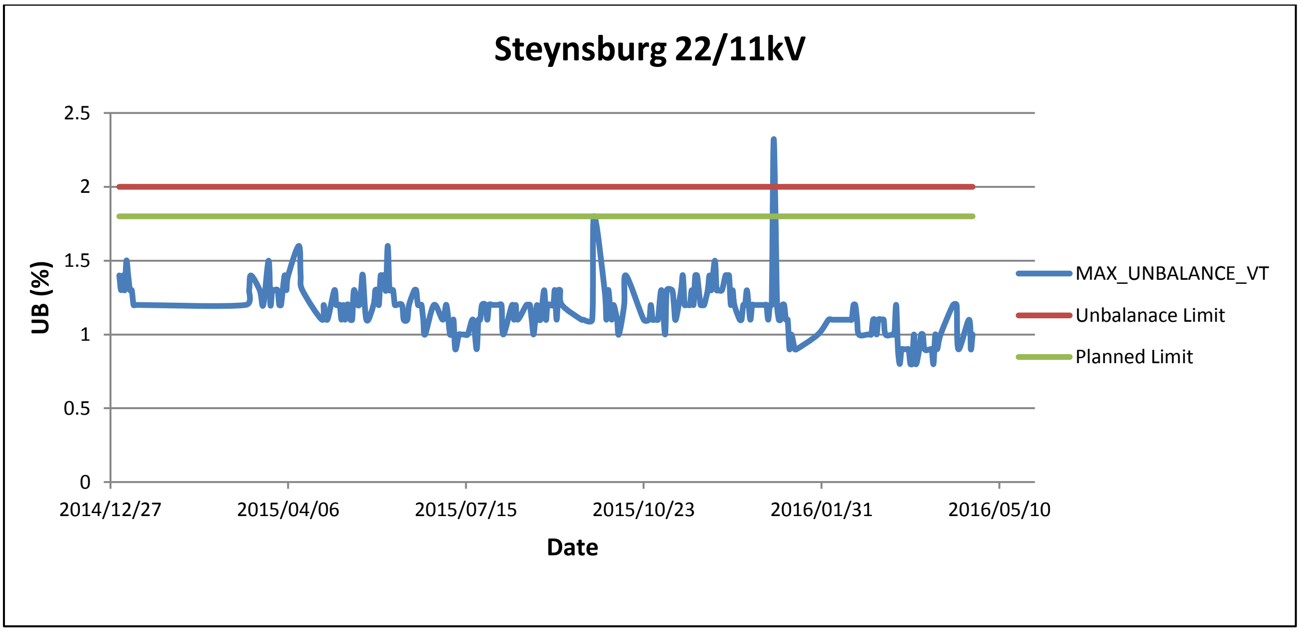


Figure 3-26: Bulhoek/Steynsburg22kV voltage unbalance - CPF 95 values 2015 data

Based on the graph in Figure 3-26 below, the unbalance limit has not been reached except for 2015/01/04 where both the planning and unbalance limits have been reached. This has been considered as a spike as it has never happened in the previous years.

3.18 Existing Teebus Hydro Technical Information

A comprehensive survey for the purpose of acquiring information for Teebus Tunnel was done. This was achieved by conducting interviews, extracting information from the reports and interacting with area field Eskom stuff. The following information was found.

Teebus Hydro generation station is situated approximately 25km from Steynsburg and is located about 30km away from Bulhoek substation and it falls within the Eastern Cape boarders on the Northern side. It is situated on the water tunnel between the Orange and the Fish River system which was commissioned in the l975. The Teebus Hydro receives water from Gariep dam and has an existing underground structure designed to allow two powered turbines generators.

The Hydro Generator station was designed to use bypass water from the canal control valves that regulate the water flow to a canal for agricultural use by about 700 farmers downstream. The water is then finally fed into the great Fish and Orange River system. The released amount is negotiated with Department of Water Affairs on a weekly basis by the farmers and varies between $10cm^3$ and a max of $45\ cm^3$ per sec. The water flow is not constant over the full year and a 5 week shut down of the tunnel takes place toward the end of each year for maintenance purposes. The pressure in the Penstock varies between 7 and 5.5 bar (Depends on the dam level).

Both penstocks into the Hydro system are 2 meter diameter steel pipes one of which is blanked off in the station. The other penstock is reduced down to about 700mm diameter via a hydraulically operator which is then piped into the turbine. According to the information received, the turbine was only started once on completion of the tunnel and ran for a short time. A month after the Turbines were installed, a vehicle skidded off the overhead loading bay and fell on top of the alternator and the auto voltage regulator control panel causing extensive damage to the alternator terminals and the housing of the unit. Most of the terminations were snapped off including some of the bus bars from the stator and the excitation windings. The cubicle housing of the AVR was crushed and that in turn broke the controls and sensing of the AVR s circuits which were damaged extensively on impact.

3.19 Information provided by generation developer

Physical location of the plant:

Generator Facility:

Latitude	**S**	3	1	°	2	1	‘’	5	0’	.	8
Longitude	**E**	2	5	°	3	9	‘’	5	1’	.	1

Electrical Connection Point:

Latitude	**S**	3	1	°	1	5	‘’	3	0’	.	5
Longitude	**E**	2	5	°	4	0	‘’	4	7’	.	3

Table 3-9: Data required for 10MW Teebus Hydro

Generator unit data	**Type/Unit**
Is the generator new or existing	New
Type of generation plant	Hydro
Fault contribution from generation plant	3MVA
Generator rated MW (5.64MW)	11.3MW
Rated generator voltage (11kV)	6.6kV or 11kV

In addition to the above, there have been a number of requests from the IPPs that want the connection in the Teebus surroundings. These are listed below:

- Navitas Power – They have already installed 4.3MW at various locations and are desperate to start exporting this power onto the grid.
- Eskom PDD (Matsoso Matsoso) – Confirmed that they want to install 10MW of hydro power at Teebus.
- Gaia Power – 4.4MW with scope to increase beyond 10MW in future
- Innowind – Scoping for a large scale wind farm (capacity not confirmed yet)
- Windcurrent SA – Scoping for a large scale wind farm (capacity not confirmed yet)

NB: In this study, only the potential approved IPPs will be demonstrated, however the solution will consider the future expected IPPs in the area.

Chapter 4. - DATA ANALYSIS AND INTERPRETATTION

4.1 Introduction

In this chapter, the results from Digsilent PowerFactory and other software applications will be discussed. The main objective of this section is to ensure the accuracy and the correctness of the data by comparing the results using calculations and simulations. For the analysis in this section Figure 4-3 was used. The 22kV and the 66kV distribution network were analysed.

4.2 Digsilent Powerfactory Data Analysis:

For the purpose of modelling and analysis of power system stability and voltage unbalance of the network with small hydro generation interconnected, Digsilent PowerFactory software will be used.

Powerfactory is widely used in Network Planning, Network Operations and maintenance of power systems by Eskom Engineers for network analysis purposes. It is seen as an integrated power system analysis tool and used for reliable system modelling. PowerFactory has a substantial list of simulation functionalities; some of which will be used in this study. These include voltage stability analysis, distribution network analysis, contingency analysis, low voltage analysis, dynamics study, short circuit analysis and normal load flow studies. [DigSilent Product Information, 2002]. The following Figure 4-1 is a snapshot that shows the main functionalities that are found in Powerfactory. Most of these functionalities will be used during the study analysis of the dissertation.

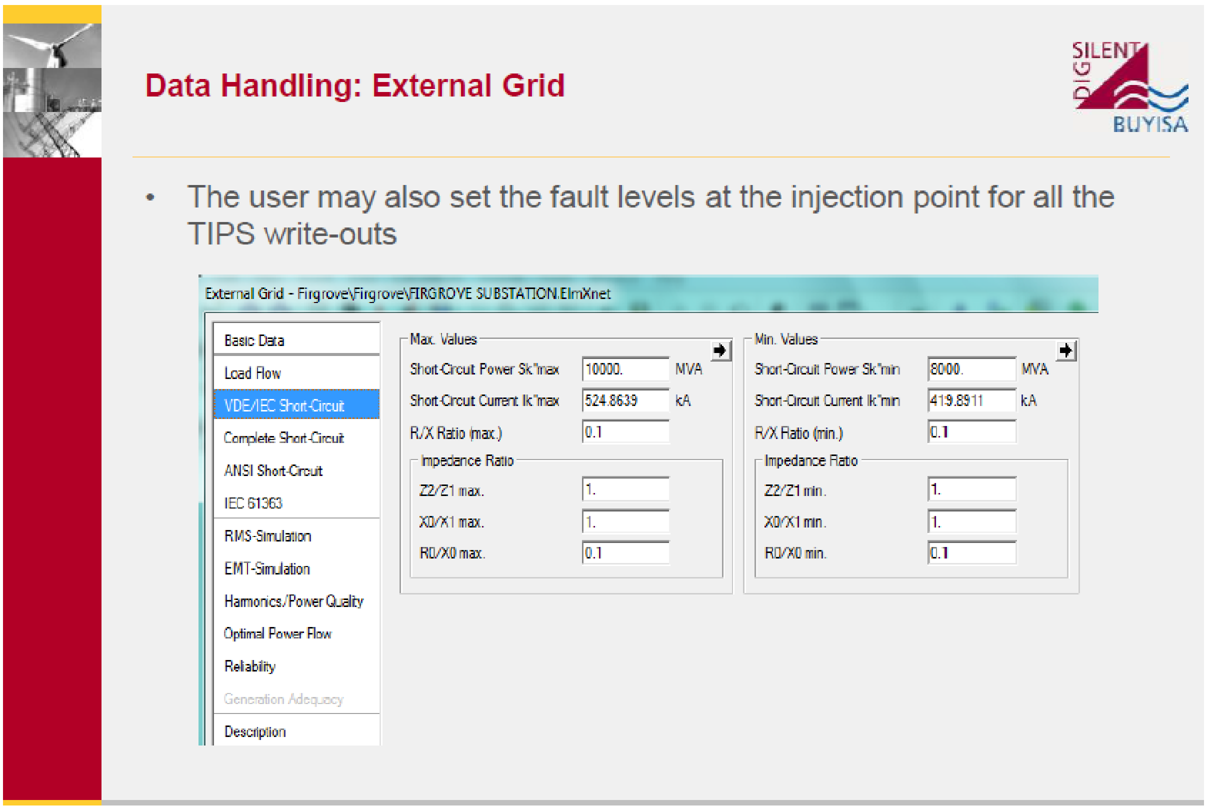


Figure 4-1: Some PowerFactory simulation functionalities [DigSilent Product Information, 2002]

The following network conditions and assumptions were used to perform all the simulations:

- The load will grow by 1-2% in total over a period of 10 years based on historical measurements.
  - The load growth was determined using the available load forecast of each development/large power user in the area provided by the town planners from the Municipality. It was mentioned that there is insignificant load growth in the Teebus area and based on the historical load data the growth rate is between 1-2%
- Low load is 40% of the network peak. Therefore the scaling factors used for the minimum and maximum network loadings are 0.4 and 1.0 respectively
  - The weekly residential load profile is shown in Figure 4-3 below for different years, there are extracted from data (per year, per season) excluding weekends. The peaks for the years and the seasons are retrieved (ignoring the day of the week). From Figure 4-3. It can be noted that there are two peaks periods of usage during the day: one in the morning and the other in the evening. In the Figure 4-2 below it can be noted that the high demand is experienced during summer (September to May) due to the fact that the energy mix for this area is predominantly agricultural (the peak is in summer during irrigation). From the analysis of various load profiles, in the entire ECOU the estimated minimum average energy levels (light) ranges between 30% and 45% of the peak load.

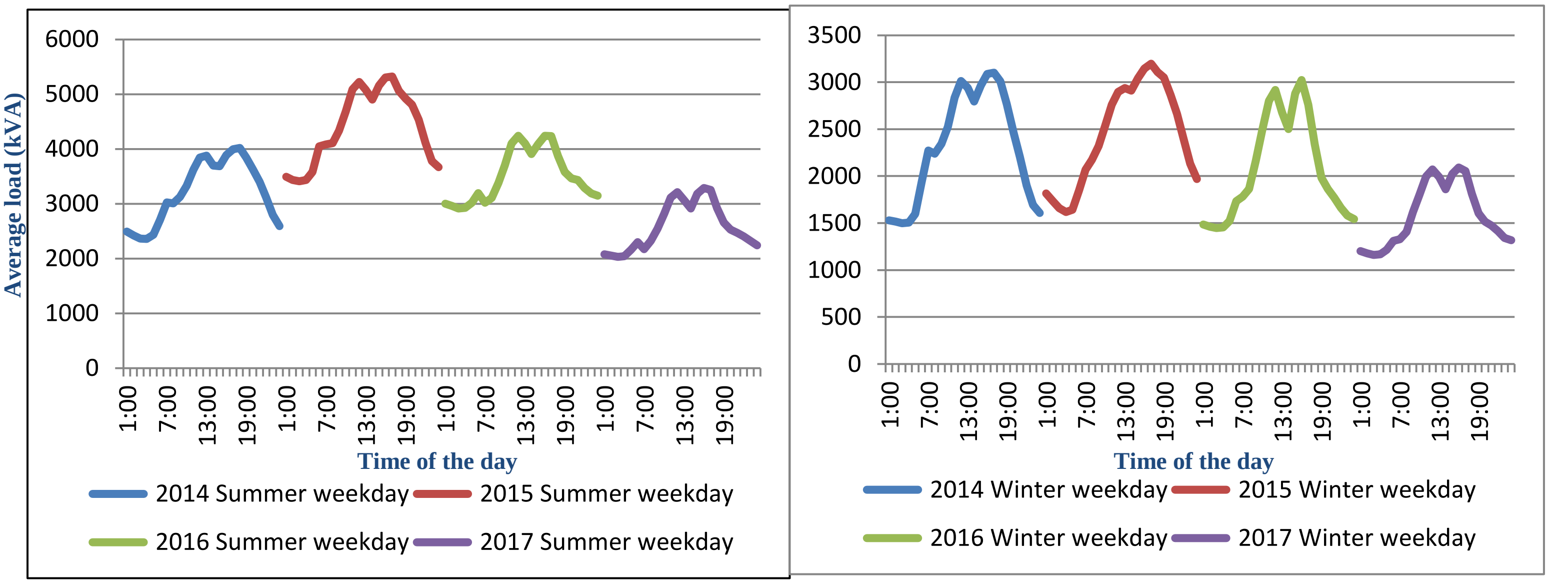


Figure 4-2: Winter and Summer Load Profiles for Bulhoek customers

- Power factor on the generator plant is 1.
  - The power factor for the approved IPP generators are modelled at the desired unity power leading factor when performing the power flow analysis/Voltage Variation Test as this is a worst case. This is done so that one is able to control the reactive power/voltages by changing the power factor should there be required at the PCC. Operating at the unity power factor means that there is less reactive flow caused by the generator on the network.

- High load refers to maximum loading on the network (100%).
- The Bulhoek substation 22kV equipment fault level rating is rated at 1.287kA
  - This information is normally provided by the developer applying for connection.
- After reviewing the Network Development Plan (NDP) for the area, they are no planned network strengthening/refurbishment/reliability projects.

NB: Throughout this document, the studies explained are confined to normal studies. In reality, contingency studies N-1 would also need to be looked at to establish the extent to which N-1 capability is impacted. This is due to the fact that islanding is not permissible. The contingency studies are performed in the shared or dedicated networks unless requested by the IPP developer.

4.3 Power Flow Analysis

The following shows the studies that were performed during this exercise.

4.4 Steady State Analysis with Hydro plant connected

- Load flow studies
- Fault level studies
- Stability /Dynamic studies

4.4.1 These studies are done to check and ensure that the planning limits are met as stipulated by NRS 048-2:

- Thermal Loading
- Voltage levels
- Voltage variation test (VVT)
- Fault Levels (1ph to ground and 3ph faults)
- V_{L-L} to be assessed, voltage profiles

4.5 Existing Supply Point

The Eskom network (transformers, lines and cables) to which the generating plant is to be connected must be analysed to determine whether the network is adequate to handle the maximum exported power of the generating facility. In most cases the existing networks may be able to support exporting power into Eskom distribution network. If the existing Eskom network is not capable of handling the maximum exported power, the existing equipment should be upgraded to facilitate installation of the new generator (this will be demonstrated in this section).

The point on the network where generator will be connected should be chosen considering the following:

- Existing networks closer to the generating plant site
- Connection voltage of the generator and the distribution networks
- The ability of the grid to support the connection without causing technical problems.

4.6 Base Case Analysis

Figure 4-3 is an existing 22kV network that was used for analysis in this study. The network is a combination of the two MV feeders dispatching out of Bulhoek substation, namely Bulhoek/Middleburg and Bulhoek/Steynesburg 22kV feeder. The two colours are to differentiate between the Bulhoek and Steynesburg 22kV feeders.

The lines/conductors and load parameters for this network are given in Appendix E. For the base study, the two generators were disconnected from the network and no generation was injected to the network. The network is depicted in geographical format for the purpose of simplicity during the identification of the load points. The network base case was extracted directly from Smallworld software and the studies are done in Digsilent PowerFactory (see Figure 4-4, base case set up in PowerFactory).

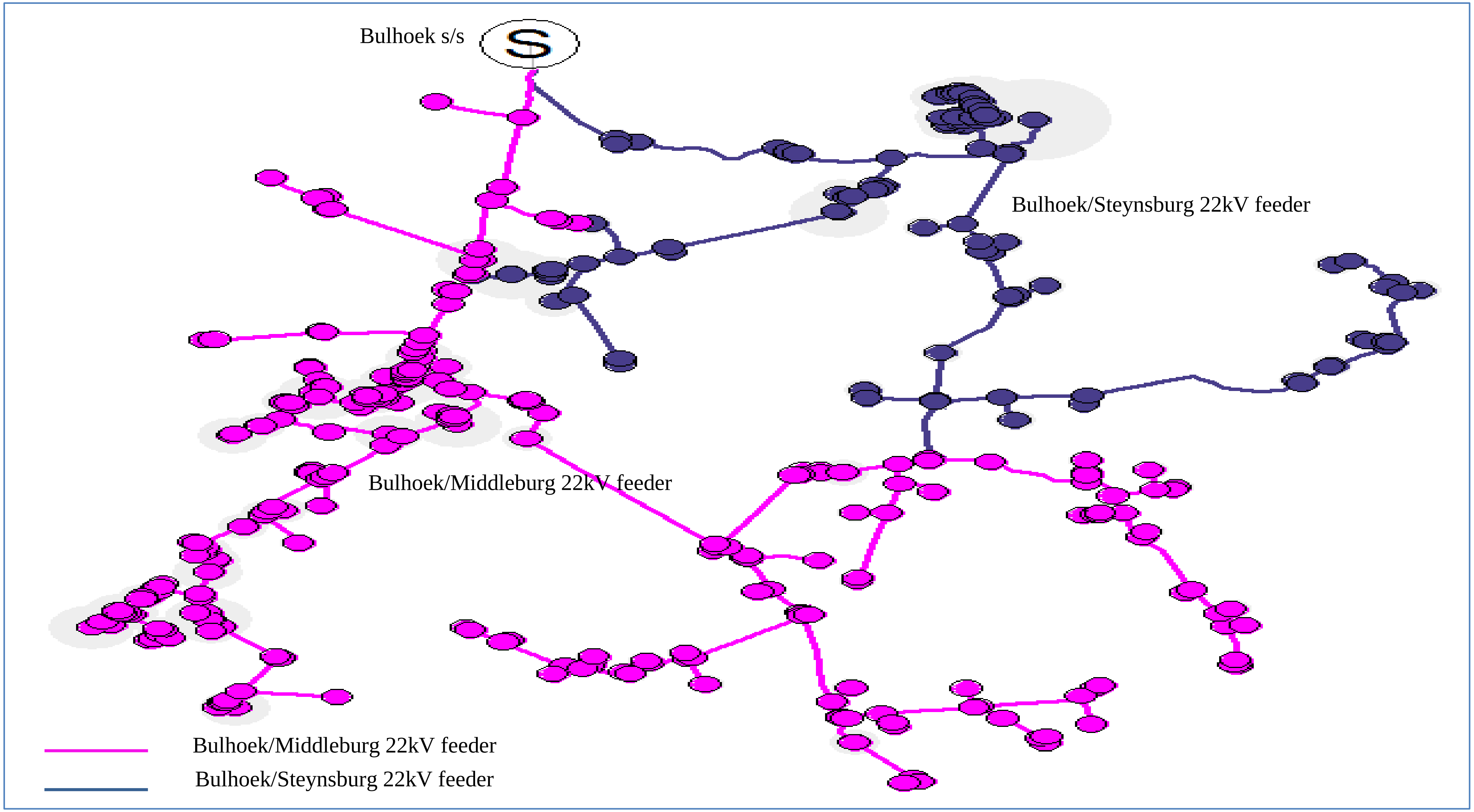


Figure 4-3: Bulhoek/Middleburg/Steynsburg Base Case network

Name	In Folder	Grid	Minimum Voltage p.u.	U1l, Magnitude kV
Bulhoek_Substation	Project(1)	Project(1)	1.029669	22.66
Dummy_N250050287	Retic11	Retic11	0.9968805	22.07928
Dummy_N250050619	Retic11	Retic11	0.9813903	21.73275
Hofmeyr_Munic_22_11kV	Retic11	Retic11	0.9871348	10.91983
ID_243849926	Retic11	Retic11	0.9848119	21.81184
ID_254389919	Retic11	Retic11	0.9713772	21.51145
ID_254571614	Retic11	Retic11	0.98088	21.71887
Incoming	22kV 100A Closed De	Retic11	0.9466884	20.90639
Incoming	Project(1)	Project(1)	1.021087	22.47784
LN243762167	Retic11	Retic11	0.9885698	21.81374
LN243762167	Project(1)	Project(1)	1.024796	22.55729
LN243766437	Retic11	Retic11	1.003382	22.2248
LN243767296	Retic11	Retic11	0.9910242	21.81706
LN243776472	Retic11	Retic11	0.9836965	21.78378
LN243810718	Retic11	Retic11	0.9959578	22.05862
LN243816182	Retic11	Retic11	0.9853619	21.82116
LN243817758	Retic11	Retic11	0.9634108	21.2688
LN243817758	Project(1)	Project(1)	1.022288	22.50397
LN243818061	Retic11	Retic11	0.9752006	21.59553
LN243818325	Retic11	Retic11	0.9900085	21.92698
LN243818775	Retic11	Retic11	0.9846991	21.80933
LN243821530	Retic11	Retic11	1.004023	22.23888
LN243821674	Retic11	Retic11	0.9813006	21.7293
LN243821776	Retic11	Retic11	0.9812903	21.72907
LN243821878	Retic11	Retic11	0.9812108	21.72708
LN243821980	Retic11	Retic11	0.980941	21.72034
LN243822082	Retic11	Retic11	0.9808785	21.71884
LN243822184	Retic11	Retic11	0.9832598	21.77396
LN243822286	Retic11	Retic11	0.9827205	21.76183
LN243822388	Retic11	Retic11	0.9826494	21.76027
LN243822490	Retic11	Retic11	0.982579	21.75872
LN243822592	Retic11	Retic11	0.9816639	21.73766
LN243822694	Retic11	Retic11	0.9813787	21.73118
LN243822796	Retic11	Retic11	0.9813899	21.73143
LN243826054	Retic11	Retic11	0.94706	20.91444
LN243826054	Project(1)	Project(1)	1.02109	22.47792
LN243826258	Retic11	Retic11	1.000373	22.15758
LN243826258	Project(1)	Project(1)	1.020979	22.47543
LN243826360	Retic11	Retic11	1.004661	22.25329
LN243826360	Project(1)	Project(1)	1.021051	22.47703
LN243826471	Retic11	Retic11	0.9968772	22.07921
LN243826573	Retic11	Retic11	1.002925	22.0811

Figure 4-4: Base case network voltages from DigSilent

Table 4-1: Base case network voltages from DigSilent-excel format

Name	In Folder	Minimum Voltage	U1l, Magnitude
Bulhoek Substation	Retic11	1.027671	22.66
Bulhoek Substation	Project(1)	1.029669	22.66
Hofmeyr_Munic_22_11kV_Trfr	Retic11	0.987135	10.91983
Incoming	22kV 100A Closed Delta	0.946688	20.90639
Incoming	Project(1)	1.021087	22.47784
LN243762167	Retic11	0.98857	21.81374
LN243762167	Project(1)	1.024796	22.55729
LN243766437	Retic11	1.003382	22.2248
LN243767296	Retic11	0.991024	21.81706
LN243776472	Retic11	0.983697	21.78378
LN243810718	Retic11	0.995958	22.05862
LN243816182	Retic11	0.985362	21.82116
LN243817758	Retic11	0.963411	21.2688
LN243817758	Project(1)	1.022288	22.50397
LN243818061	Retic11	0.975201	21.59553
LN243818325	Retic11	0.990009	21.92698
LN243818775	Retic11	0.984699	21.80933
LN243821530	Retic11	1.004023	22.23888
LN243821674	Retic11	0.981301	21.7293
LN243821776	Retic11	0.98129	21.72907
LN243821878	Retic11	0.981211	21.72708
LN243821980	Retic11	0.980941	21.72034
LN243822082	Retic11	0.980879	21.71884
LN243822184	Retic11	0.98326	21.77396
LN243822286	Retic11	0.982721	21.76183
LN243822388	Retic11	0.982649	21.76027
LN243822490	Retic11	0.982579	21.75872
LN243822592	Retic11	0.981664	21.73766
LN243822694	Retic11	0.981379	21.73118
LN243822796	Retic11	0.98139	21.73143
LN243826054	Retic11	0.94706	20.91444
LN243826054	Project(1)	1.02109	22.47792
LN243826258	Retic11	1.000373	22.15758
LN243826258	Project(1)	1.020979	22.47543
LN243826360	Retic11	1.004661	22.25329
LN243826360	Project(1)	1.021051	22.47703

Table ***4-1*** above shows the base case busbar voltages. The 22kV busbar source voltage was set to 1.03p.u by tapping the 66/22kV 5MVA transformer to tap 9 and scaling the loads as per the measured data. Although the voltage at the 22kV source was raised to 1.03p.u, the voltages towards the end of the line still dropped as low as 0.94p.u.

Figure 4-5 below shows the voltage profile of the existing network status for Bulhoek-Middleburg 22kV feeder. It can be noted that the simulated results shown on this profile match the measured minimum voltage of 94% of the nominal voltage taken from the MV-90 tool. The voltage profile illustrated below also includes the MV/LV booster transformers (dashed lines). It can also be noted that the voltage regulator location is such that it has an impact on per unit voltages downstream.

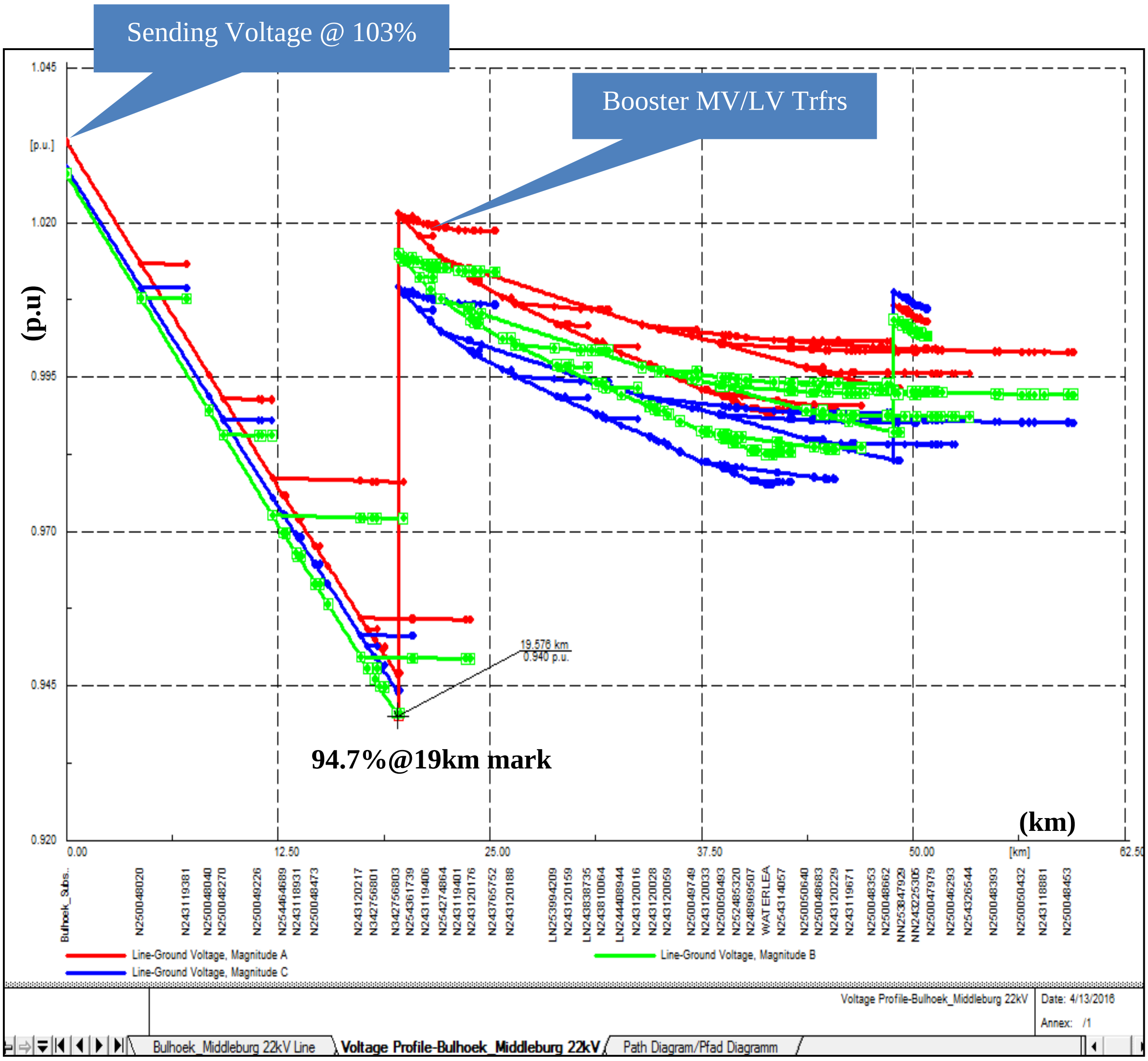


Figure 4-5: Bulhoek/Middleburg 22kV voltage profile simulated from DigSilent

The Figure 4-6 below depicts the recorded voltage and it correlates with the simulated results shown above. This is the base voltage that is going to be used in this study assuming that the sending voltage busbar at Bulhoek s/s is set to 103%.

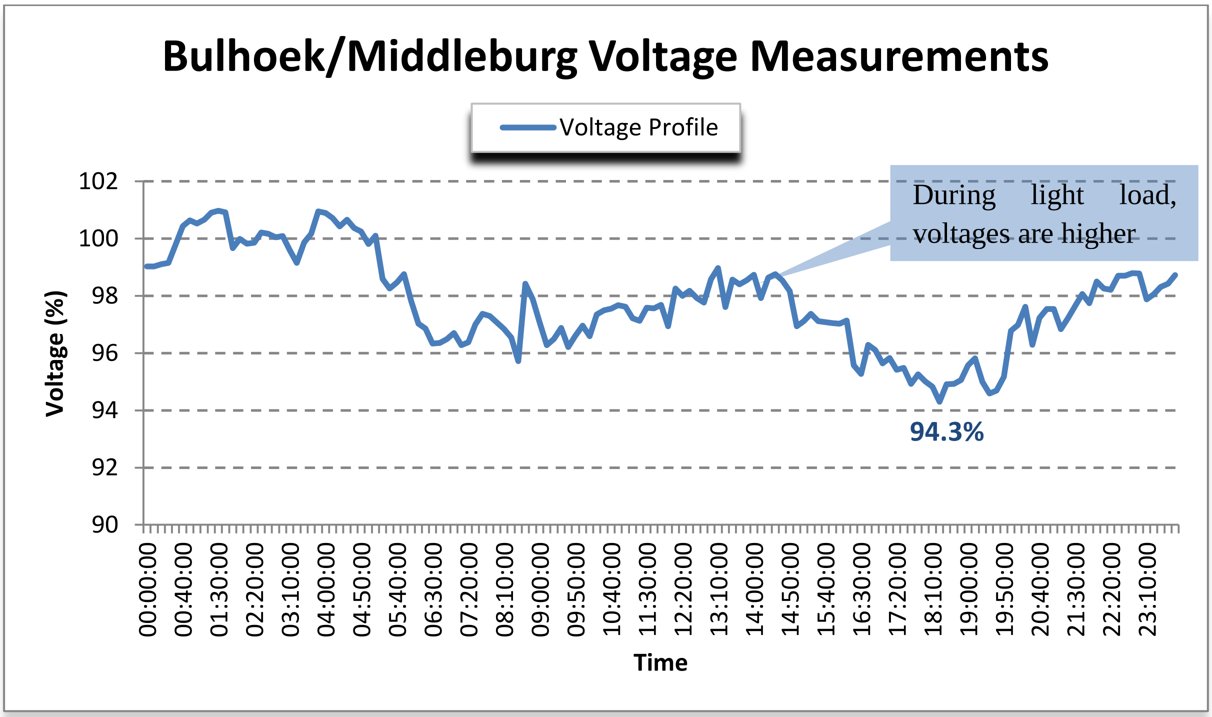


Figure 4-6: Bulhoek/Middleburg 22kV voltage profile recorded

For the base case study, the two planned hydro power machines were disconnected from the network and normal condition study was assumed. The busbar voltages are given in Figure 4-4. The 22kV busbar source voltage was raised to 1.03p.u by tapping the 66/22kV transformer to tap 9. Although the voltage at the 22kV source was raised to 1.03p.u, the voltage towards the end of the line still dropped below 0.94p.u (see Figure 4-7, this is showing the location of where the lowest voltage is measured). The value of .94p.u was measured.

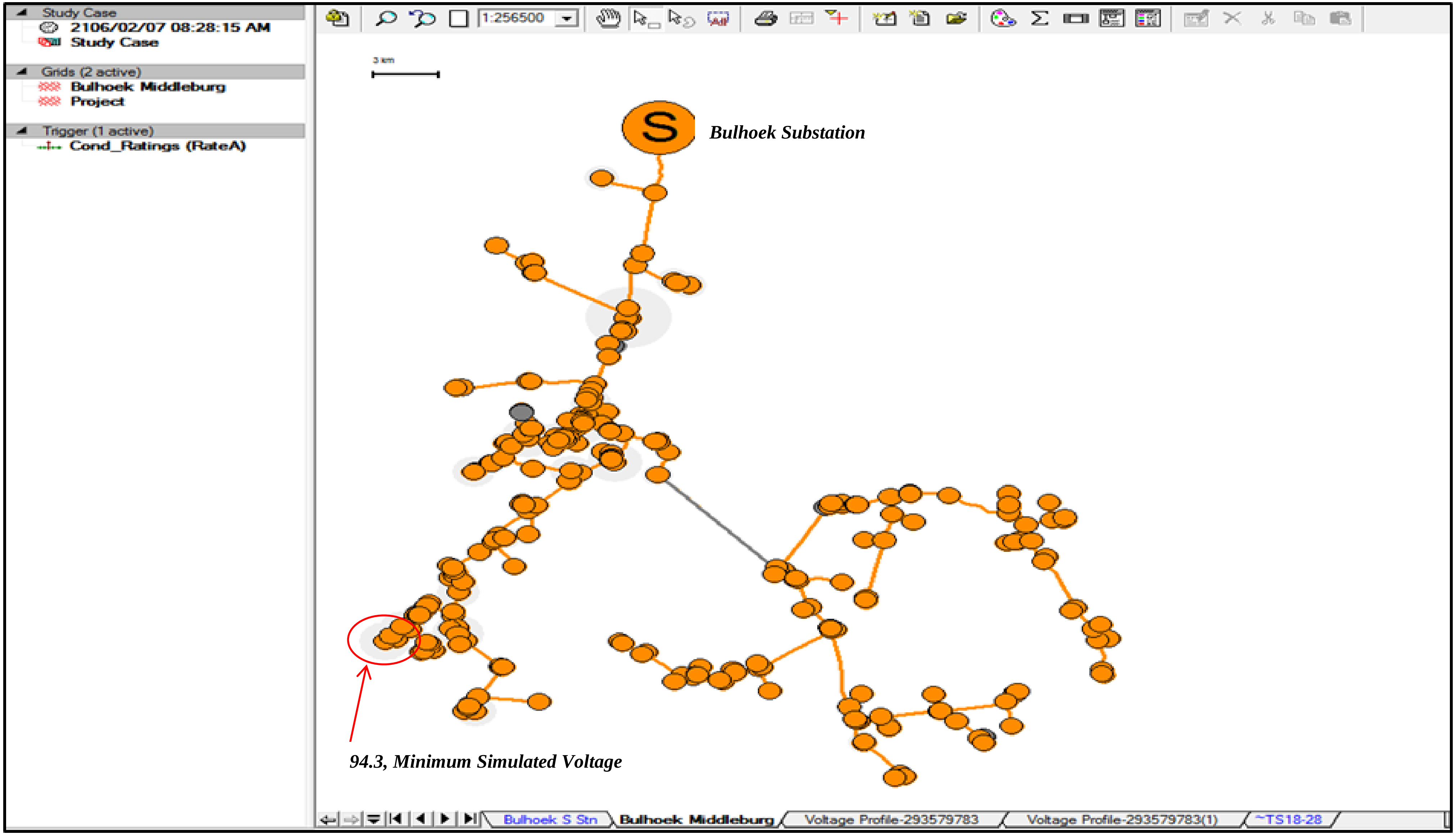


Figure 4-7: Bulhoek/Middleburg 22kV voltage lowest voltage point

4.7 Connection of the proposed 10MW Teebus Hydro Plant to the future network

4.7.1 Power System Analysis for connecting Teebus Hydro Plant:

The initial proposal was to connect the two generators onto the existing 22kV distribution network. Due to the weakness (low fault levels) of the existing Bulhoek 22kV network, the 10MW Hydro plant could not be accommodated on the existing network. The load in the Teebus area is relatively small (see the load forecast on Figure 3-18); if the generator is connected, it results in over-voltages and thermal problems. The results (see Figure 4-8 marked in red border) indicate that the voltage limit, voltage variation test limit (see Figure 4-17) and the thermal loading were exceeded thus strengthening of the network was required. In addition, looking at the overall existing network layout, there is no sub-transmission network close-by to connect the said Hydro Power plant and the extension of the sub-transmission networks would be costly.

Object Filter: *.ElmTerm Expression: iUsage=0

Name	In Folder	Grid	Minimum Voltage p.u.	U1l, Magnitude kV	Losses, down kW
Bulhoek_Substation	Retic11	Retic11	1.04895	23.1	2297.4
Teebus 10MW_Wind_Fa	Retic11	Retic11	1.04895	23.4353	540.3468
N250048020	Retic11	Retic11	1.03056	22.69952	247.1962
N250048040	Retic11	Retic11	1.013938	22.3375	202.4319
N250048270	Retic11	Retic11	1.010331	22.25892	192.711
N250050058	Retic11	Retic11	0.9984322	21.99973	160.8903
N254464689	Retic11	Retic11	0.9957628	21.94151	153.7749
N243845987	Retic11	Retic11	0.9928055	21.87703	146.1184
N243118931	Retic11	Retic11	0.9923431	21.86695	144.9217
N250048932	Retic11	Retic11	0.9923232	21.86651	144.8701
N250048473	Retic11	Retic11	0.9882373	21.77742	134.2928
N250048494	Retic11	Retic11	0.985254	21.71237	126.5852
N342756799	Retic11	Retic11	0.9773427	21.53967	106.5301
N342756800	Retic11	Retic11	0.9757325	21.50451	102.4712
N342756801	Retic11	Retic11	0.9741139	21.46917	98.39426
N342756802	Retic11	Retic11	0.9730132	21.44514	95.62159
N342756803	Retic11	Retic11	0.9689403	21.35621	85.54365
N250048536	Retic11	Retic11	0.9685568	21.34784	84.58626
N243810948	Retic11	Retic11	0.9685261	21.34718	84.50969
N250048557	Retic11	Retic11	0.9684954	21.34651	84.43312
N250046067	Retic11	Retic11	0.9680582	21.33697	83.342

Figure 4-8: Voltages exceeding the limits with the generators on the existing network

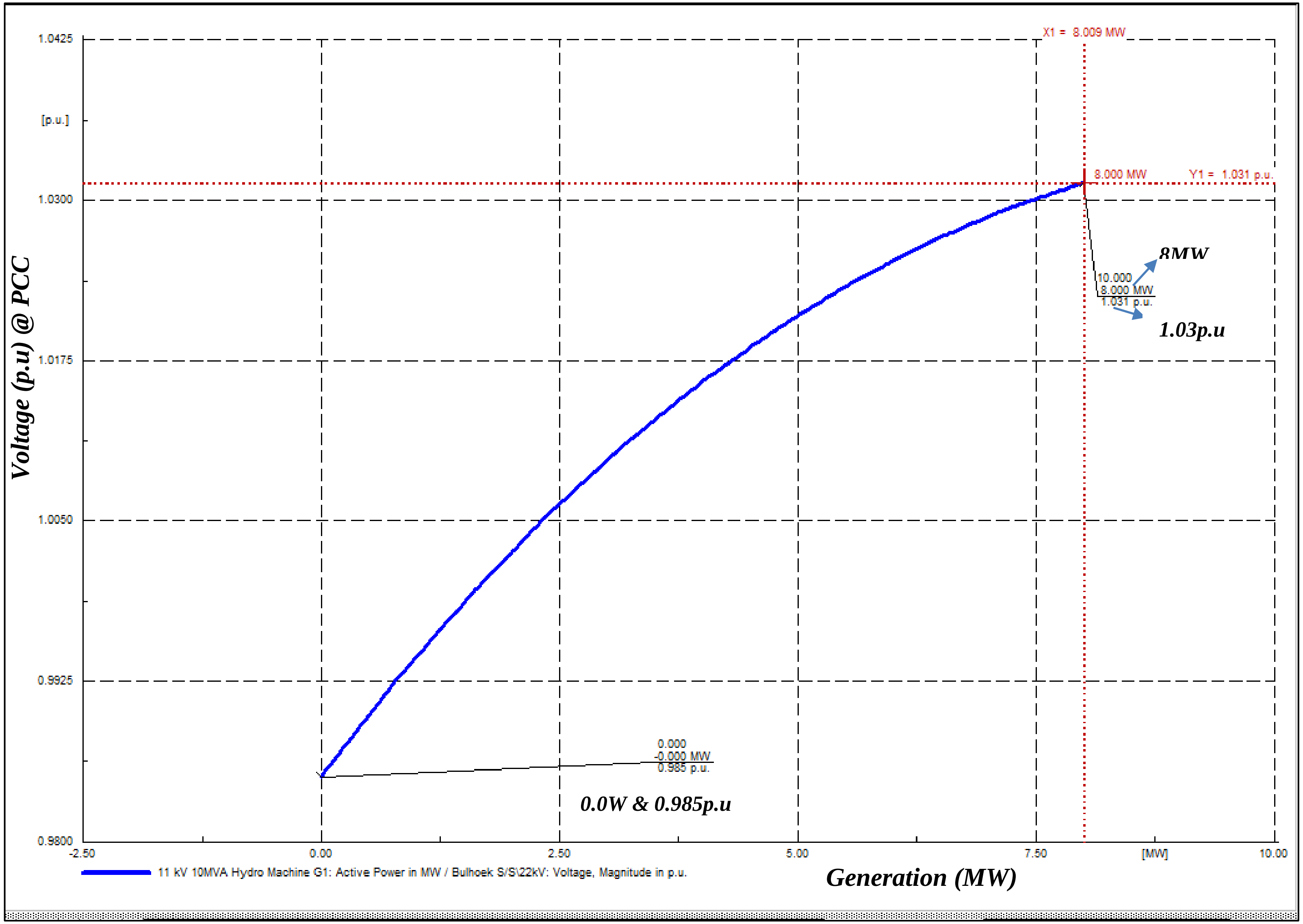


Figure 4-9 : Generator Power (MW) vs Busbar Voltage at Bulhoek S/S

A PV curve on Figure 4-9 above shows the voltage trend as the generation power (MW) increases. It can be seen that the more power generated to the system causes the voltage to rise gradually. In this PV curve the maximum power of 10MW was generated and the voltage at Bulhoek 22kV busbar increased to 1.03pu as shown on Figure 4-9. The Table 4-2 below shows the generation output and the voltages simulated at the PCC (Bulhoek S/S busbar) in a table format.

Table 4-2: Generator Power (MW) vs Simulated Voltages

Generation (MW)	Voltages (p.u)
0.00	94.3
2.50	99.3
5.00	1.01
7.50	1.02
8.00	1.03
10.00	1.03

The preferred analysed alternative would be to build the dedicated new 22kV line from Bulhoek substation and connect the proposed Hydro generation. The alternatives are evaluated using Project Evaluation Model (PEM) (see Figure 4-10). PEM is a Microsoft Excel base tool that can provide comparative life cycle costs of multiple project alternatives. PEM provides the total life cycle cost of each alternative together with other relevant cost and reliability indicators.

PEM uses SAIDI and Power losses values to calculate the results. PEM will select the option with least life cycle cost (marked in red on Figure 4-10) as preferred from the life cycle cost comparison. The environmental assessment was made for each alternative of the human and natural environmental impacts. This was done to check if the proposed lines/substation extensions are not violating the environmental laws.

It is evident from Figure 4-10 that alternative 1 is the preferred option to connect the proposed Teebus generators as it has the least life cycle cost.

Table 4-3: Advantages and disadvantages of alternatives

	Preferred Alternative 1	**Alternative 2**
Description	• Connect Teebus Hydro directly to Bulhoek substation via a 15km Chicadee 22kV line. • Build a switching next to the Teebus Tunnel and then connect the two generators to the switching station via a 22kV feeder bay.	• Build a new Teebus 132/22kV 2x20MVA substation with 2x22kV feeder bays, 1x132kV Fdr Bay • Build a 43km 132kV Chicadee line from Genoegsaam Substation. • Connect the proposed two generators to newly built Teebus substation
Advantages	• Will facilitate interconnection with the proposed Teebus Hydro generation and the future small Hydro in the area • Voltages will improve • Create capacity for the unexpected future load growth	• Will facilitate interconnection with the proposed Teebus Hydro generation and the future small Hydro in the area • Voltages will improve • Create capacity for the unexpected future load growth • Will improve reliability of supply
Disadvantages	• None	• It will take long to construct • High cost
Cost (2015/16R)	**R 34 000 000**	**R 430 000 000**

Project Evaluation Model v 14-01

Project inputs	
Network Investment Category	Direct Customer - Premium
Decision criteria	Eskom LCC
Project start year	2016
Final year of evaluation	2041
Year of commercial operation	2018

☐ Show incremental costs

Print

Project ID	
Project Name	Teebus Hydropower Plant (11.3MW)

Project summary results (Net Present Costs in 2014 base year)

	Alternative 1	Alternative 2			Do Nothing
NPC Acquisition	R 26 499 272	R 279 143 217			-
NPC Losses	R 2 469 931	R 890 870 126			R 2 825 458
NPC O&M Scheduled (exc Energy)	R 1 450 114	R 1 180 306			R 0
NPC O&M Unscheduled	R 1 610 317	R 350 634			R 0
NP Disposal Cost / Value	R 0	R 0			R 0
Life-Cycle Cost to Eskom	**R 32 029 635**	**R 1 171 544 283**			**R 2 825 458**

☑ Alternative 1: Connect Teebus Hydro Plant directly to Bulhoek substation
☑ Alternative 2: Supply Teebus from Genoegsaam & STACOM
☐ Alternative 3:
☐ Alternative 4:

Summary Table

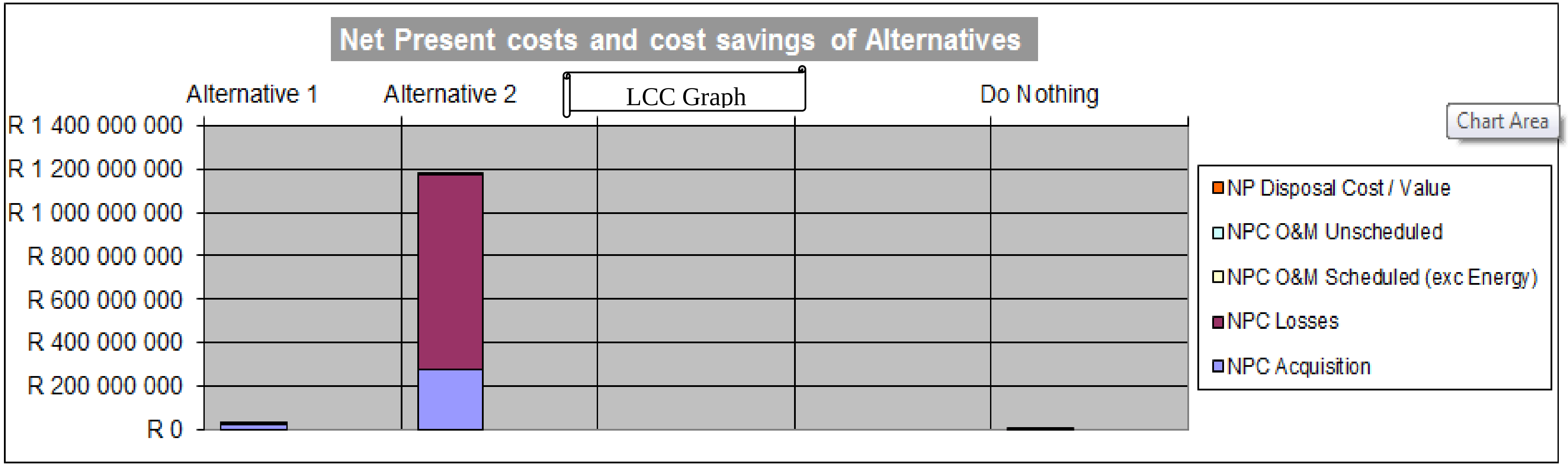


Figure 4-10: PEM for two evaluated alternatives

The high level scope (see Figure 4-11) of work to connect the Teebus Hydro is as follows:

- It is proposed to connect the Teebus Hydro Plant directly to the existing Bulhoek substation
- Construct ±15 km of 22kV Chicadee line from Teebus plant to Bulhoek s/s
- Upgrade the existing 66/22kV 5MVA trfr to 10MVA trfr and 22kV feeder bay
- Build a new switching station to connect the two generators
- Build new control room and extend the existing substation to be able to fit the new protection schemes

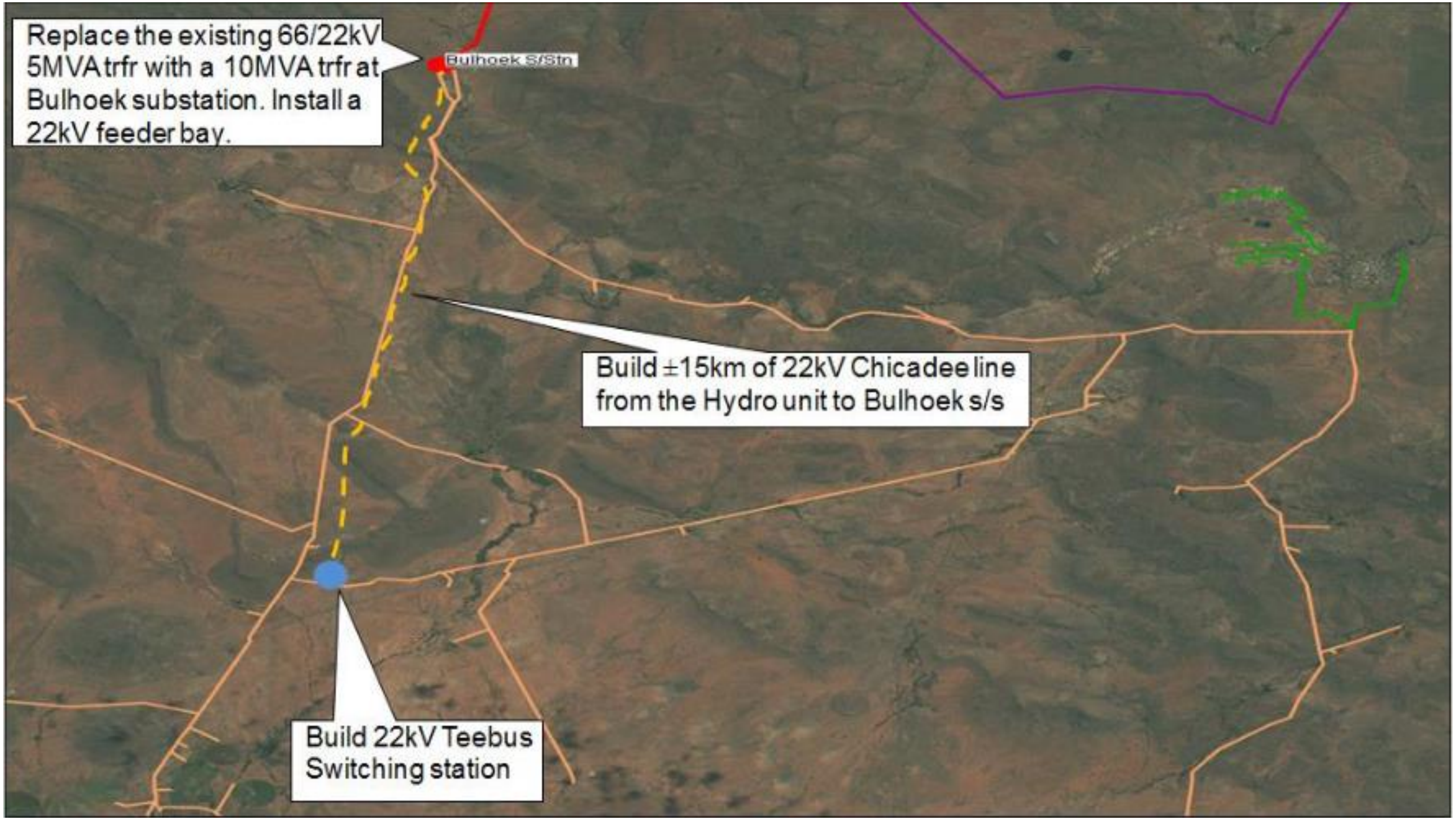


Figure 4-11: Geographical Overview of the study area & High level scope (From Small World program)

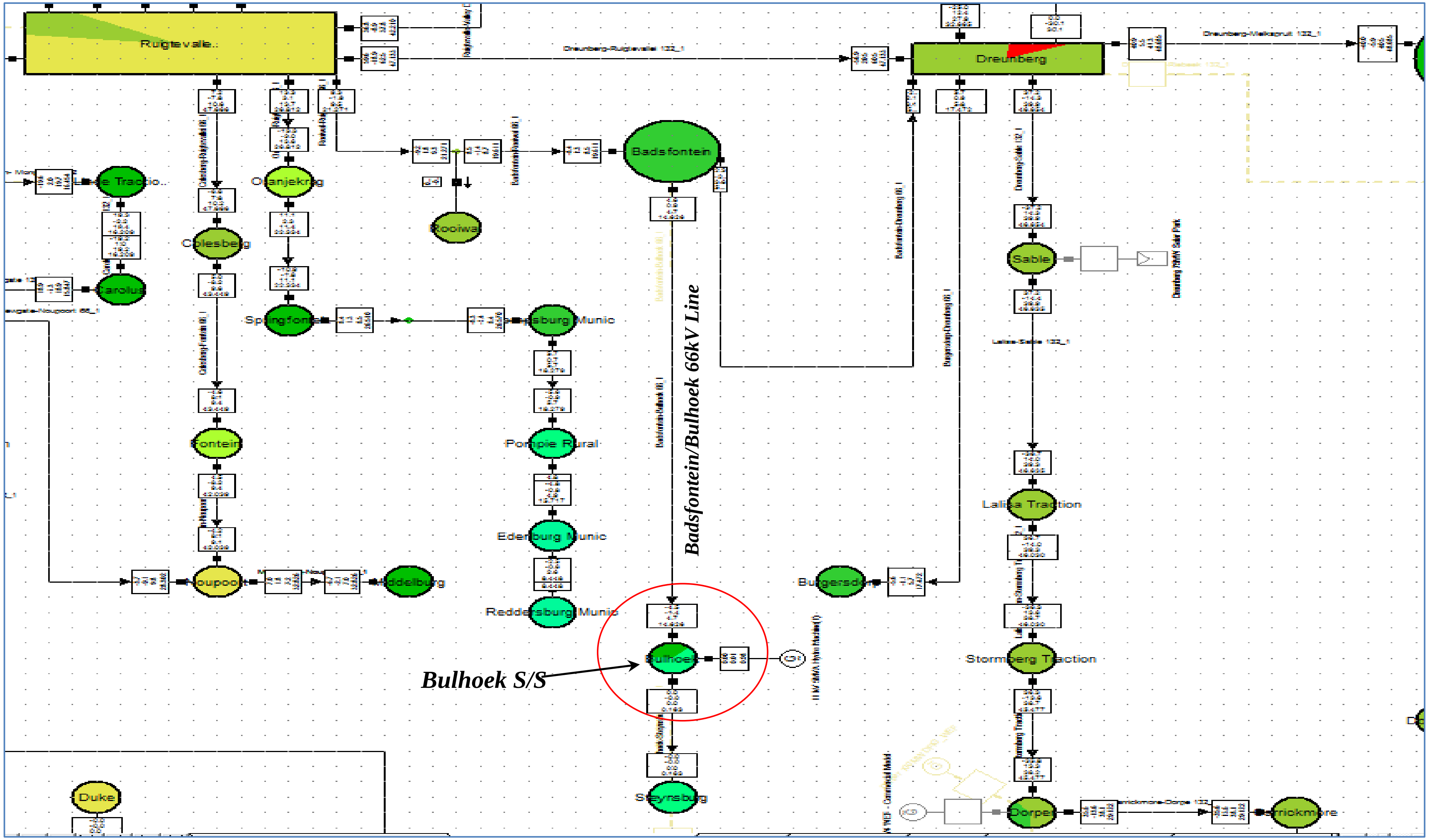


Figure 4-12: Teebus Hydro Modelled in PowerFactory showing the surrounding substations

The Figure 4-12 above is showing the connection of Bulhoek substation relative to the surrounding substation. The red ring fenced section depicts the Bulhoek substation with a generator plant connected to it. The Figure 4-13 below shows a Bulhoek substation with the two planned generators.

Figure 4-14 shows the zoomed version of the Figure 4-12 and Figure 4-15 as it appears blurry; it is also demonstrating the switching station of the developers with the two proposed generators.

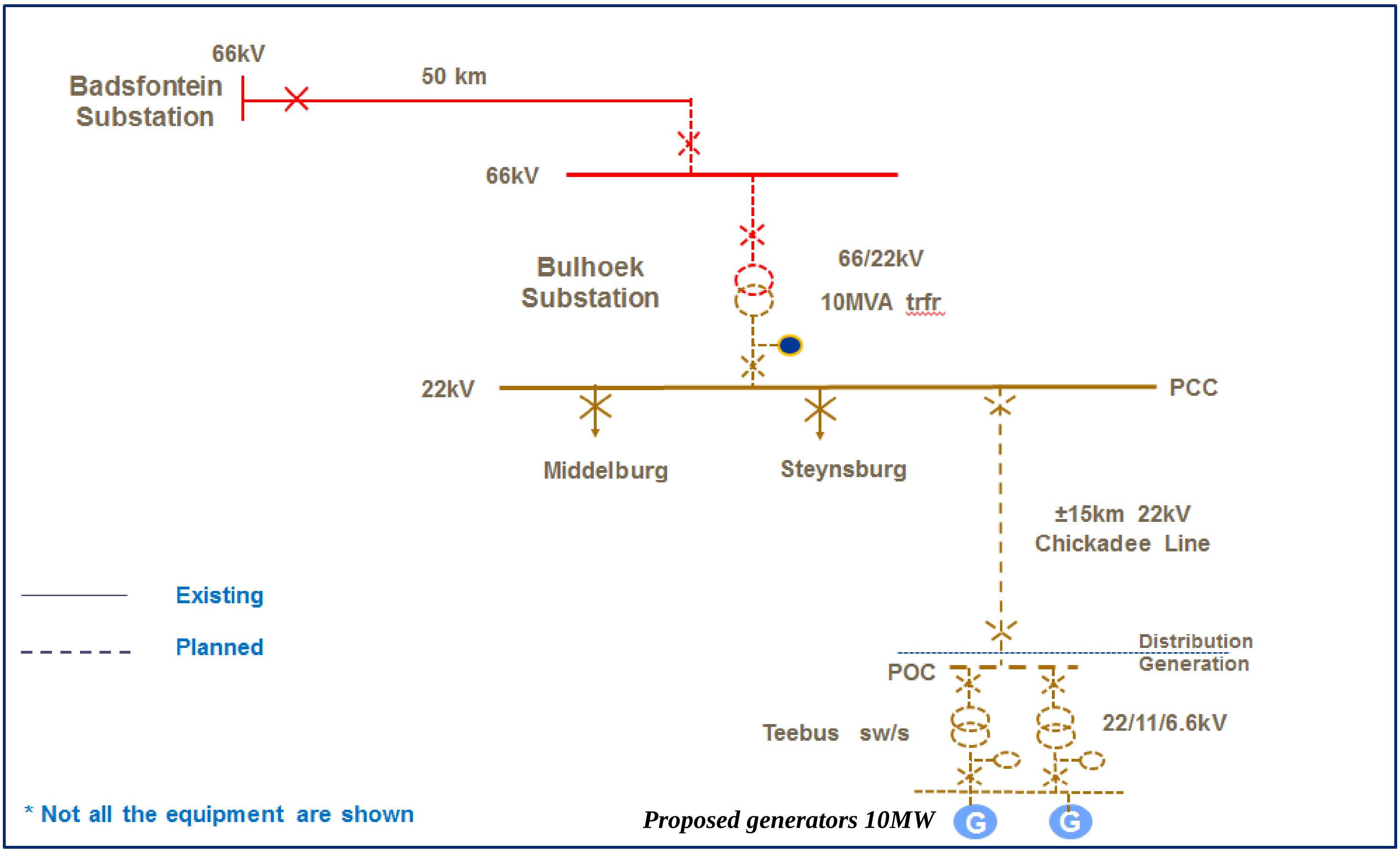


Figure 4-13: SLD showing the Teebus switching station configuration

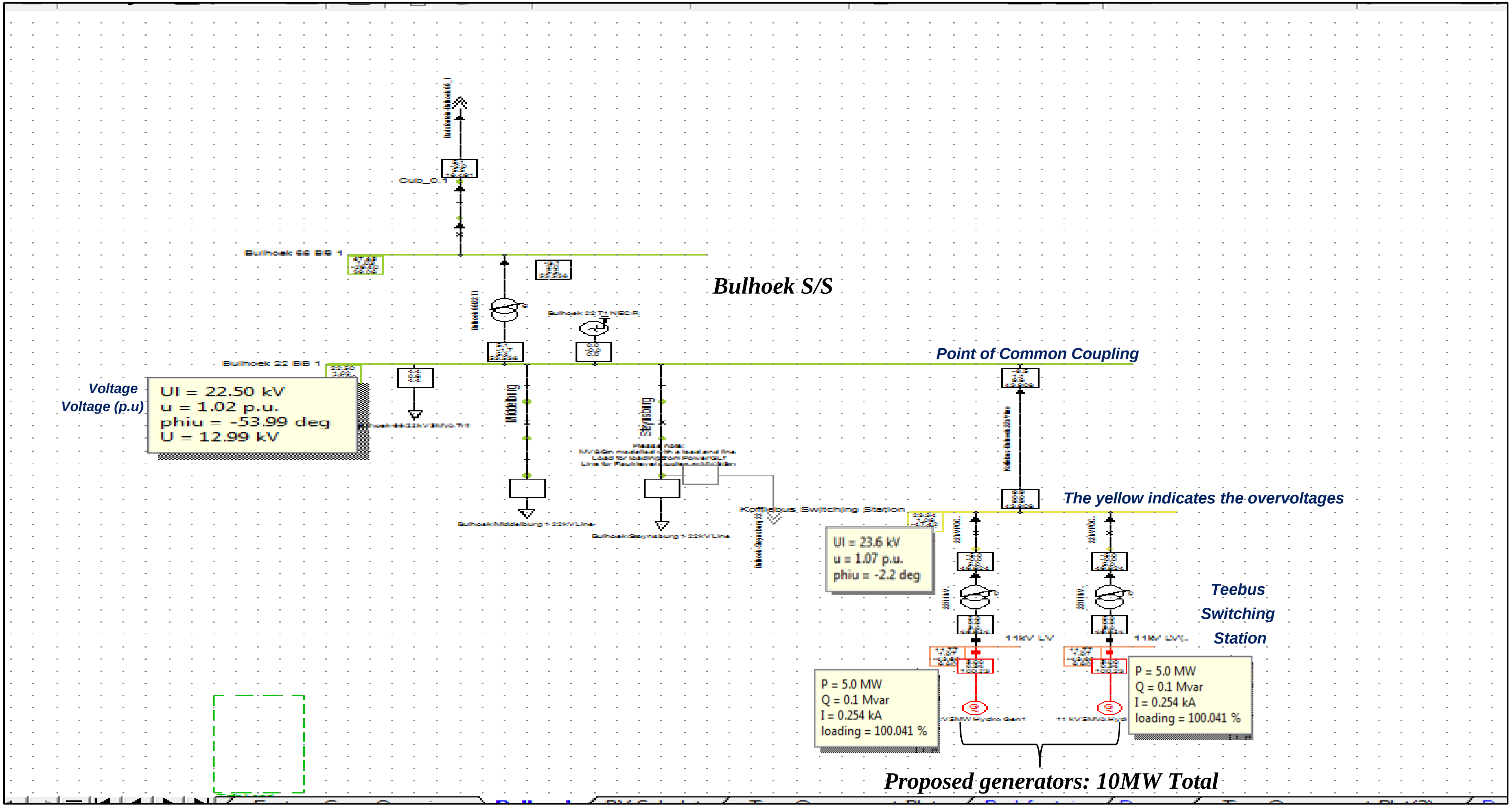


Figure 4-14: Single Line Diagram of the study area with two generators

4.8 Steady State voltage violation check:

There is a standard voltage regulation limit, which in most cases is a key constraint to the integration of generators to networks. During all loading and generation patterns, voltage rise and voltage drop need to be kept within specific limits, so that voltage variation, at all points of supply especially at the PCC, is within required limits, as specified in [3] NRS 048-2 (i.e. for >11kV and <=132kV: range is 0.95pu – 1.05pu).

The reverse flow of power on networks from generators may cause voltage rise in networks, which have been designed to mitigate the effects of voltage drop (not voltage rise), particularly in distribution and sub-transmission networks.

The Figure 4-15 below shows that the busbar voltage magnitudes for the Badsfontein and Bulhoek 66kV (highlighted in red) are within the operational limits and these should be checked continuously during any network configuration to ensure they are within limits. The busbar voltage ranges are set up in accordance with the Distribution voltage regulation and apportionment limits (range is 0.95 to 1.05). The focus is on the Badsfontein and Bulhoek 66kV feeder.

Object Filter: *.ElmTerm Expression: iUsage=0

Name	In Folder	Grid	Nom.L-L Volt. kV	Ul, Magnitude kV	u, Magnitude p.u.	U, Angle deg	Power Flow, Activ... MW	Power Flow, Reac... Mvar
Acacia 66 kV Node 85	Acacia Internal Node:	Western TX	66.	68.66716	1.04041	-68.19354	137.9765	32.77518
Acacia 66 kV Node 86	Acacia Internal Node:	Western TX	66.	68.66716	1.04041	-68.19354	137.9765	32.77518
Acacia 66 kV Node 87	Acacia Internal Node:	Western TX	66.	68.66716	1.04041	-68.19354	137.9765	32.77518
Acacia 66 kV Node 88	Acacia Internal Node:	Western TX	66.	68.66716	1.04041	-68.19354	137.9765	32.77518
Aggeneis 66 BB1	Aggeneis	Western TX	66.	67.05892	1.01604	-46.82624	21.03429	0.
Aggeneis 66 BB2	Aggeneis	Western TX	66.	67.05892	1.01604	-46.82624	21.03429	0.
Albany 66 BB 1	Albany	Eastern Cape HV	66.	0.	0.	0.	0.	0.
Albany 66 BB 2	Albany	Eastern Cape HV	66.	68.65311	1.04019	-42.92243	36.6156	10.5915
Aloe Glen 66 BB 1	Aloe Glen	Eastern Cape HV	66.	67.36836	1.02073	-34.38048	52.95861	23.62986
Aloe Glen 66 BB 2	Aloe Glen	Eastern Cape HV	66.	67.36836	1.02073	-34.38048	44.89546	23.62725
Amatola 66 BB 1	Amatola	Eastern Cape HV	66.	67.26999	1.01924	-39.08008	3.326962	0.7855379
Badsfontein 66 BB 1	Badsfontein	Northern Cape HV (F	66.	67.58964	1.02408	-26.43556	17.06918	6.732966
Binfield Park 66 BB 1	Binfield Park	Eastern Cape HV	66.	65.92849	0.99891	-40.58904	2.598535	0.3283269
Bitou 66 BB1	Bitou	HV Network	66.	64.15223	0.97200	-66.89424	9.027492	2.627628
Blanco 66 BB 1	Blanco	HV Network	66.	66.14546	1.00220	-61.4067	37.87442	13.74496
Blanco 66 BB 2	Blanco	HV Network	66.	66.14546	1.00220	-61.4067	37.87442	13.74496
Bosberg 66 BB 1	Bosberg	Eastern Cape HV	66.	65.49021	0.99227	-37.46108	12.50867	2.466562
Bosberg 66 BB 2	Bosberg	Eastern Cape HV	66.	65.49021	0.99227	-37.46108	12.50867	2.466562
Brakkloof 66 BB 1	Brakkloof	HV Network	66.	64.48962	0.97711	-66.86743	0.01321782	0.0363088
Breakfastvlei 66 BB 1	Breakfastvlei	Eastern Cape HV	66.	66.46583	1.00705	-45.34522	9.342941	0.2314826
Buffalo 66 BB1	Buffalo	Southern TX	66.	66.853	1.01292	-33.72672	14.37724	18.36859
Buffalo 66 BB2	Buffalo	Southern TX	66.	66.853	1.01292	-33.72672	14.37724	18.36859
Bulembu 66 BB 1	Bulembu	Eastern Cape HV	66.	65.9016	0.99850	-39.4227	2.676517	0.5055827
Bulhoek 66 BB 1	Bulhoek	Eastern Cape HV	66.	67.97626	1.02994	-24.62541	5.500993	2.733042
Burgersdorp 66 BB 1	Burgersdorp	Eastern Cape HV	66.	66.90243	1.01367	-29.98515	5.658846	1.103841
Butterworth 66 BB 1A	Butterworth	Eastern Cape HV	66.	68.55816	1.03876	-40.68079	19.29662	5.475103
Butterworth 66 BB 1B	Butterworth	Eastern Cape HV	66.	68.55816	1.03876	-40.68079	0.1161805	1.570354

Figure 4-15: Voltage magnitude status on the 66kV busbars

Due to the relatively low capacities of distribution MV and Low Voltage (LV) networks, distribution connected generators have a significant impact on voltage regulation. As power is transferred from the generator through LV and MV feeders to the source, the voltage rises between the MV feeder source and the generator terminals. The Distribution MV/LV transformers (i.e. 11kv and 22kV) are operated on fixed tap position, it has been noted that this voltage rise could have a direct impact on customers.

The impact of a generating plant on a 22 kV feeder is indicated in the voltage profile in Figure 4-16. This illustration is for a 22kV feeder with a system peak load of 4.3 MVA and a minimum load of 1.72 MVA (40% of maximum). The generating plant is connected at the end of the feeder and exports about 10 MW at a power factor of 1 (exporting reactive power).

Without the generator, the end of line voltage varies between 94% and 98%. With the generator connected, the maximum end of line voltage rises to between 100% and 105%. However, if the generator does not generate, the minimum end of the line voltage (Bulhoek/Middleburg 22kV feeder) still drops back to 94%. This implies that with the connection of a generator to this particular 22kV line, there is an increase in the line voltage regulation range. This has an effect of increasing the voltage magnitude on Bulhoek/Middleburg 22kV feeder to better support voltages of the customers connected. Voltage rise is typically the main constraint for the connection of generators to LV and MV networks. It is evident that for an increase in hydro power penetration, the voltage stability margin was increased.

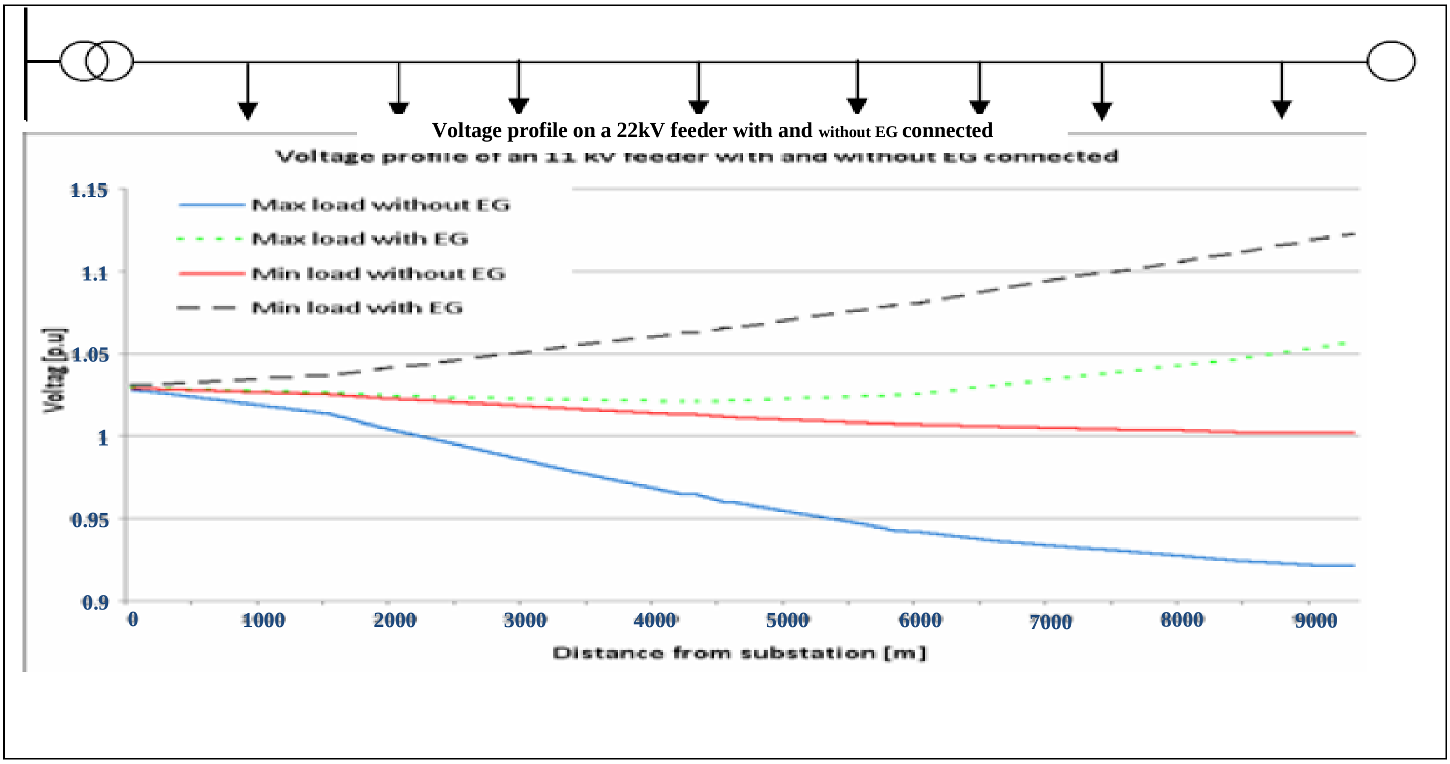


Figure 4-16: Voltage rise on a 22kV feeder with and without a generator

4.9 Voltage Variation Test

The voltage variation test (VVT) study was carried out with the generators generating at maximum output. For any stable generation plants, such as concentrated Solar Power Plant (CSP) and Hydro Plant (which seldom trips), a VVT limit value of 5% is specified because rapid output changes and tripping of plant occurs infrequently.

There are two methods to perform the VVT in PowerFactory that have been determined. The two methods are: using a PV (Power vs Voltage) curve and generator switching (on/off) method. In the event of disconnection of one generation plant or several plants simultaneously at one network connection point, the voltage change at every point in the network is limited to 5%. The step by step of setting up each method is demonstrated in the Appendix B at the end of the section.

4.10 Method 1 (Generator on/off)

The results shown on the Figure 4-17 below are for both the low load and the high load scenarios. These results were taken directly from PowerFactory using the Generator switching method. The VVT is within the stipulated limit of 5% for Hydro Power Systems.

The figures below show that the voltage variation limits were not exceeded on the two scenarios; low load and high load scenarios. The low load scenario is demonstrated in Figure 4-18. The minus sign means percentage decrease, in other words it is the voltage change from high to low as the generators switches on and off.

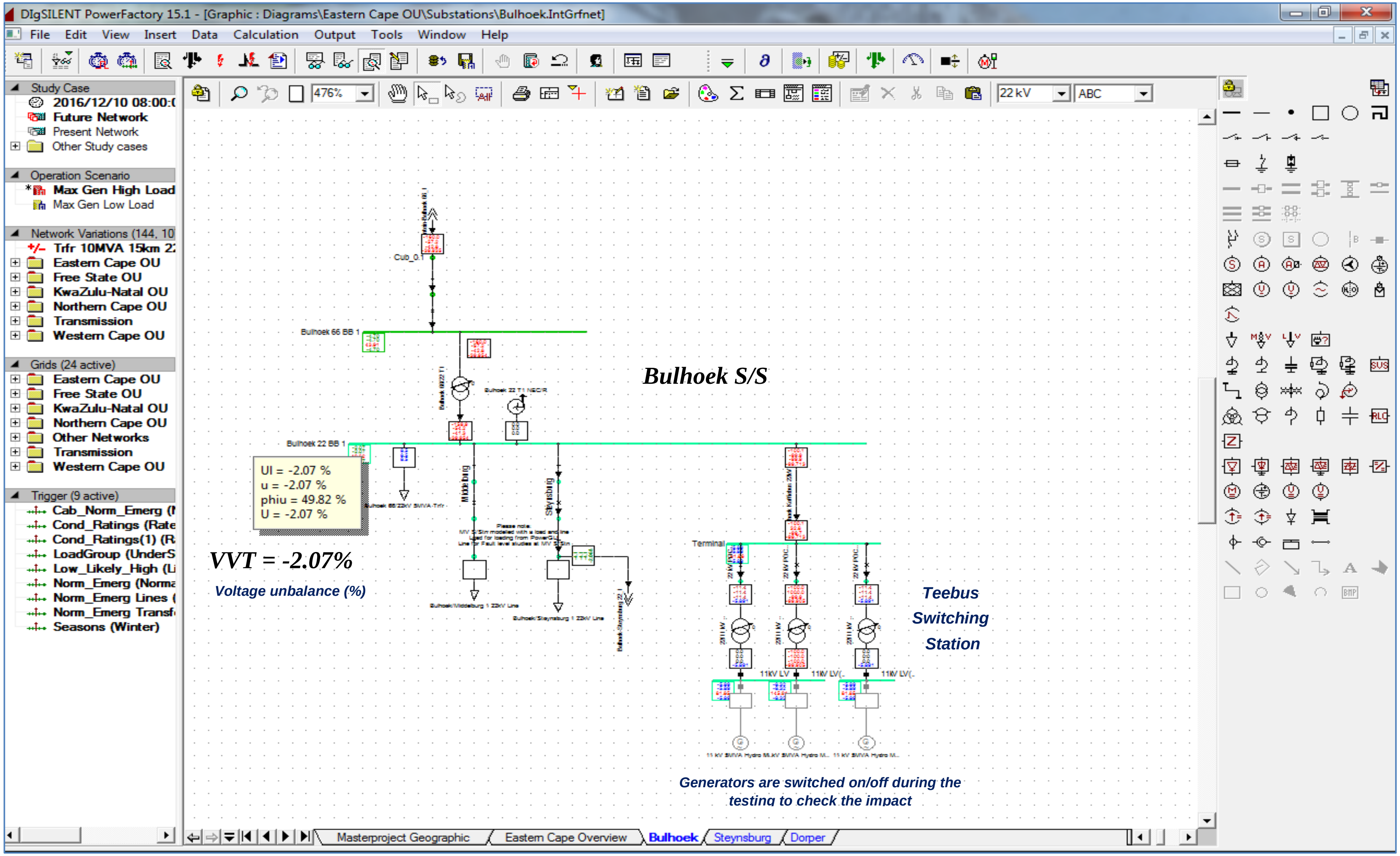


Figure 4-17: Voltage Variation Test for HL Scenario

The Figure 4-18 and Figure 4-17 below show that the voltage variation limits were not exceeded on the two scenarios; low and high load scenario.

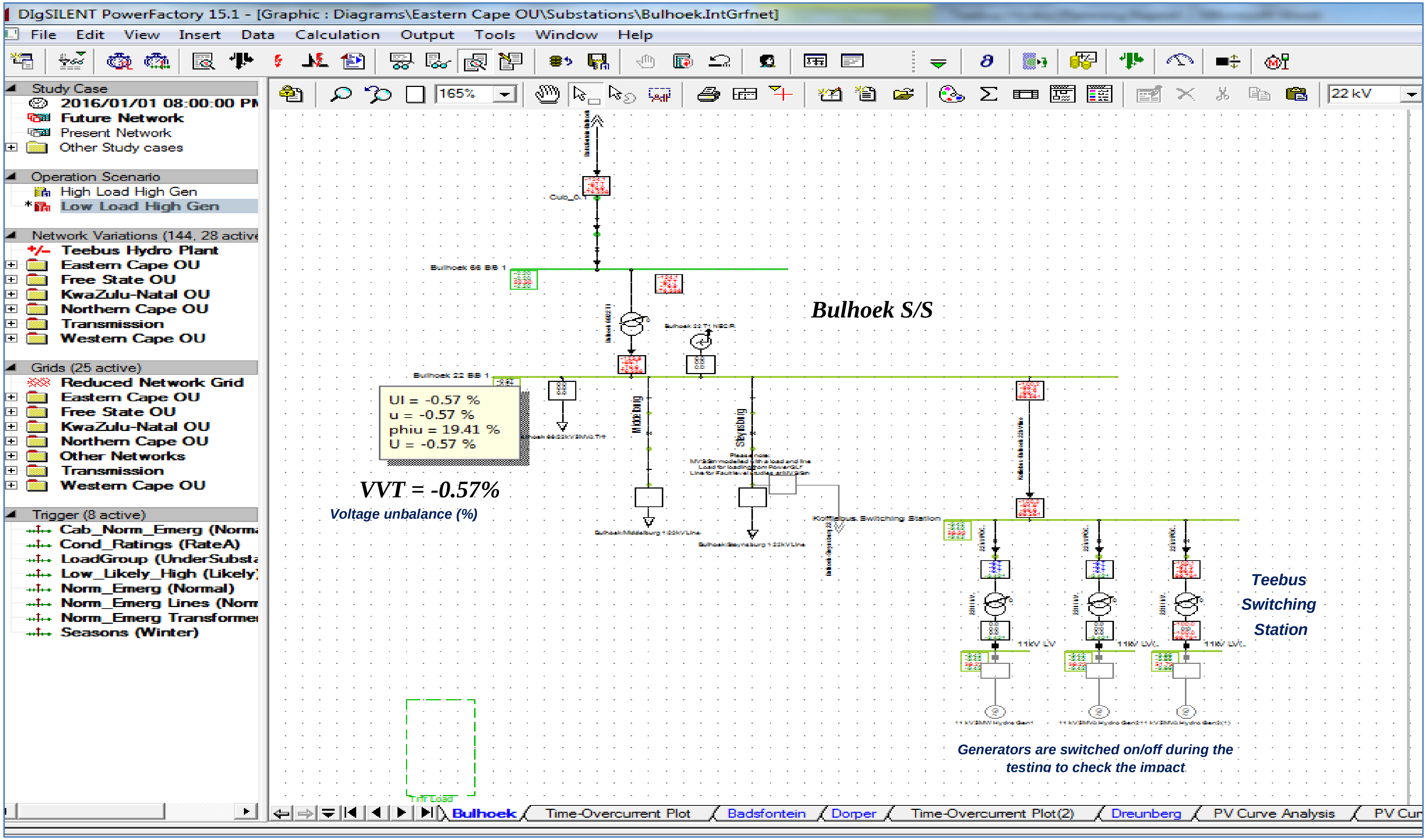


Figure 4-18: Voltage variation Test for LL scenario

The table below shows the summary of VVT results recorded from the Bulhoek 22kV busbar during maximum generation simulation.

Table 4-4: Voltage Variation Test with Generator connected

Busbar	HG HL (%)	HG LL (%)	Limits (%)
Bulhoek substation 66kV	2.48	2.24	5
Bulhoek substation 22kV	2.07	0.75	5
Teebus switching station 22kV	2.77	2.31	5
Max loading of Badsfontein/Bulhoek 66kV line	7	7	100
Max loading of Bulhoek/Teebus 22kV line	54	55	100

4.11 Method 2 (PV Curve)

This is another method of assessing the VVT. This is one of the widely used methods of voltage stability analysis. The purpose of a PV curve is to observe the impact of the varying amounts of injected active power from the generator on the voltage at the selected PCC. A PV curve can be advantageous because it can be used to help identify a suitable method of fixing any unacceptable voltage rise. From the Figure 4-19 below, it can be seen that the more power generated to the system causes the voltage to rise gradually. The Figure 4-19 below depicts the results for both the high load and low load scenarios study with the 10MW Teebus Hydro scheme connected onto the MV network.

The results are identical when comparing the results using the two methods (PV curve and Generator on/off); therefore any method can be used to calculate the VVT. The red line (curve) represents the low load scenario on Figure 4-19. The power from the generator starts from zero and gradually increases up to the maximum generator (10MW) capacity causing the voltage to rise as well. In this PV curve the maximum power of 10MW was generated and the voltage at Bulhoek 22kV busbar increased to 1.018pu as shown on Figure 4-19.

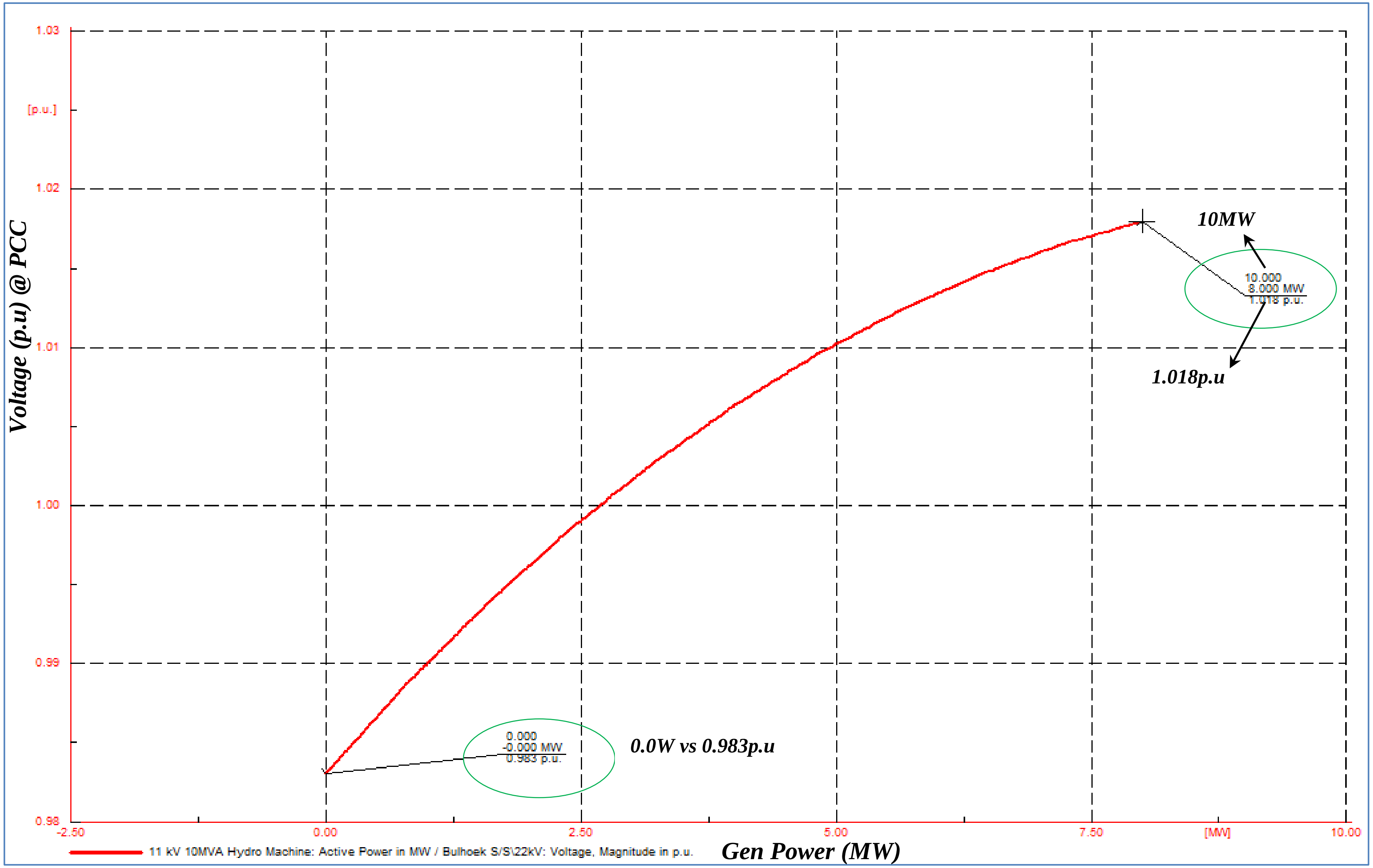


Figure 4-19: PV Curve with the generator connected to the system

From the graph above a VVT for high load scenario may be calculated using the following formula:

From the above Figure 4-19 it can be seen that: V_{min} = 0.983, V_{max} = 1.018

Therefore:

Equation 4-1: Voltage Variation Test

$$VVT = \frac{0.983-1.018}{0.983} \, x \, 100\%$$

$$= -3.561\%$$

4.12 Fault Levels Assessment

To determine a generating plant's short-circuited current contribution, the following rough values can be assumed (Eskom-according to Grid Planning Standard):

- For synchronous generators – eight times the rated current;
- For asynchronous generators and double-fed asynchronous generators – three to five times the rated current;
- For generators with inverters – 1.2 times the rated current.

To ensure correct calculations the impedances between the generator and the network connection point (customer transformer, lines, etc.) need to be taken into consideration.

Connecting a generator to a network has the effect of increasing the fault levels in the network at the point of generation connection. This may result in the violation of equipment fault level ratings. Generators contribute fault currents in response to network faults. It can be observed from Figure 4-20 that the generating plants have increased the existing network fault level.

Single phase to ground and three phase short-circuit calculations are to be carried out at each busbar where fault interrupting switchgear (circuit breakers) are installed at Bulhoek substation (more than one busbar per substation must be selected if the substation is being run split). For this study the short-circuit analysis will be carried out on the 66kV and 22kV Bulhoek busbars.

The impact of a generating plant on a 22 kV feeder is indicated in the fault level rise in Figure 4-20. This illustration is for a Bulhoek/Middleburg 22 kV feeder with a peak load of 4.3 MVA and a minimum load of 1.72 MVA (40% of maximum). The generating plant is connected at the end of the feeder and exports 10 MW of power direct to Bulhoek substation. The three-phase fault level at the start of the feeder increased by 2,52kA, while the three-phase fault level at the end of the feeder increased by 0,63kA.

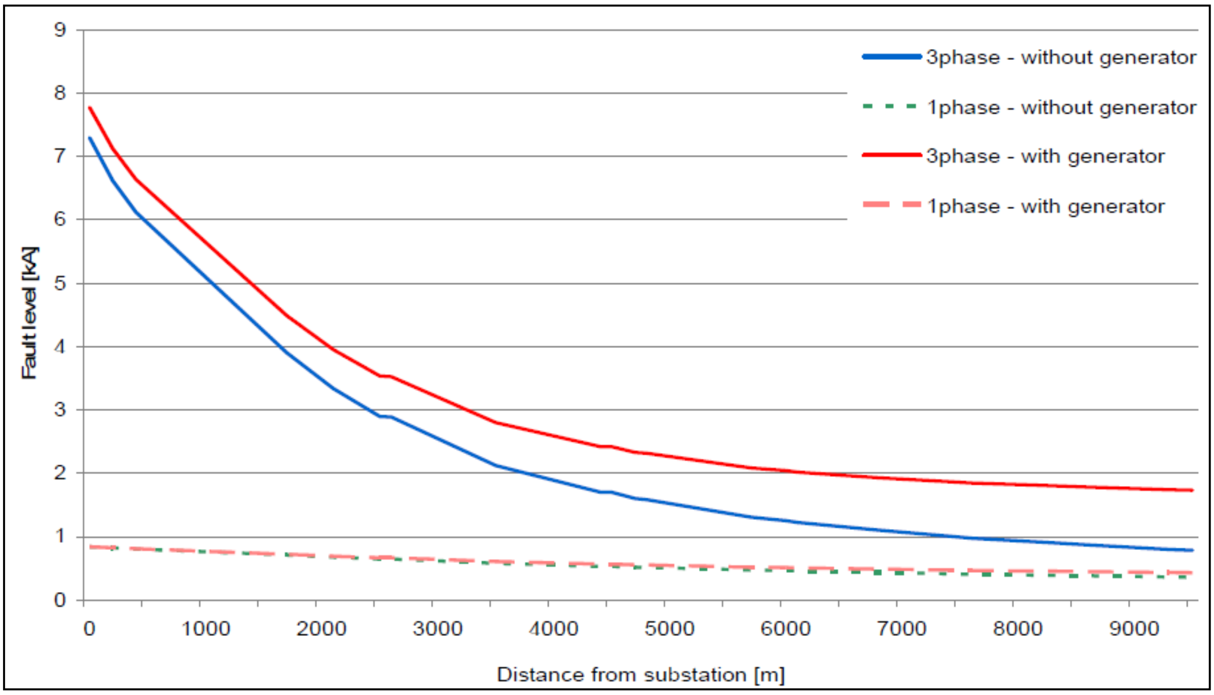


Figure 4-20: Fault level rise on a 22kV feeder with and without Hydro Plant

The fault levels given in this section have been calculated with the network in its normal state, with maximum generation available and all reactive devices in service. During the performance of the fault studies calculations, the study case was set up (according to IEC 60909 method) as shown below.

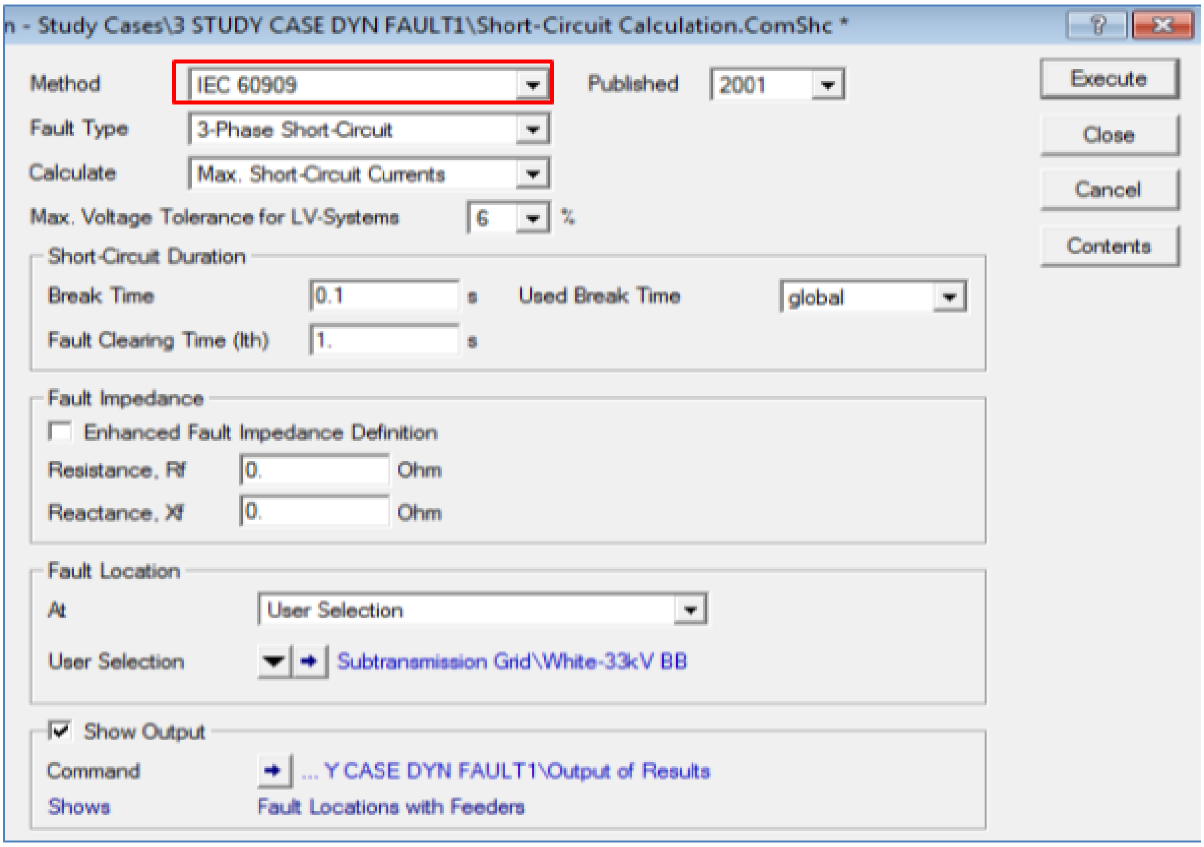


Figure 4-21: Faults Levels (IEC 60909) set up

The fault study results are summarized in a table below:

Table 4-5: Faults Levels with/without generator connected

Busbar	**With Gen 3ph (kA)**	**Without Generator (3 ph)**	**With Gen 1ph (kA)**	**Without Generator (1 ph)**
Bulhoek 22kV	1.4	0.87	0.9	0.31
Bulhoek 66kV	1.5	0.68	0.75	0.7
Teebus Hydro switching station	1.90	0	1.94	0

Table 4-6: Faults Levels and breaker rupturing capacity

FAULT LEVELS AND BREAKER RUPTURING CAPACITY								
Substation	Busbar (kV)	Ik (3-ph) Fault kA	Ik (1-ph) Fault kA	3*Sk (3-ph) Fault MVA	Ik (1-ph) Fault MVA	Ik (3-ph) Angle (Deg)	Ik (1-ph) Angle (Deg)	Breaker Rupturing Capacity kA
Bulhoek	66	0.68	0.70	77.67	26.66	-58.50	-63.37	25
	22	0.84	0.31	32.04	3.99	-69.37	-36.5	25

The results indicate that the fault levels at the customer point of supply, the point of connection (POC) and the Point of Common Coupling (PCC) are below the existing equipment rating even after the addition of the 10MW generator. It can also be noted from the Figure 4-22 and Figure 4-23 below that the fault levels increase when the 10MW generator is connected and the network has been expanded.

Station Name	Bus Name	Unom Unom [kV]	3-Phase I [kA]	3-Phase Angle [deg]	1-Phase I [kA]	1-Phase Angle [deg]	Phase-Phase I [kA]	Phase-Phase Angle [deg]	Positive Seq R [pu]	Positive Seq X [pu]	Zero Seq R0 [pu]	Zero Seq X0 [pu]	Ratio X0/X1 [-]	Ratio R0/X0 [-]	Ratio R0/X1 [-]
	Bulhoek 22 BB 1	22.0	0.8	-75.6	0.3	-41.4	0.7	13.2	0.6608	3.1627	17.4013	10.0979	3.193	1.723	5.502

IgSI/info - DPL program 'FaultReport' successfully executed

Figure 4-22: Faults Levels Report before connecting the generators

Station Name	Bus Name	Unom Unom [kV]	3-Phase I [kA]	3-Phase Angle [deg]	1-Phase I [kA]	1-Phase Angle [deg]	Phase-Phase I [kA]	Phase-Phase Angle [deg]	Positive Seq R [pu]	Positive Seq X [pu]	Zero Seq R0 [pu]	Zero Seq X0 [pu]	Ratio X0/X1 [-]	Ratio R0/X0 [-]	Ratio R0/X1 [-]
	Bulhoek 22 BB 1	22.0	1.4	-72.6	0.9	-70.5	1.3	-166.0	0.4064	1.7443	1.9634	5.1665	2.962	0.380	1.126

DIgSI/info - DPL program 'FaultReport' successfully executed

Figure 4-23: Faults Levels results after connecting the generators

The formula for calculating the maximum fault level (Three phase):

Equation 4-2: Fault current from generator

$$I_K = \frac{C \times S_G}{\sqrt{3} \times \left|R_g + jX_d''\right| \times V_G}$$

$$I_K = \frac{1.1 \times 10^6}{\sqrt{3} \times (0.6608 + 3.1627) \times 11x10^3}$$

$$= 1.511kA = 4.5\text{kA}$$

*A general rule to determine the total faults contribution of a generator is multiplying the generator MW output by 3 [16].

Where:

I_K = Fault current contribution from the generator (kA)

C = Voltage factor. For all distribution networks above 1 kV, the voltage factor is 1.1.

S_G = MVA rating of generator (10MW)

$X_{d''}$ = Sub-transient reactance of generator (pu)

R_g = Generator stator resistance (pu)

V_G = Output voltage of the generator (kV)

The reason for using this calculation approach is to ensure that the worst possible fault level is calculated and any possibility of a fault level being exceeded is captured. The correct protective relay/equipment settings and the fuse sizing will be drawn thereafter. These short-circuit studies are done for the existing and future network configurations.

Two types of fault levels that are performed in this paper are:

- Single-phase to ground faults.
- Three-phase faults.

4.13 Voltage Unbalance

From the Figure 4-24 below, it can be observed that the voltage unbalance limits for the 22kV distribution feeders have not been contravened. The values depicted from the Figure 4-24 below are set such that the simulated result matches the measured values from the QOS recorders.

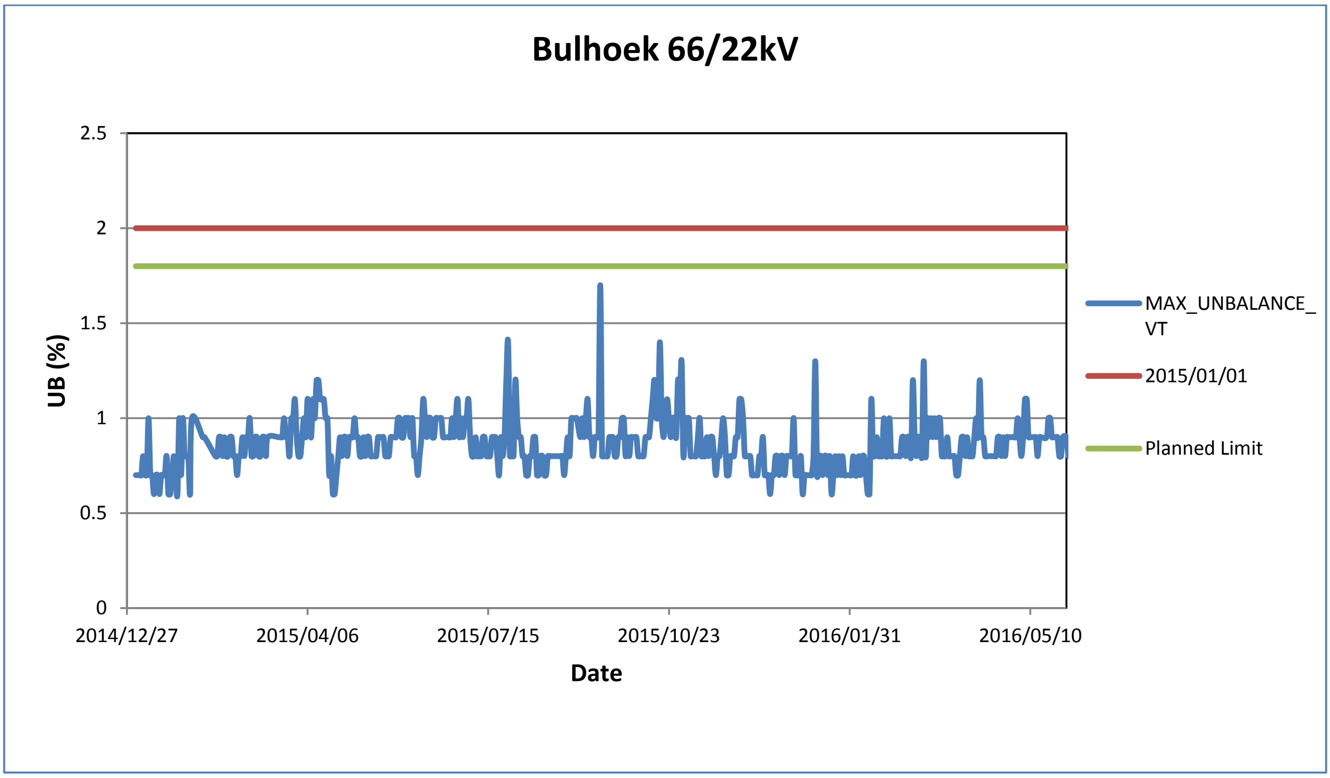


Figure 4-24: Voltage unbalance of the existing network (without the generators)

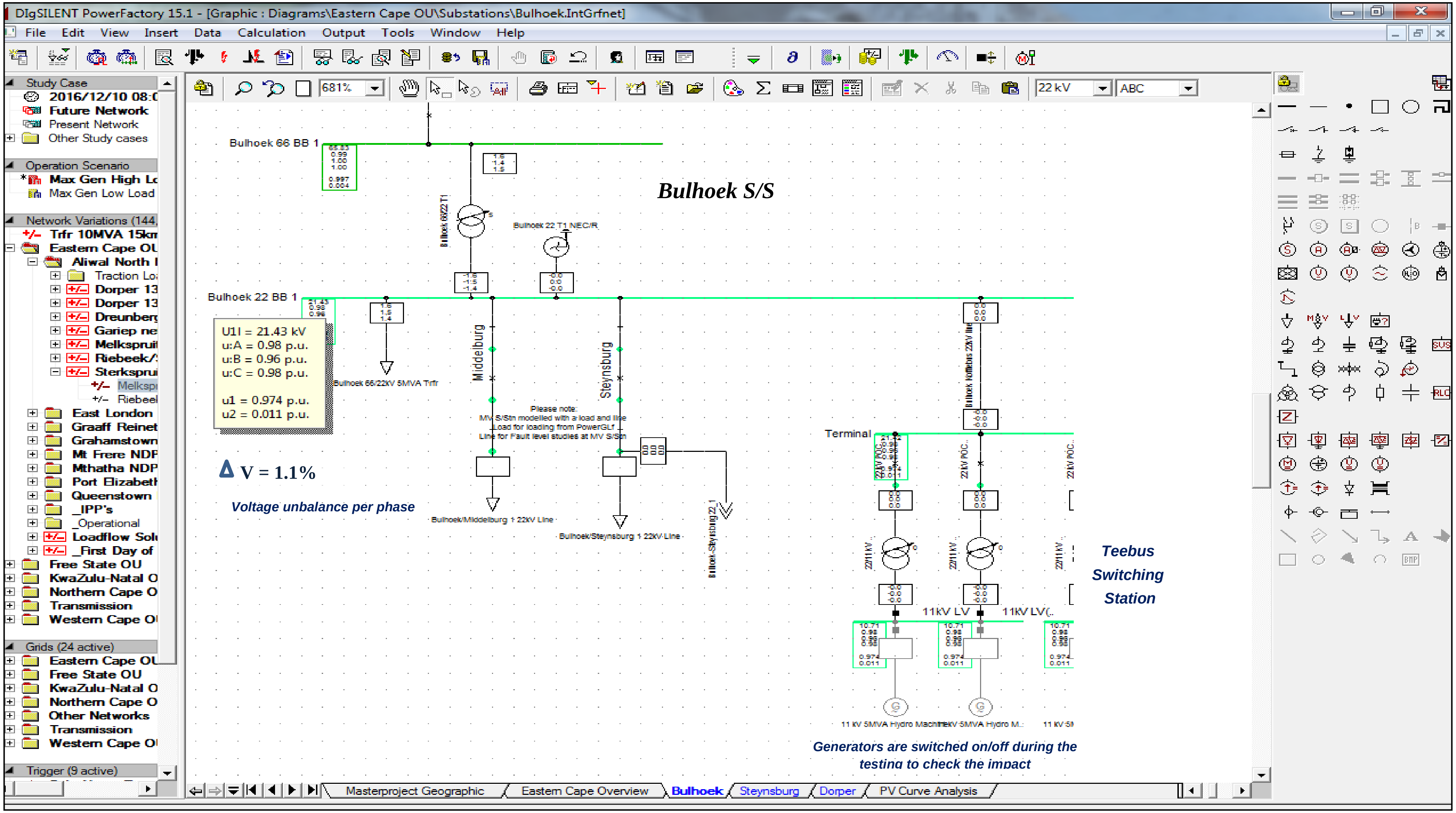


Figure 4-25: Voltage unbalance of the existing network (without the generators)

Figure 4-25 above shows the existing voltage unbalance measured at the PCC performed from PowerFactory. The simulated voltage unbalance slightly corresponds with the measured values. It is important to take note that even though the voltage unbalance is over 1%, it is still under the required compatibility limit of 2% as per NRS 042 standard.

Equation 4-3: Voltage unbalance without the Gen

- $V_{Unbalance} = \left|\frac{V_{Negative\ sequence}}{V_{Positive\ Sequence}}\right| \times 100$
- $= \frac{0.011}{0.974} \times 100\%$

$= 1.13\%$

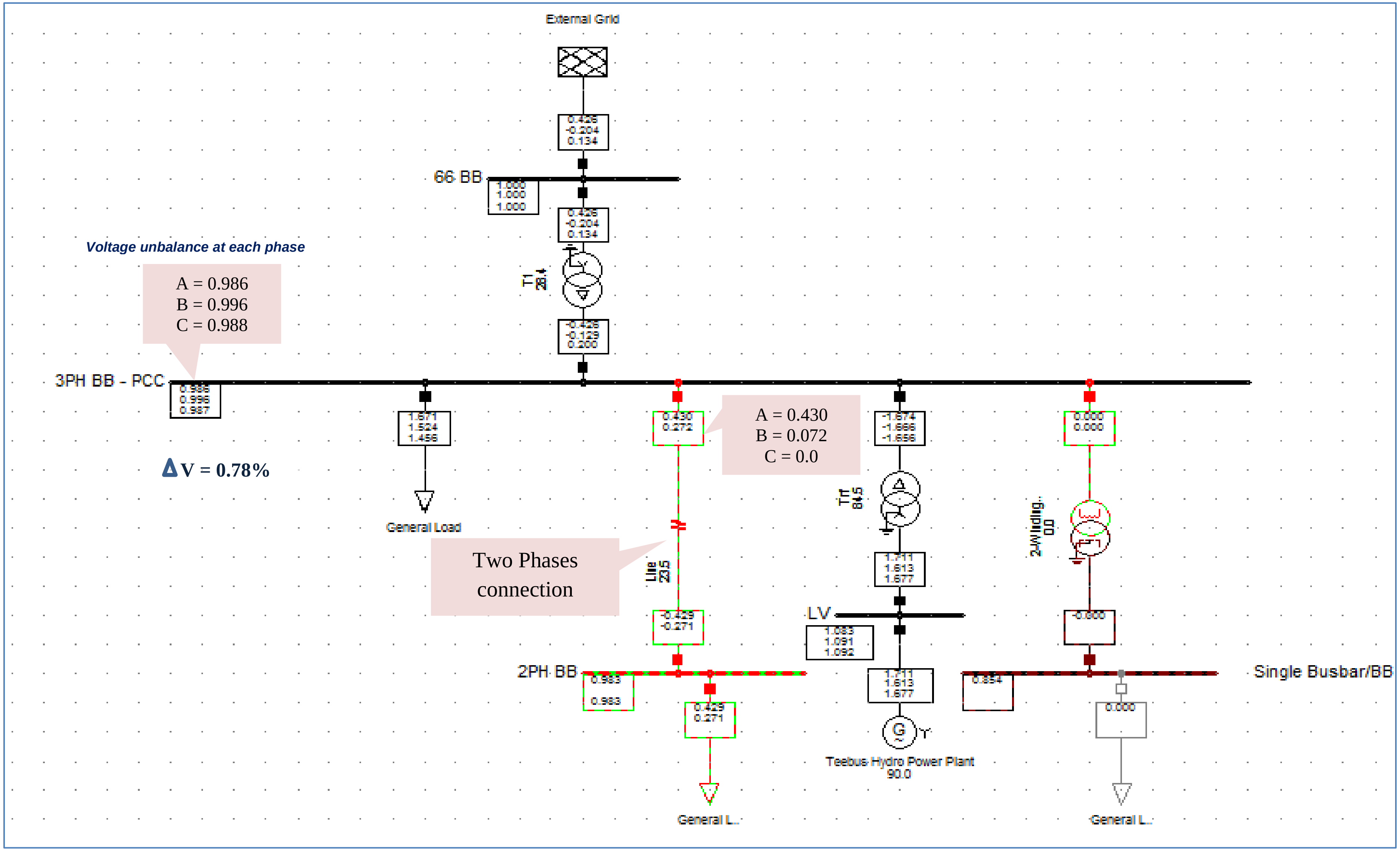


Figure 4-26: Voltage unbalance of the existing network (with one generator)

Figure 4-26 above shows voltage unbalance after the connection of the planned generators. The red and green colours represent the technology on the existing system (two/three phase system).

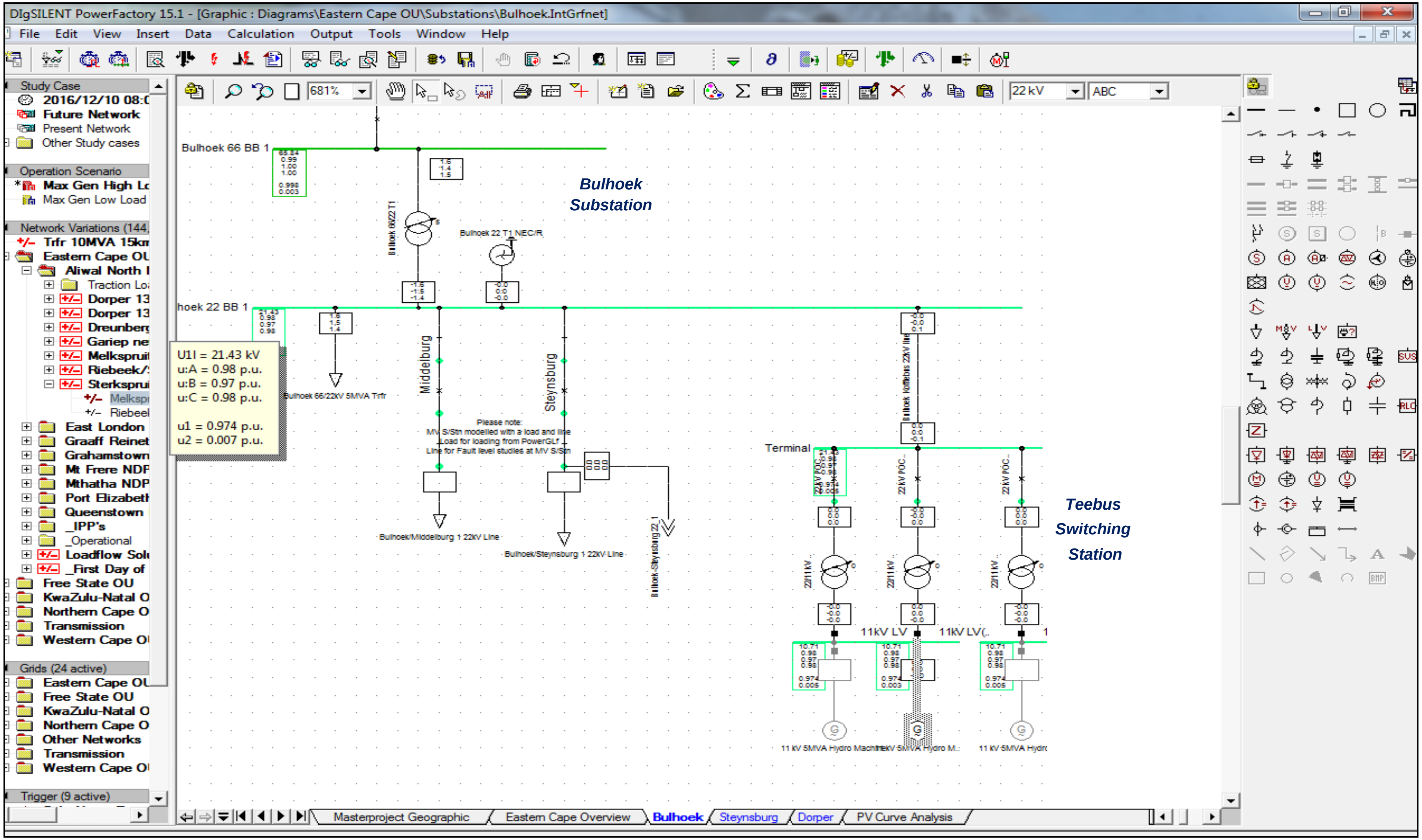


Figure 4-27: Voltage unbalance with the two generators connected

From the above results, negative sequence components is 0.007p.u and positive components = 0.974pu. Therefore,

Equation 4-4: Voltage unbalance with Gen

- $V_{Unbalance} = \left|\frac{V_{Negative\ sequence}}{V_{Positive\ Sequence}}\right| \times 100$
- $= \frac{0.007}{0.974} \times 100\%$

$= 0.72\%$

The Figure 4-27 above shows that the voltage unbalance has been improved with the generators connected.

4.14 Voltage Regulation

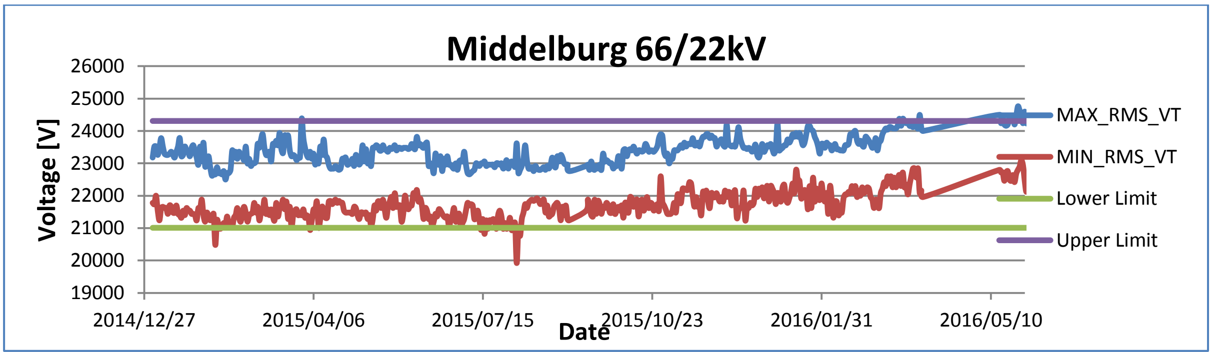


Figure 4-28: Bulhoek/Middleburg 22kV feeder RMS voltages

Based on the graph in Figure 4-28 above, it is found that the voltage regulation is within limits; except for 2015/02/07 and 2015/08/06 where the voltage is below the lower limit. The voltage is above the upper limit on 2015/03/30 and from 2016/03/24 to 2016/05/15. This was due to the outage that took place during this period where some of the load was transferred to this feeder. The outage information was captured from the field service Engineer for the area where Teebus Hydro is located. The Steynsburg 11kV feeder is also dispatching from a step down transformer from Bulhoek/Steynsburg 22kV feeder.

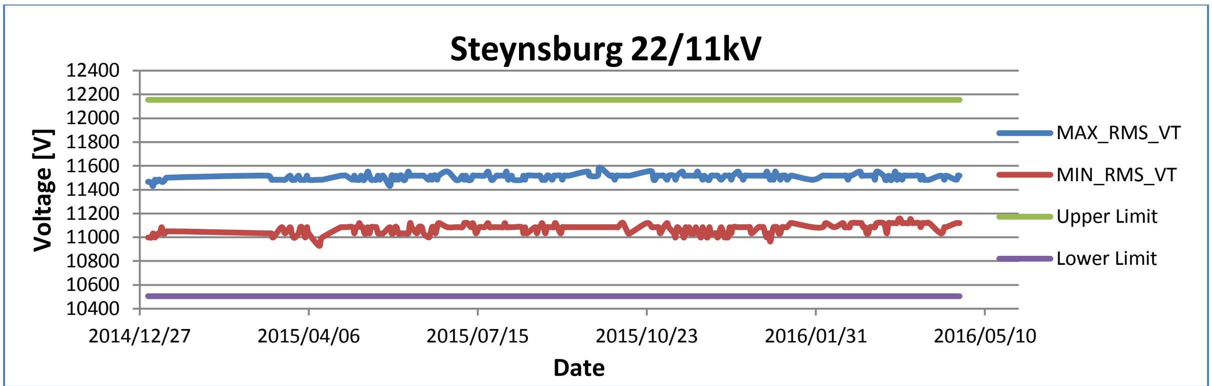


Figure 4-29: Bulhoek/Steynesburg 11kV feeder RMS voltages

The above Figure 4-29 shows that the voltage regulation is within the stipulated limits

4.15 Dynamic Studies

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on transmission facilities, loss of generation, or loss of a large load [7].

The following planning scenarios were followed:

- Peak load scenario
- Maximum output of the generating plant
- Low excitation voltage (absorbing Q)
- Minimum network strength i.e. low fault levels (single phase-ground faults level)
- Using a generator model with a tuned Automatic Voltage Regulator (AVR)
- No Power system stabilizer (PSS) in the generator model

For RMS simulations, only the fundamental components of voltages and currents are taken into account, using a symmetrical and steady-state representation of the passive electrical network. For EMT simulations, voltages and currents are represented by their instantaneous values, so that the dynamic behaviour of passive network elements are also taken into account.

The control system responds to inject active and reactive power according to the target values requested. This is achieved within milliseconds, therefore there is no time for any effects to be passed to the mechanical side (fault ride through events are the exception). Therefore regardless of the terminal conditions (within reason) the machines will inject exactly the requested active and reactive power/current. This is particularly the case for small signal, frequency, and in parts for transient stability.

4.16 Interpretation of the Graph Results during Transient Stability Studies

For the simulations the following conditions were assumed:

- For each case two generator turbines were connected at the switching station
- Hydro Generation units were operating at the unity power factor
- The results are similar with either generator is switched on/off

The event for simulations is set up as per the following Figure 4-30 below. Transient stability studies are analysed based on the two scenarios namely; a loss of any of the two major lines and fault on a generator busbar (see figures below). There is a short circuit simulation that is set on the main infeed (Ruigtevallei/Badsfontein and Badsfontein/Dreunberg 66kV line). The three phase short circuit fault is modelled/set to occur at 1sec and clears by opening the associated circuit breakers 100ms after the fault for each of the faults. When the fault occurs on the Ruigtevallei/Badsfontein 66kV line, the Badsfontein substation will be supplied via Badsfontein/Dreunberg 66kV line and vice versa. The results show that, the voltages and thermals remain acceptable even if one of the feeders is out of service. This is due to the fact that the network is a ring. The study will further discuss and investigate the transient stability enhancement by using a STATCOM.

On the simulation plot or resulting graph Figure 4-30 and Figure 4-33 for both study cases (Ruigtevallei/Badsfontein and Badsfontein/Dreunberg 66kV line), it can be noted that the duration for a faults simulation is set to stop at 15sec in order to clearly observe the behaviour of stability. The generator pole slip at the Teebus Hydro is set to occur at 1.10 seconds. Also note the variables plotted in each of these graphs. The variables for synchronous generators were defined in order to show the desired records for the dynamic simulation. There was no voltage collapse during faults therefore the system or the synchronous machines are stable for this study (for two scenarios). The critical infeed scenario is when Badsfontein/Bulhoek 66kV line (Radial infeed) is lost. It can be noted that the system becomes unstable (see Figure 4-34). Transient instability is evident on Figure 4-34 as there is a 'run away' situation shortly after fault clearance (machine speed). A STATCOM with reactive power capability of 4MVAr was connected at the switching station to help maintain acceptable voltage levels during faults. I can be noted that the problem was completely alleviated with the connection of the 4MVar STATCOM; the results are shown in Figure 4-36.

An illustration of the procedure for conducting transient stability studies in power factory is also explained in Appendix A. When a fault occurs on the network, the fault needs to be cleared within a certain amount of time to avoid the disconnection of the generators from the network and to ensure network stability. The time wherein the fault needs to be cleared is called the Critical Clearing Time (CCT).

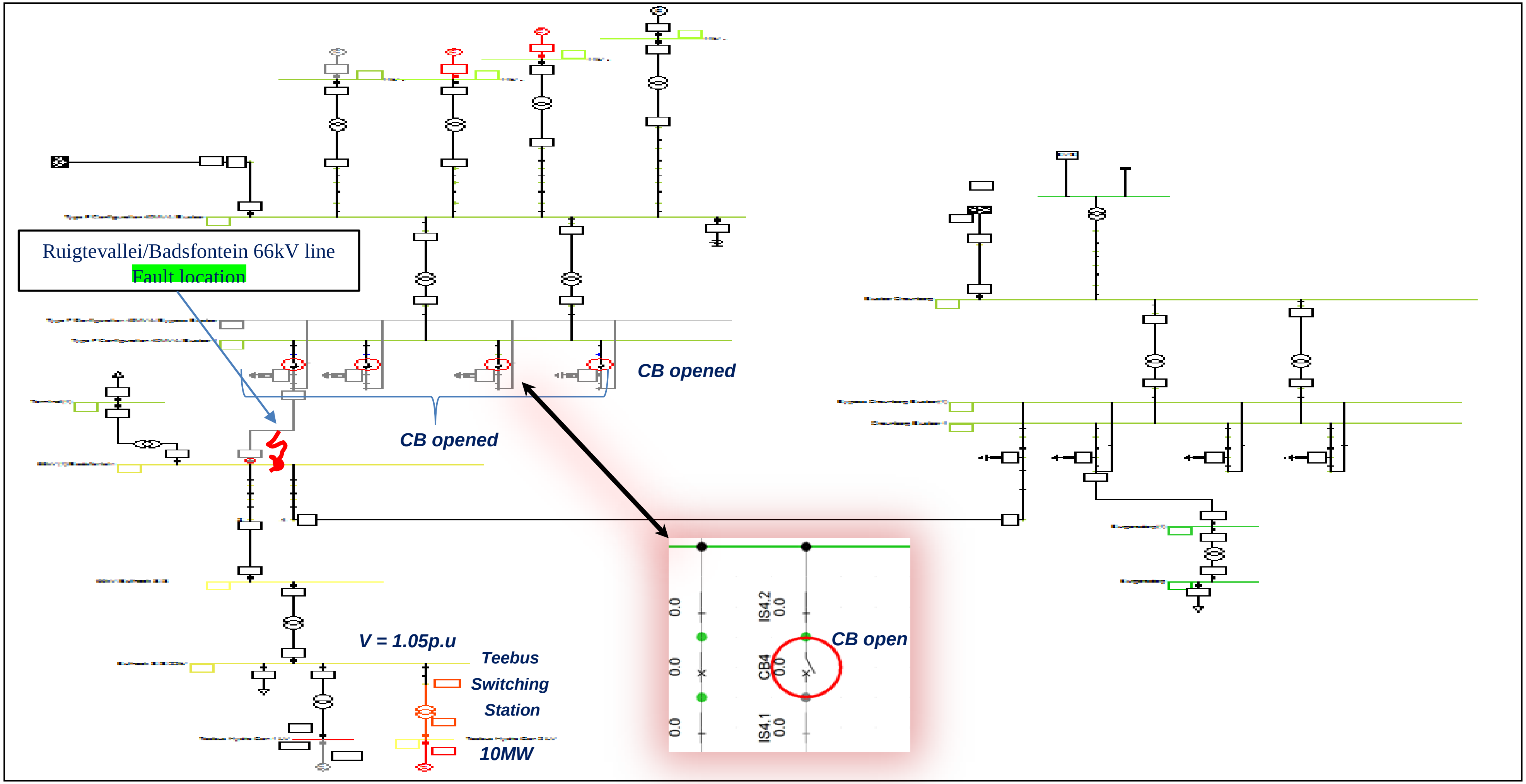


Figure 4-30: Single line diagram for Dynamic Simulation Ruigtevallei-Badsfontein 66kV line

On the simulation plot Figure 4-30 above and Figure 4-31, it can be noted that the fault is applied on Ruigtevallei/Badsfontein 66kV line. The system is fed via a Dreunberg/Badsfontein 66kV line as a reliability security. The faults simulation is set to stop at 15sec in order to clearly observe the behaviour of stability. The voltages and the thermals are below the allowable limits even during the fault; therefore, system is able to maintain the stability.

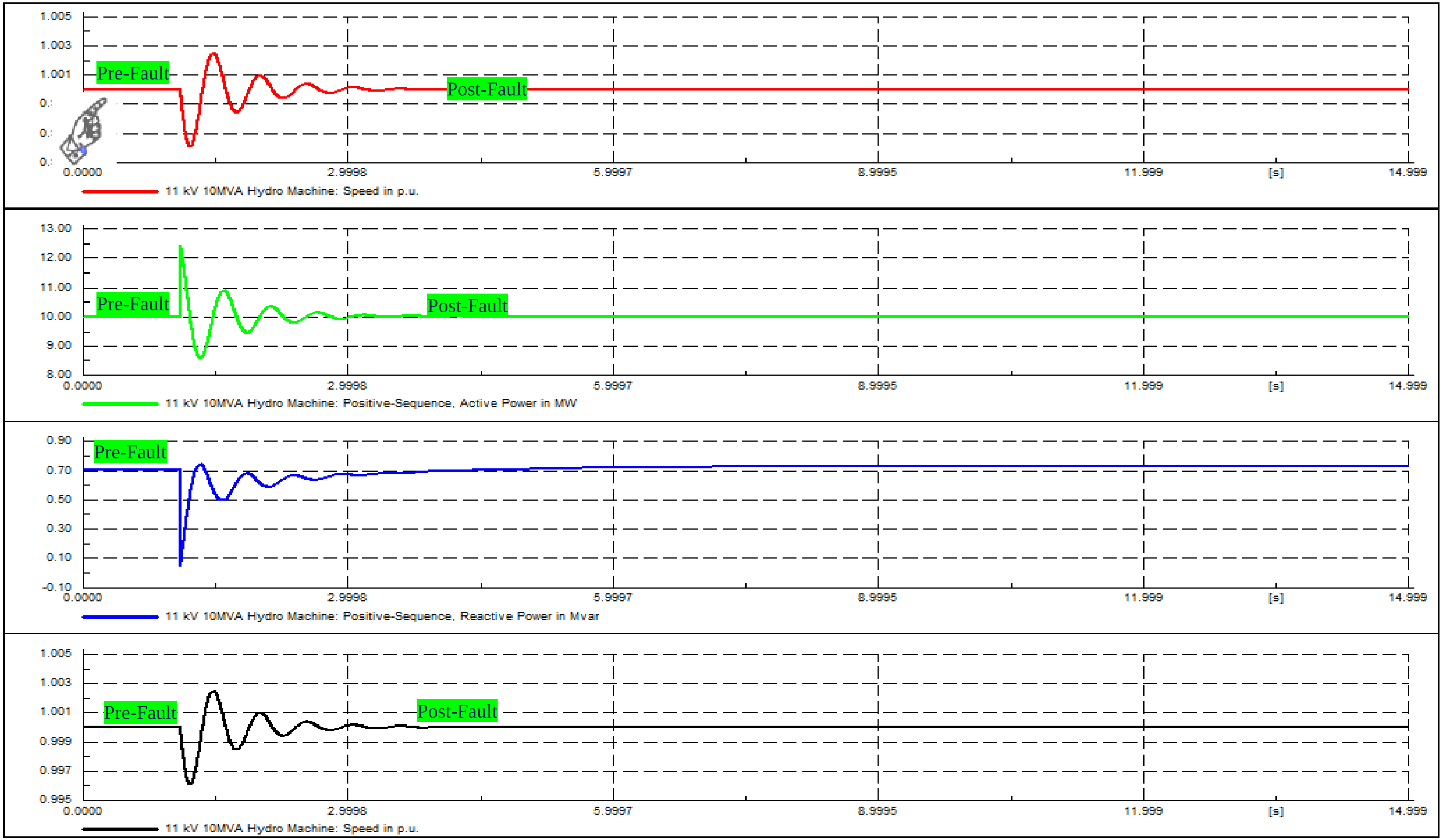


Figure 4-31: Teebus Hydro Plant dynamic simulation plots with contingency 'Ruigtevallei/Badsfontein 66kV line'

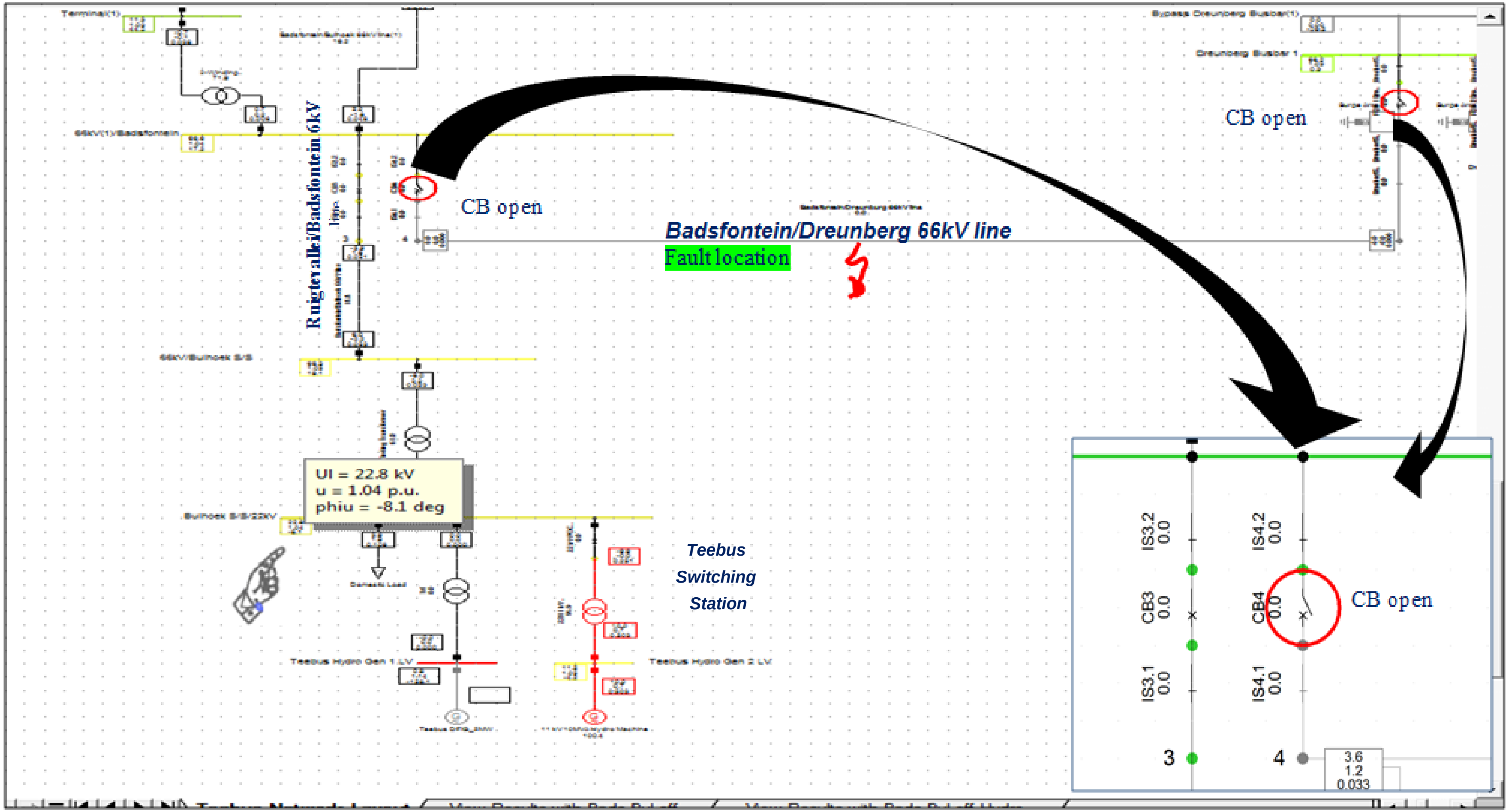


Figure 4-32: Single line diagram dynamic plots with Dreunberg-Badsfontein 66kV line

On the simulation plot Figure 4-32 above, it can be noted that the fault is applied on Ruigtevallei/Dreunberg 66kV line. The system is fed via a Ruigtevallei/Badsfontein 66kV line as a reliability security. The faults simulation is set to stop at 15sec in order to clearly observe the behaviour of stability. The system is able to maintain the stability after the fault.

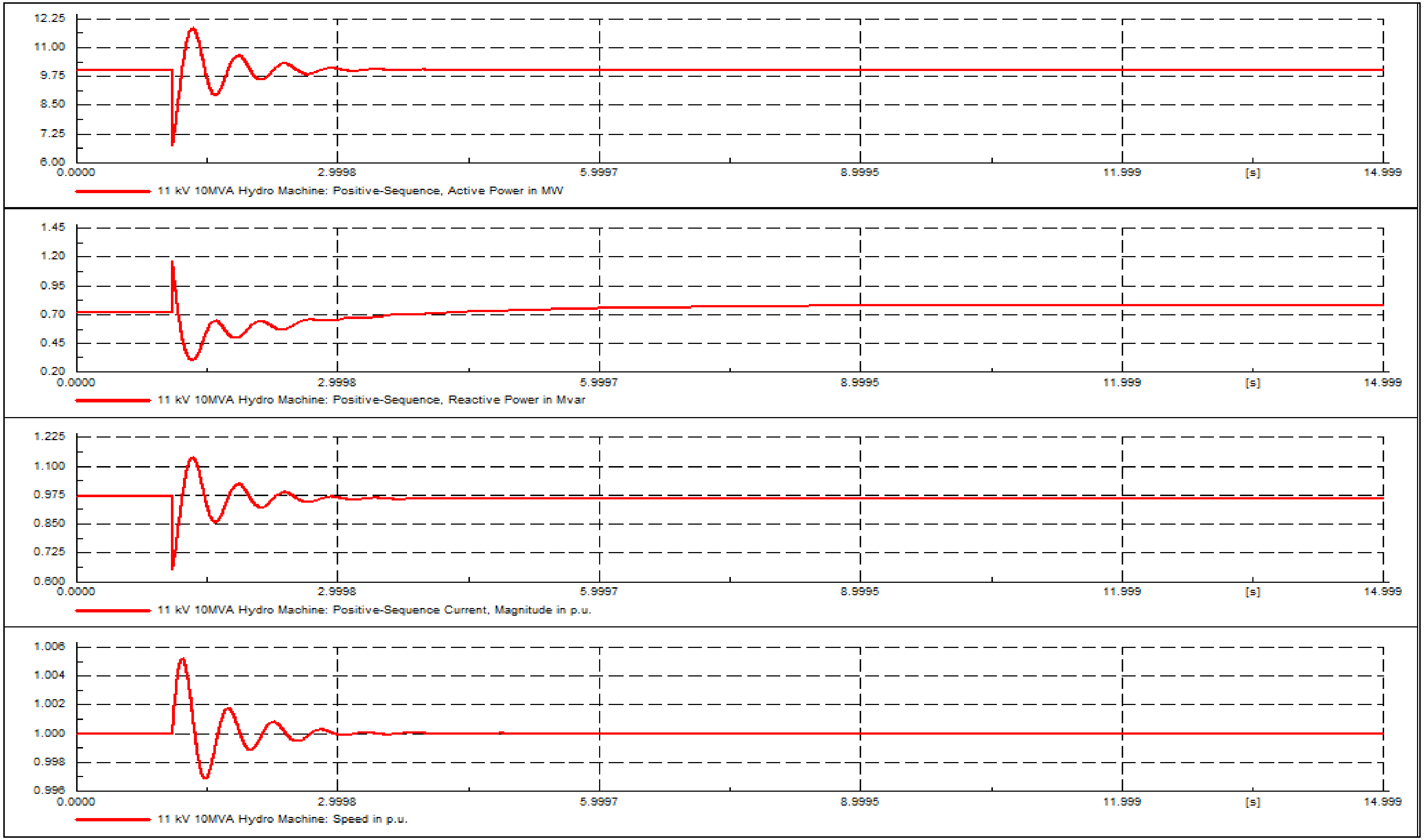


Figure 4-33: Teebus Hydro Plant dynamic simulation plots with contingency 'Badsfontein/Bulhoek 66kV line' fault cleared in 0.1s

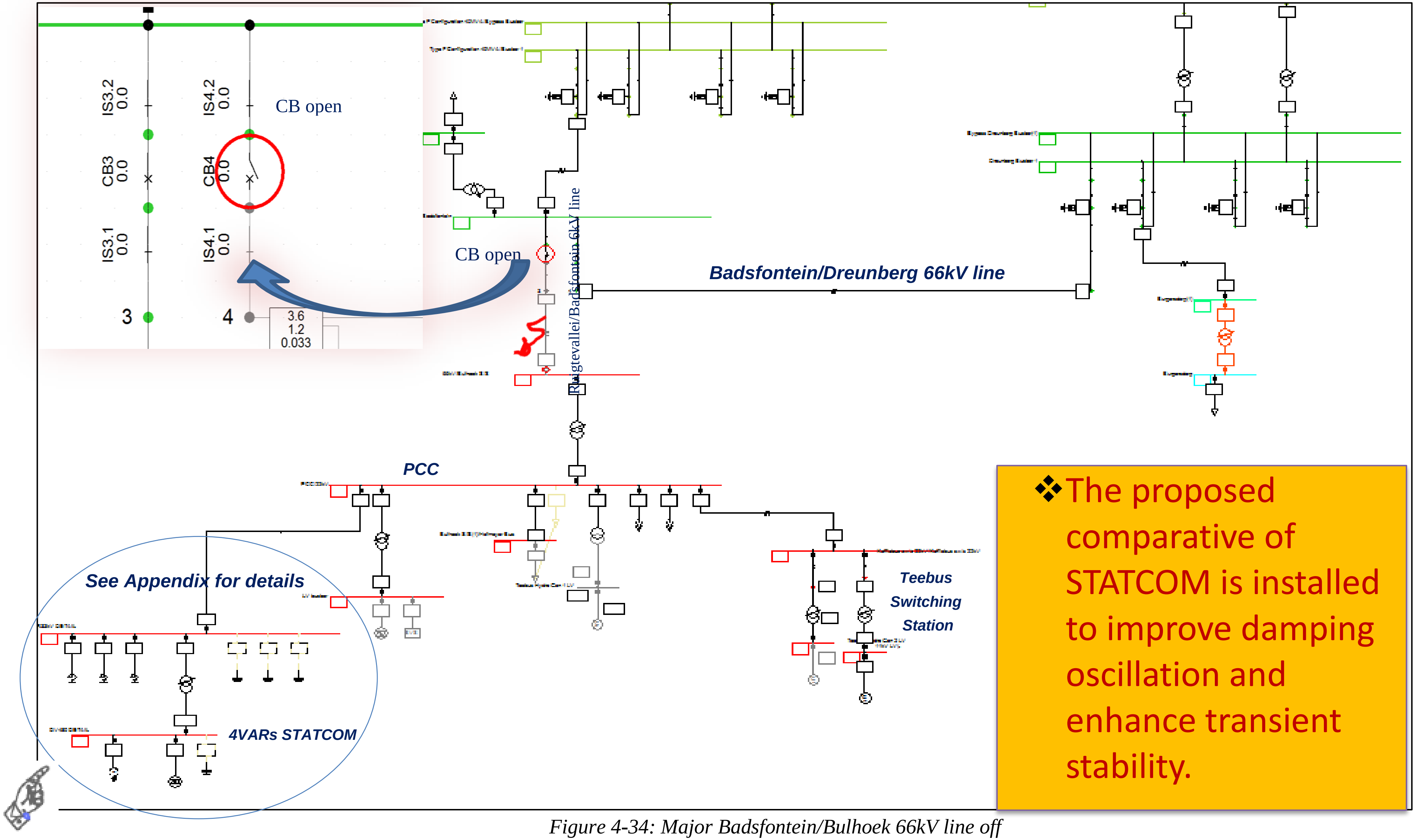


Figure 4-34: Major Badsfontein/Bulhoek 66kV line off

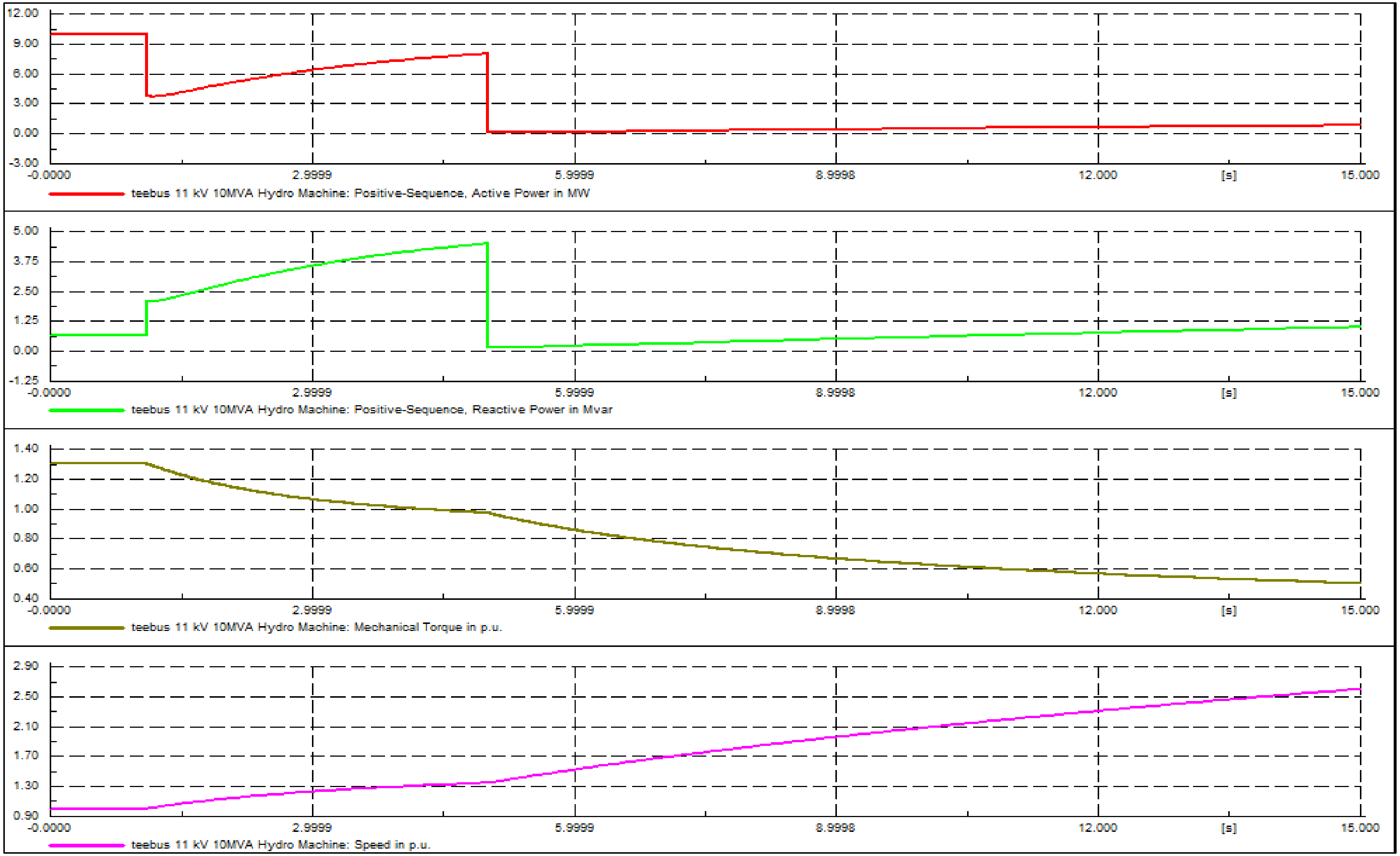
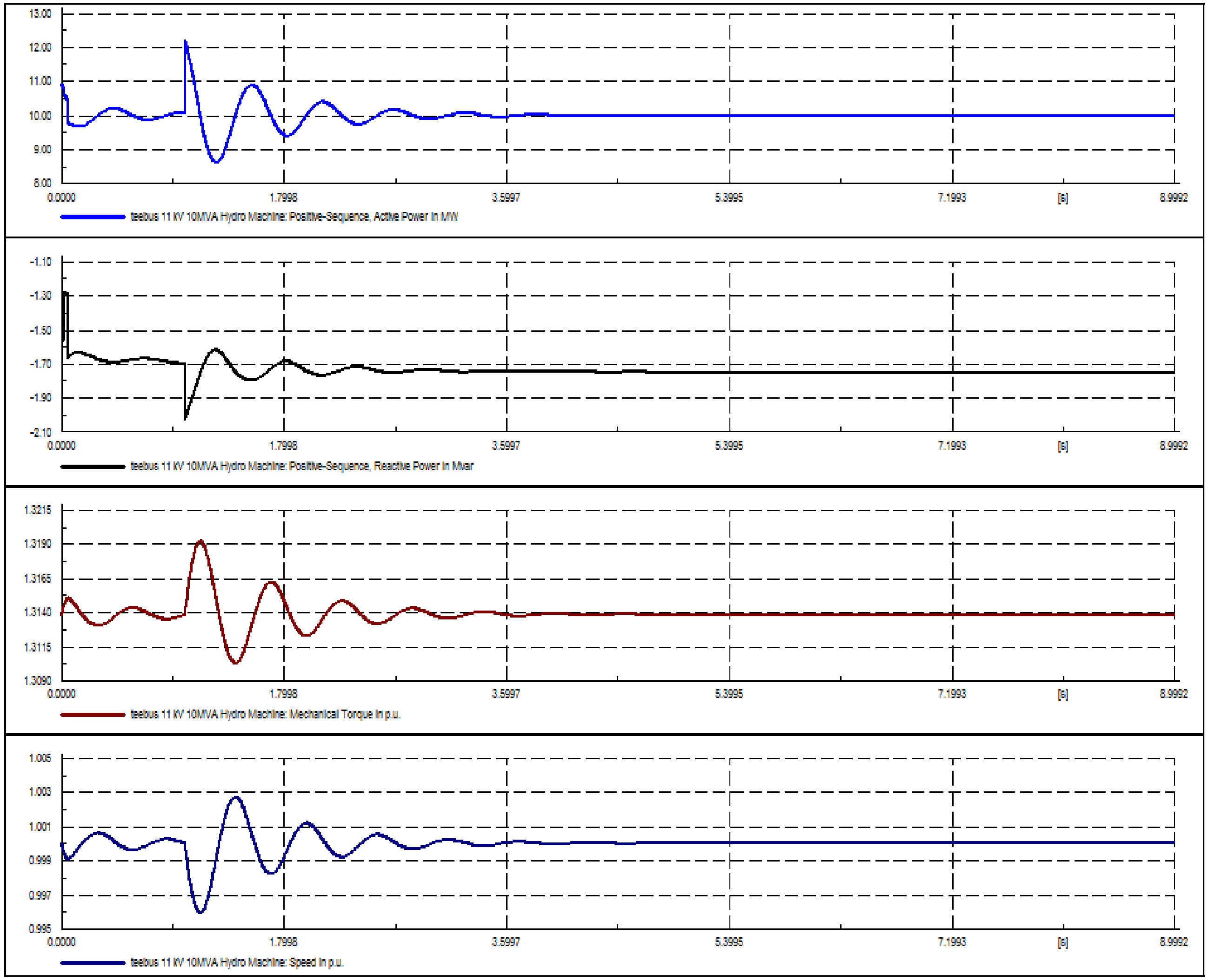


Figure 4-35: Results when major infeed (Badsfontein/Bulhoek 66kV is lost) – lost stability without STATCOM



The results show that the system is able to stabilize when the 4MVArs STATCOM is connected after a fault.

Figure 4-36: Results with 4MVars STATCOM- Stayed in stability

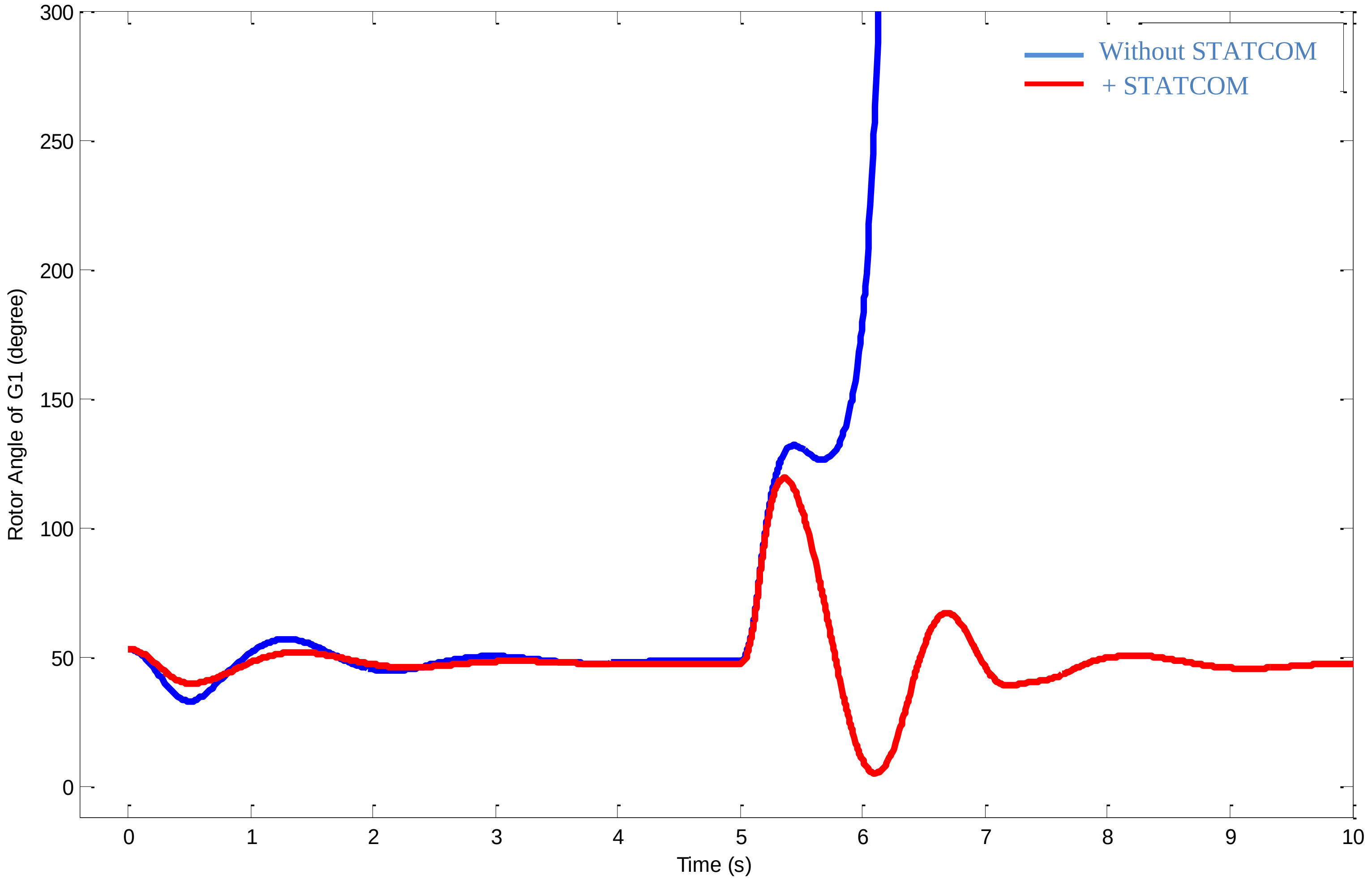


Figure 4-37: Rotor angle difference of Teebus generator

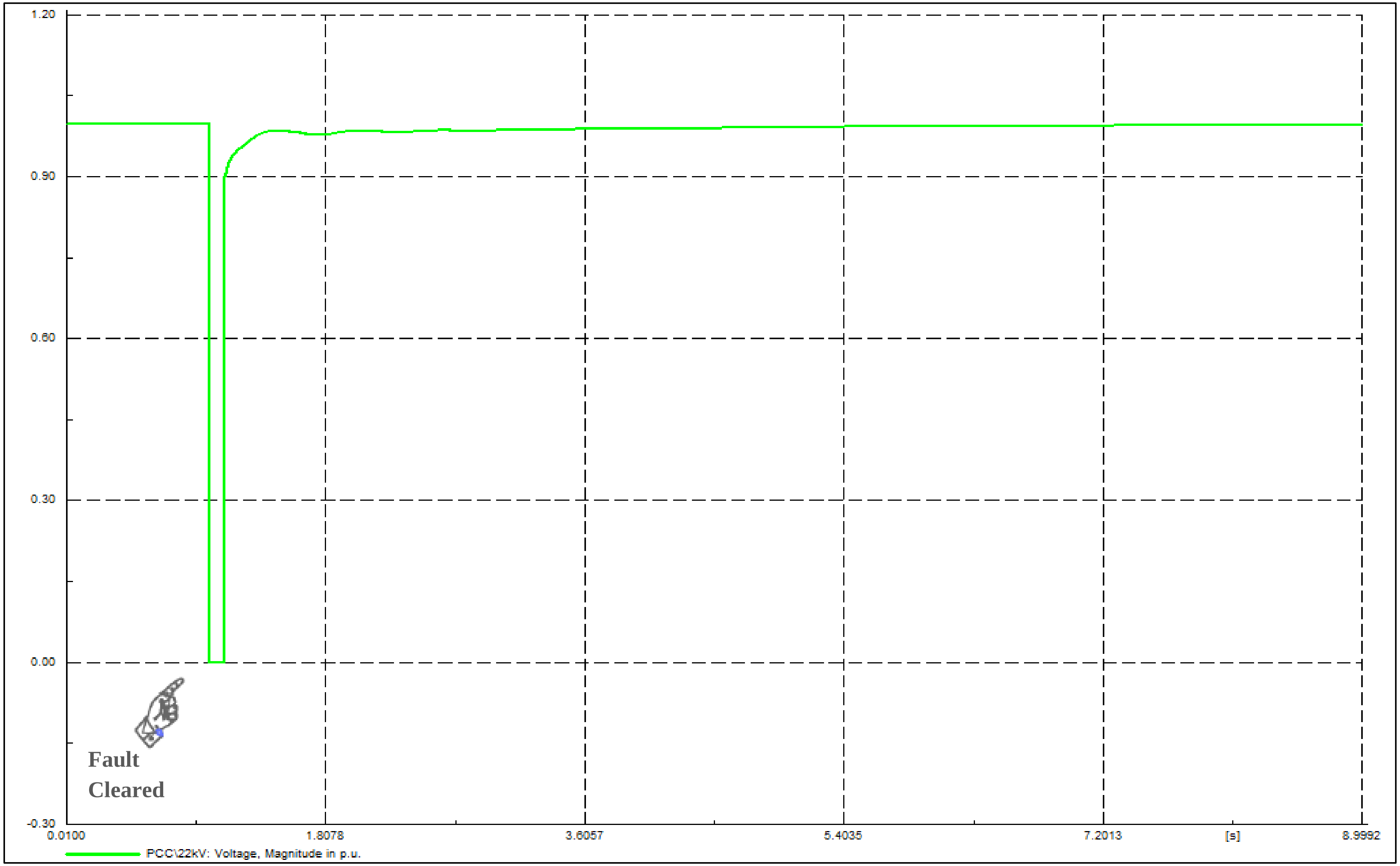


Figure 4-38: Low Fault Ride through (3ph) measured at PCC

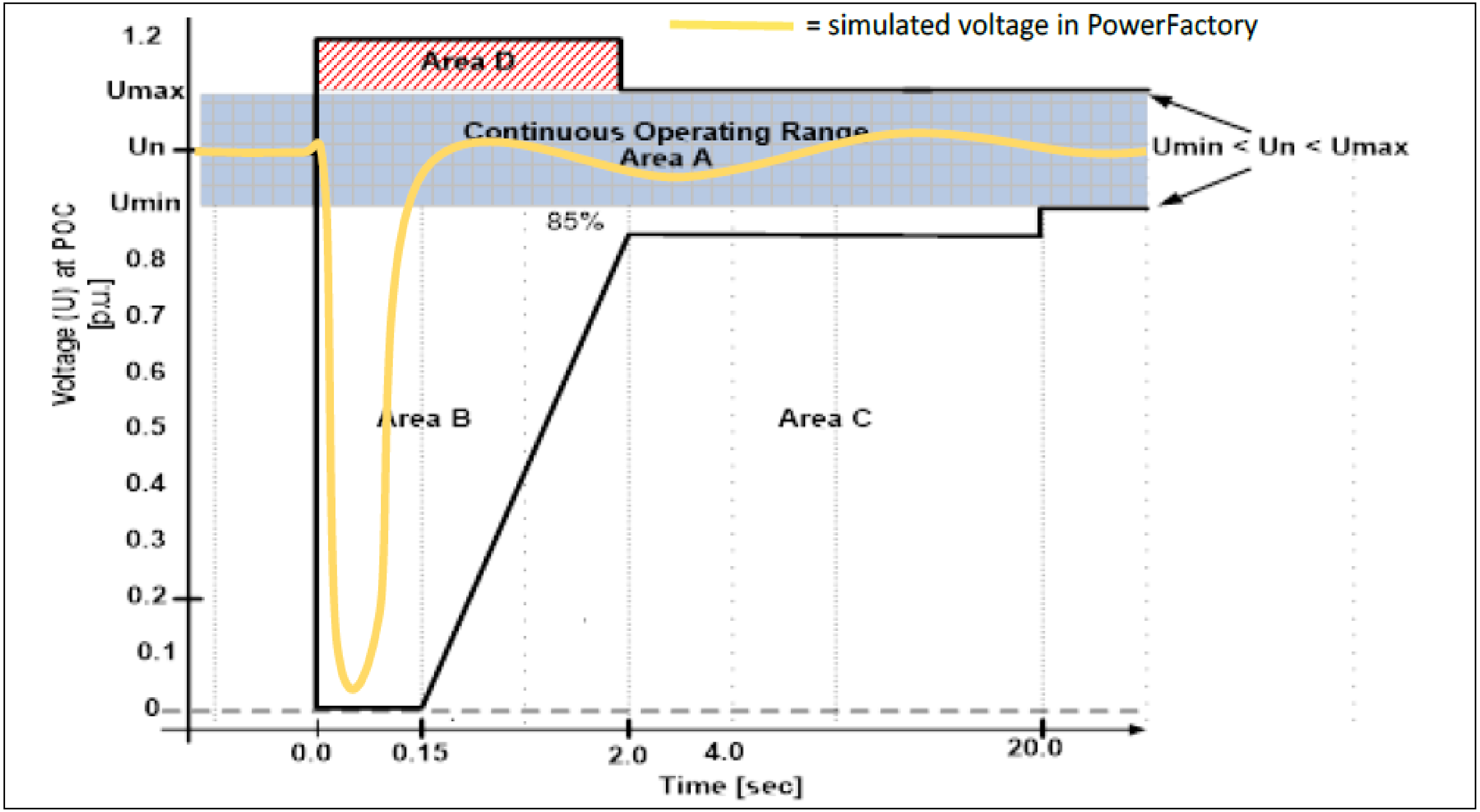


Figure 4-39: Successful fault ride through (Guide) [50]

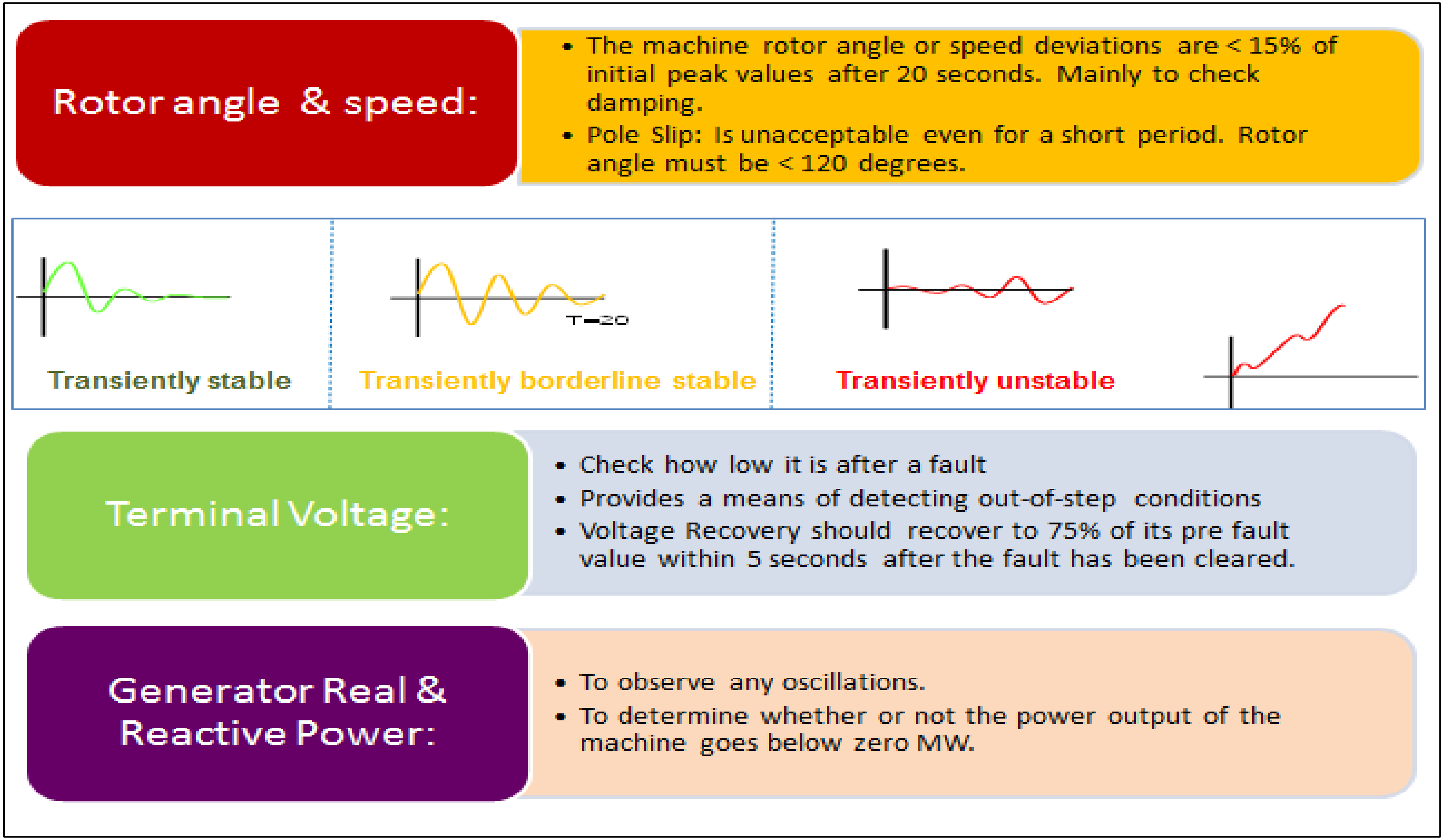


Figure 4-40: Guideline to determine the stability of the network [50]

Figure 4-39 and Figure 4-40 above is sourced from the SA Distribution Grid Code for Renewable Power Producers; this is used as a Standard that should be adhered to when performing the analysis. Figure 4-39 depicts correct manner in which all generators should be capable of riding through low voltage conditions in which generators unit stability is maintained. Small signal instability is generally evident by a lightly damped, or sustained or increasing oscillation of the machine variable as shown on Figure 4-40. Any machine variable which is still not sustainable damped by 20 seconds requires action.

If the instability is observed (see Figure *4-35*), the best solution would be to use an inter-trip to remove particular generator causing the problem. In this case the 4MVArs STATCOM is employed to alleviate the instability. STATCOM demonstrates faster voltage recovery after fault. Alternatively a reduction in generation power, and operation at unity or lagging power factor would potentially help improve stability. The analysis on Figure 4-38 shows the effect on respective voltage changes during the fault ride through capability of the Hydro generator plant. The generator analysis shown in Figure 4-38 reflects that voltage trace passing fault ride through is within the curve as required by the Grid Code. The greater fault ride through capability of the 5MW generator is due to the higher inertia of the bigger generator indicating the effect of the physical size of the machine on the capability of the generator to ride through network fault.

4.17 Voltage stability analysis - 22kV system

- The X/R ratio does have an effect on the voltage stability of the system
- A lower X/R ratio had a negative effect on the voltage stability margin
- A higher X/R ratio had a positive effect on the voltage stability margin
- An increase in hydro power penetration increased the stability margin

The simulation has been performed in PowerFactory software to understand the variation busbar voltage against X/R ratio for the MV lines feeding the Hydro Power Plant and the local loads. In this software the values of L and R of the distribution line have categorically selected and have been calculated using different X/R ratio in which the power from the generators has been injected. The Table 4-7 below describes the different values of X/R values calculated from the L and R distribution/MV lines against voltages at the PCC.

Table 4-7: Calculation of X/R values from L & R against voltages

L (H)	X (Ohms)	R (ohms)	X/R	V (Volts)
0.0001	0.0314	1	0.0314	410
0.0005	0.157	1	0.157	400
0.001	0.314	1	0.314	380
0.0012	0.3768	1	0.3768	345
0.005	1.57	1	1.57	240
0.01	3.14	1	3.14	190
0.1	15.7	1	15.7	173

Amount X and the amount R of the grid impedance can be calculated as,

Equation 4-5: X and R calculations **[32]**

- $X = \frac{Z}{\sqrt{1+\frac{1}{(XRR)^2}}}$
- $R = \frac{Z}{\sqrt{1+(XRR)^2}}$

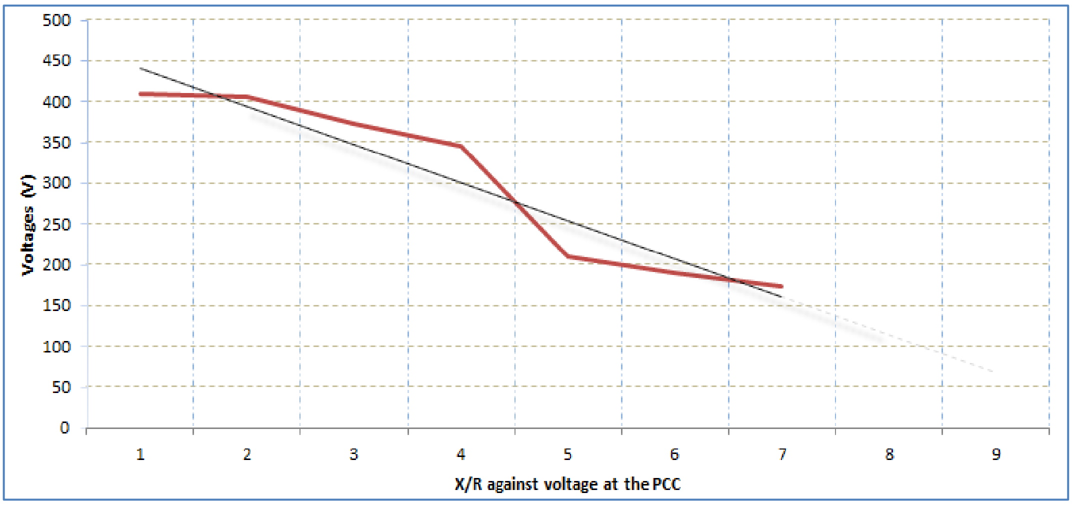


Figure 4-41: Curve for X/R ratio Vs Voltages

The curve plotted for the values of X/R against voltages ratio, it is observed that the higher the X/R ratio lowers the voltages. For higher values of the X/R ratio, there is also a high variation on the voltages. From the system stability point of view, the Figure 4-41 above clearly shows that for a distribution network with high X/R ratio the voltages reduces dramatically. When the X/R value is increased from 0.0314 to 0.3768 voltages drops from 410 to 380V.

4.18 Improving Transient Stability:

4.18.1 Transient stability is improved by the following:

- Decrease mechanical power
- Decrease the total reactance between the load and generator (i.e. more lines)
- Increase the load (this provides ‘braking’ force)
- Increase inertia (higher inertia means less angle deviation during fault)
- Increase excitation voltage (i.e. export more Q)

An illustration of the procedure for conducting transient stability studies in power factory is also explained in Appendix A.

4.19 Dynamic Studies Summary

The stability studies look at how a power system operates during disturbances. A common objective is to see how long the protection device can take to clear a fault before the generator becomes unstable. It can be observed that when there is insufficient time to clear a fault and excessive frequency variations, this poses an issue in stability. The major potential challenge is noticed when there is insufficient voltage recovery after transient events. This is clearly demonstrated in Figure 4-35 results, the stability is lost.

Due to the lack of generator control, the speed is not reduced and the only option is to disconnect the generator and reconnect after the system fault is cleared. It can thus be concluded that for the change in voltage, from the lower to the upper range of the selected transformer tap positions, the turbine will remain unstable for the 150ms fault.

It was also shown from the simulation results that an increase in hydro power penetration increased the stability margin but it did not affect the performance of the turbine types relative to each other. The disturbance causes high reactive power losses and voltage sags in loads areas. The fundamental cause of voltage instability is identified as incapability of combined transmission and generation system to meet excessive load demand in either real power or reactive power form generation. The key concepts of voltage stability are the load characteristics as seen from the bulk power network. The available means for voltage control at generators and in the network the ability of network is to transfer power particularly reactive power from the point of production to the point of consumption.

4.20 Protection Data Analysis

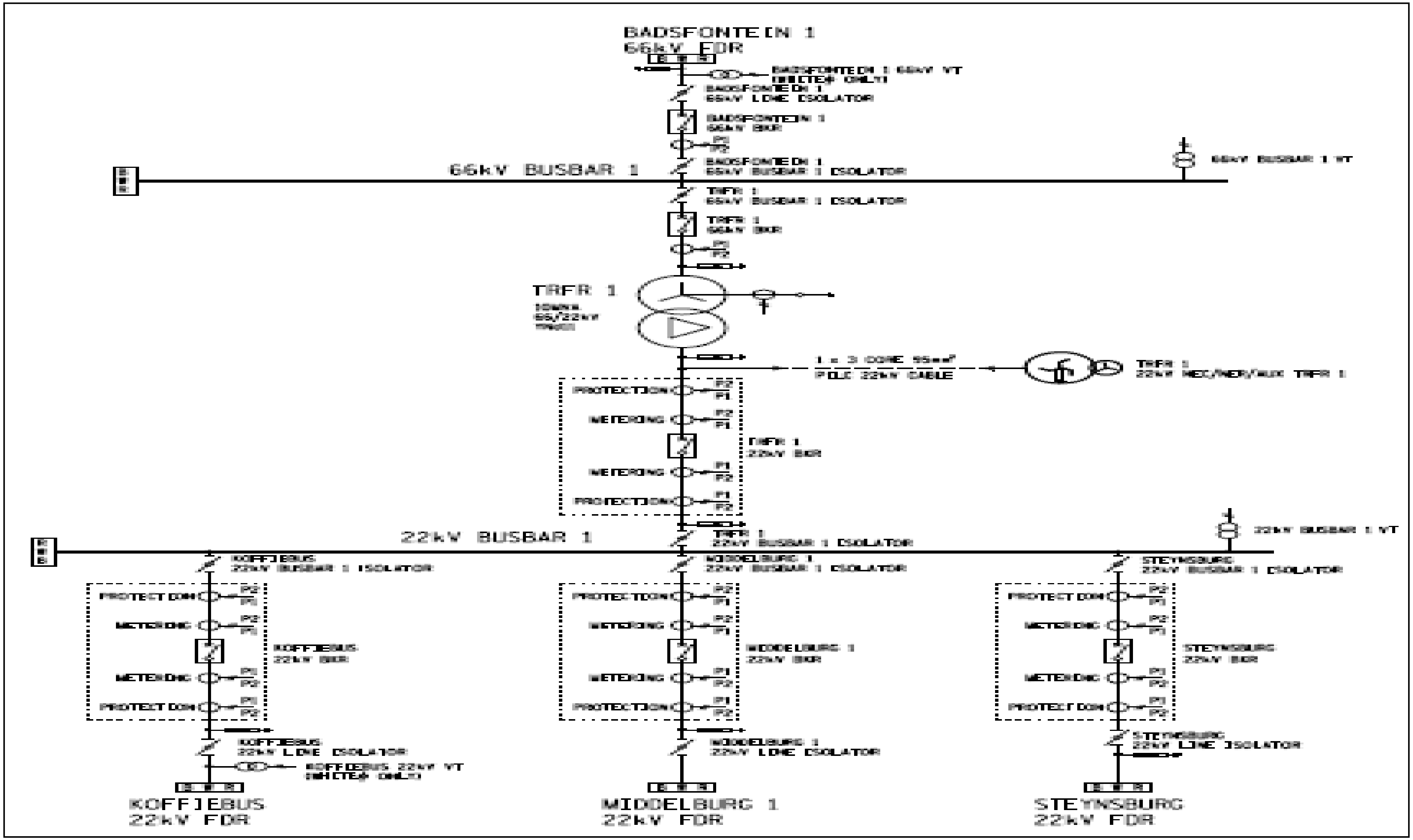


Figure 4-42: New Bulhoek substation schematic layout with protection equipment

The above Figure 4-42 shows the proposed control plant (secondary equipment) plan in terms of the protection after connecting the Teebus Hydro Plant. This section will demonstrate the protection scheme used in this system. This is achieved by adding relays and their associated instruments transformers at the appropriate places within the network model. The 22kV feeders will be protected by the SEL-351S and the 66kV will protected by 4FZD 3920 three-pole distance/differential feeder protection scheme. This scheme offers distance/differential protection (RED670) and the directional back-up protection O/C and E/F (REF615). For 66kV buszone single busbar, a high impedance buszone protection scheme will be used since it consists of a F35 relay which offers two zone protection with a check zone for a single busbar with bus-section breaker. This will ensure fast selective protection for buszone faults.

The protection schemes shall be matched to provide the inter-tripping between Badsfontein and Bulhoek substation. **Note:** The islanding is not catered for; the protection is set in such a way that whenever the fault is experienced the generation will be curtailed or switched off completely. In terms of the protection, once the system goes to Islanding the protection will be able to disconnect the energised area with synch check mechanism.

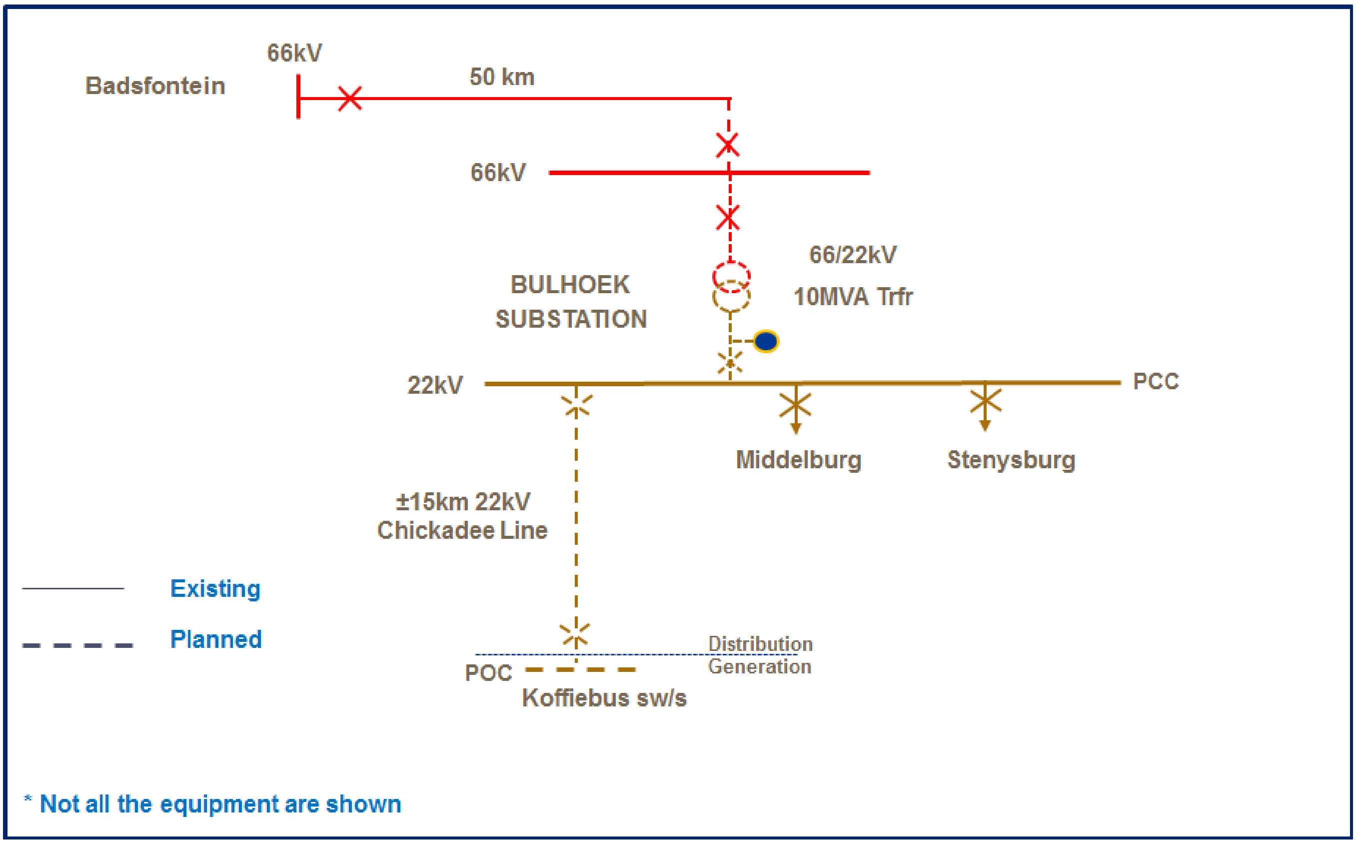


Figure 4-43: New Bulhoek substation schematic layout

Figure 4-43 depicts the proposed new line where the new Hydro plant will be connected. It also shows the changes that will take place due to the additional power i.e. transformer upgrade. Preliminary relays settings are calculated based on the information obtained from power flow, stability and short circuit studies.

The existing Current Transformer ration at the secondary side of the transformer: CT ratio = 400/1A

The formula to determine Plug Setting Multiplier is as follows:

$$Current\ setting = \frac{Pick\ up\ current}{Rated\ secondary\ cuurent} \times 100\%$$

Note: Current setting for current relay generally ranges between 50% to 200%, in steps of 25% and for earth fault if ranges from 10 to 70%, in steps of 10%. Time Setting Multiple (TSM) ranges from 0.5 to 1pu in steps of 0.01pu or in steps of 0.05pu depending on the relay.

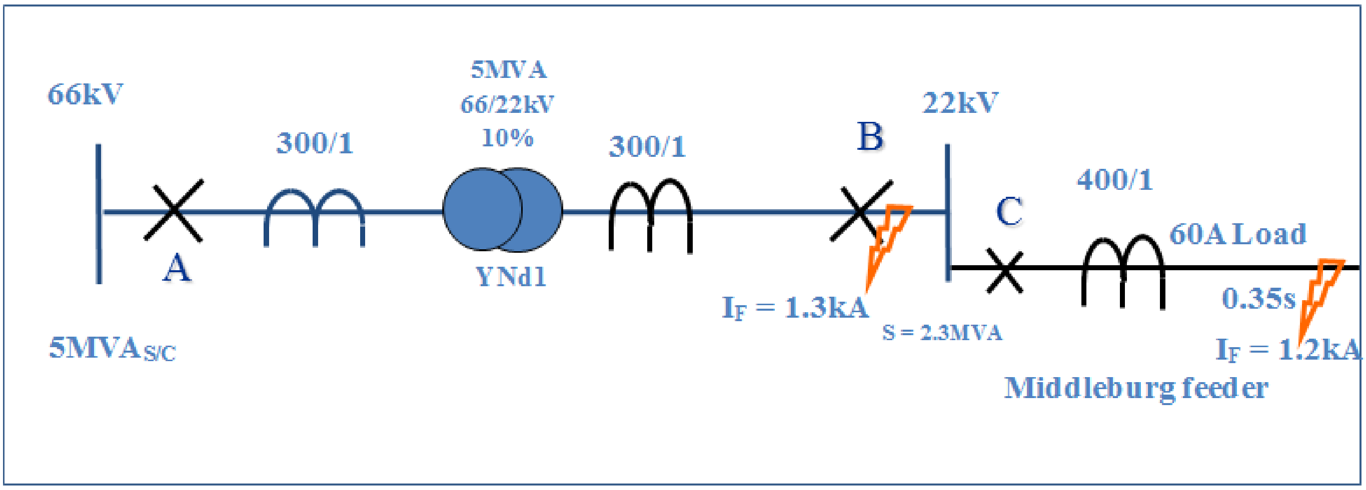


Figure 4-44: Existing Bulhoek/Middleburg coordination (Equivalent cct)

These calculations are for the relay settings for an existing Bulhoek/Middleburg 22kV feeder.

With Respect To (W.R.T) breaker C;

Equation 4-6: Relay setting calculation equations

$I_F = 1200A,\qquad T_{req} = 0.35sec$
I_L= 60A

$$PS = \frac{60\ X\ 1.2}{400} = 0.18pu \rightarrow Choose\ 50\%\ (Min)$$

$$Effective\ Settings\ (ES) = PBS \times CTprimary\ rating$$
$$ES = 0.5 \times 400$$

Ensure this is above the Max load current = 200A

$$PSM = \frac{1200\ X\ 1}{400 \times 0.5} = 6\text{pu}$$

$$TSM = \frac{0.35\ X\ (6^{0.02} - 1)}{0.14} = 0.09$$

$$Actual\ Trip\ time = \frac{0.09X\ 0.14}{(6^{0.02} - 1)} = 0.35sec$$

W.R.T breaker B, trfr, 5MVA;

$I_F = 1200A, \qquad T_{req} = 0.35 + 0.5 = 0.85\,\text{sec}\ (the\ next\ upstream\ relay\ is\ delayed\ by\ 0.5s)$

$IL = \frac{5\times10^6}{\sqrt{3}\times22\times10^3} = 131A$

$$PS = \frac{131\ X\ 1.2}{300} = 0.524 \rightarrow Choose\ 75\%$$

$$PSM = \frac{1200\ X\ 1}{300 \times 0.75} = 5.33$$

$$TSM = \frac{0.75\ X\ (5.33^{0.02} - 1)}{0.14} = 0.18, choose\ 0.2$$

$$Actual\ Trip\ time = \frac{0.2X\ 0.14}{(5.33^{0.02} - 1)} = 0.823sec$$

Note: Relay A is required to be graded with relay B with the fault current of 1200A @ breaker C

$I_F = 1200A, \qquad T_{req} = 0.823 + 0.5 = 1.323sec$
I_L= 140A

$$PS = \frac{140\ X\ 1.2}{300} = 0.564 \rightarrow Choose\ 75\%$$

$$PSM = \frac{1200 \times 1}{300 \times 0.75} = 5.33$$

Feeder breaker must trip in 0.823 + 0.5sec = 1.323sec

$Stndard\ Inverse\ (SI): TM = \frac{01.323\times(5.33^{0.02}-1)}{0.14}$ = 0.32, choose 0.3

TMS = $Actual\ Trip\ Time = \frac{0.3\times0.14}{5.33^{0.02}-1}$ = 1.234Sec

These calculations are for the relay settings for an existing Bulhoek/Steynsburg 22kV feeder.

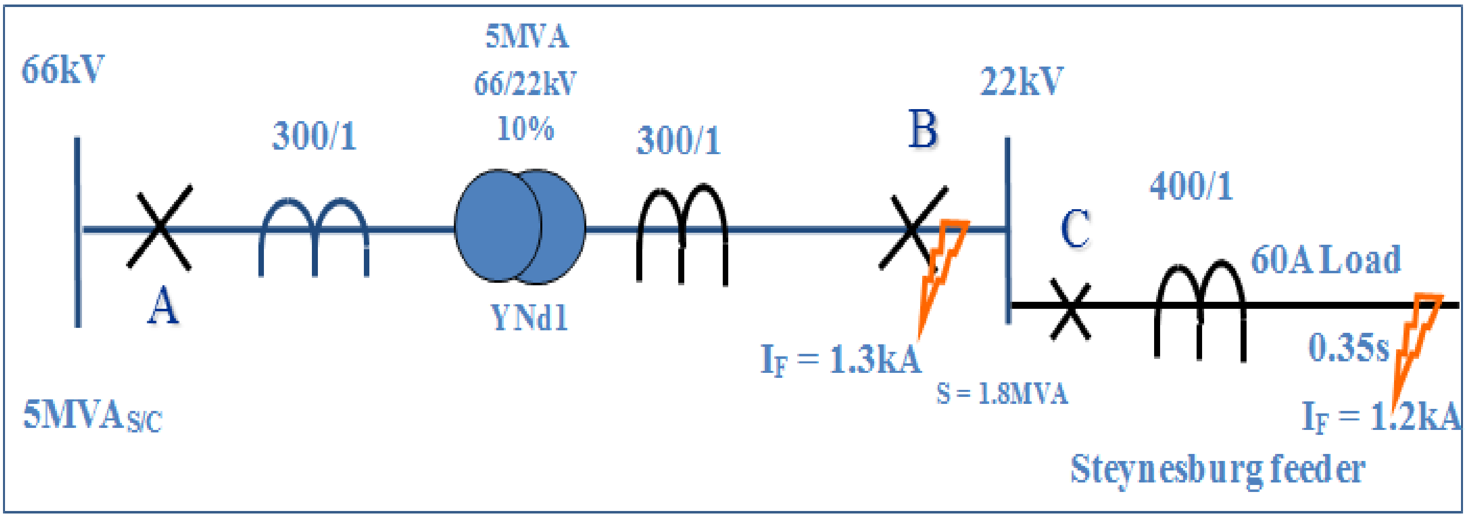


Figure 4-45: Existing Bulhoek/Steynesburg22kV coordination (Equivalent cct)

W.R.T breaker C;

$I_F = 1200A, \qquad T_{req} = 0.35sec$

$I_L = \frac{1.8\times10^6}{\sqrt{3}\times22\times10^3} = 47A$ 60A

$$PS = \frac{47\ X\ 1.2}{400} = 0.14 \rightarrow Choose\ 50\%\ (Min)$$

$$Effective\ Settings\ (ES) = PBS \times CTpru$$

$$PSM = \frac{1200\ X\ 1}{400\times0.5} = 6\text{pu}$$

$$TSM = \frac{0.35\ X\ (6^{0.02}-1)}{0.14} = 0.09$$

$$Actual\ Trip\ time = \frac{0.09X\ 0.14}{(6^{0.02}-1)} = 0.35sec$$

W.R.T breaker B, trfr, 5MVA;

$I_F = 1200A, \qquad T_{req} = 0.35 + 0.5 = 0.85sec$

$I_L = \frac{5\times10^6}{\sqrt{3}\times22\times10^3} = 131A$

$$PS = \frac{131\ X\ 1.2}{300} = 0.524 \rightarrow Choose\ 75\%$$

$$PSM = \frac{1200\ X\ 1}{300\times0.75} = 5.33$$

$$TSM = \frac{0.75\ X\ (5.33^{0.02}-1)}{0.14} = 0.18, choose\ 0.2$$

$$Actual\ Trip\ time = \frac{0.2X\ 0.14}{(5.33^{0.02} - 1)} = 0.823sec$$

Note: Relay A is required to be graded with relay B with the fault current of 1200A @ breaker C

$I_F = 1200A, \qquad T_{req} = 0.823 + 0.5 = 1.323sec$
I_L= 140A

$$PS = \frac{140\ X\ 1.2}{300} = 0.564 \rightarrow Choose\ 75\%$$

$$PSM = \frac{1200 \times 1}{300 \times 0.75} = 5.33$$

Feeder breaker must trip in 0.823 + 0.5sec = 1.323sec

$TM = \frac{01.323 \times (5.33^{0.02} - 1)}{0.14}$ = 0.32, choose 0.3

TMS = $Actual\ Trip\ Time = \frac{0.3 \times 0.14}{5.33^{0.02} - 1}$ = 1.234Sec

From the above calculation it can be noted that the grading margin used is slightly more than the recommended minimum of 0.4 to ensure the correct tripping sequence whilst maintaining optimum sensitivity of each relay.

These calculations are for the relay settings for existing new feeder Bulhoek/Teebus 22kV feeder.

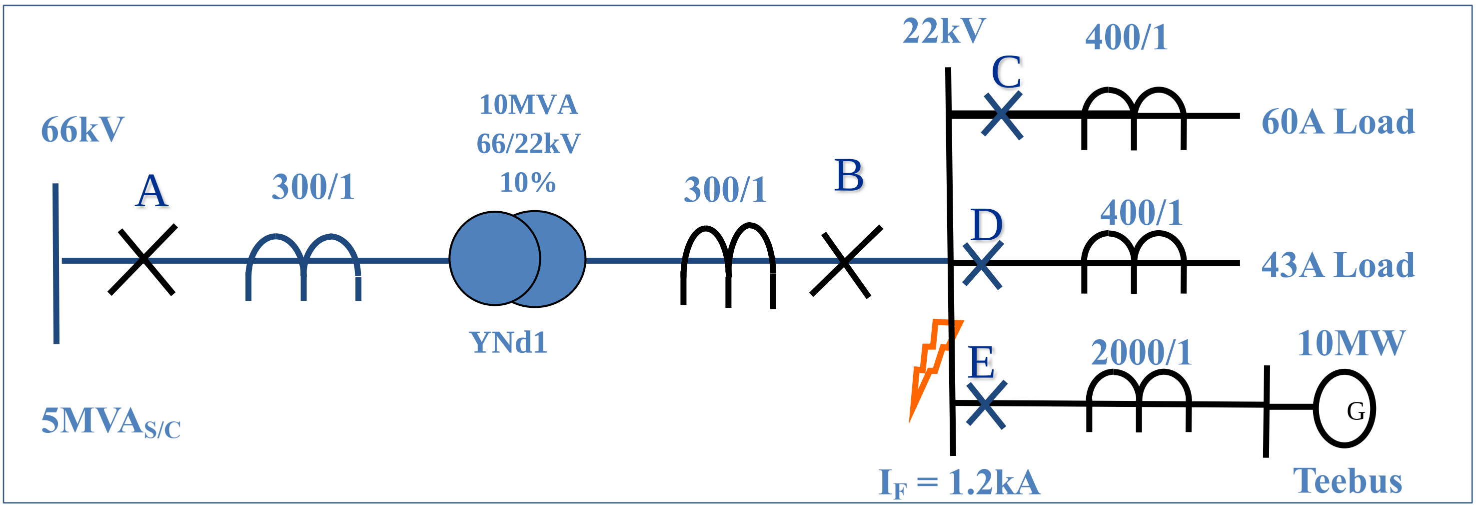


Figure 4-46: Existing Bulhoek/Teebus22kV coordination (Equivalent cct)

With regards to breaker E, generator, 11kV, 10MVA, 90%, 0.75

$$\mu = \frac{P_o}{P_i} = \frac{10 \times 10^6}{P_i}$$

$$P_i = \frac{10MW}{0.9} = 11.1MW$$

$I_L = \frac{11.1\times10^6}{\sqrt{3}\times11\times0.75} = 777.58A$

Instantaneous = 6 X I = 4.67kA, Direct on Line starter

Note: Maximum time allowed for end user to clear fault = 1.5s

$$PS = \frac{4665}{2000} = 2.33 \rightarrow Choose\ 200\%$$

$$PSM = \frac{4665 \times 1}{2000 \times 2} = 11.66pu$$

TMS = $Actual\ Trip\ Time = \frac{0.14}{11.6^{0.02}-1}$ = 2.8Sec

If relay E must allow 0.2s for a generator terminal:

$$TMS = \frac{Tdesire}{t(TSM-1)} = \frac{0.2}{2.8} = 0.071pu$$

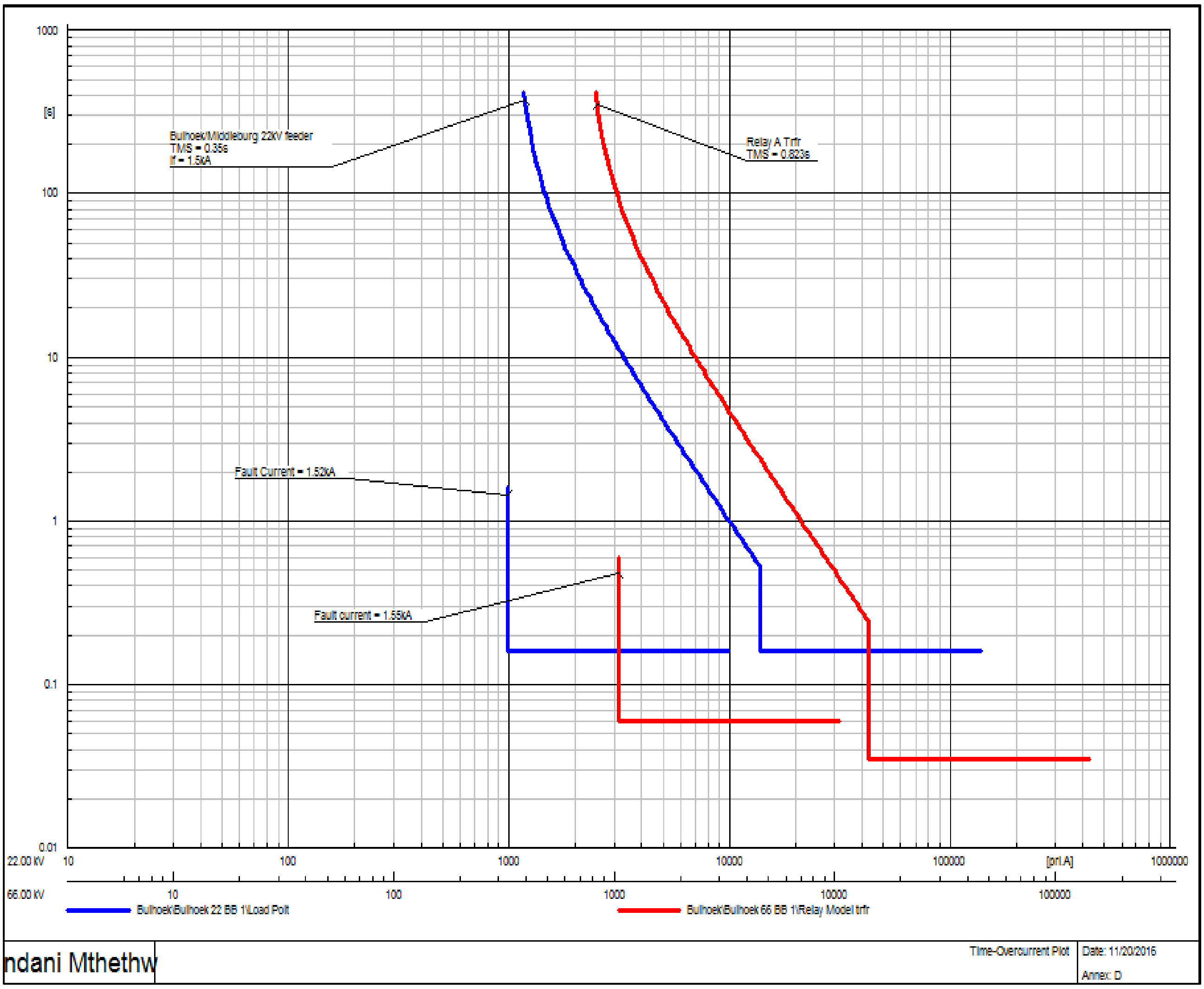


Figure 4-47: Bulhoek/Middleburg 22kV line and Relay at the trfr

4.21 Overcurrent Relay Ratings

Voltage Rating: The voltage rating of the overcurrent protective device is set to be at least equal to or greater than the circuit voltage. The overcurrent protective device rating can be higher than the system voltage but never lower.

Ampere Rating: The ampere rating of a overcurrent protecting device does not exceed the current carrying capacity of the conductors As a general rule, the ampere rating of a overcurrent protecting device is selected at 125% of the continuous load current.

4.22 Performance Data Analysis

The six major component failures of overhead lines were used as an input to analyse the performance based on failure rates. The following table shows the failure rates of these six components for the entire Bulhoek/Middleburg MV overhead line.

The equipment that exceed their design failure rate and/or contributed total of 80% to SAIDI impact are regarded as major contributors for the purpose of root cause analysis. These are:

- Conductor
- Isolator
- Jumper
- Transformer
- Transients

Table 4-8: MV Network Components Failures Rates

	Structure failures	Conductor failures	Jumper failures	Trfr failures	Isolator failures	Insulator failures
Actual failure Count	**3**	**5**	**5**	**9**	**6**	**1**
Actual failure rate	**0.11%**	**2.09%**	**0.12%**	**3.24%**	**1.95%**	**0.01%**
Designed failure rate	**0.10%**	**2.50%**	**0.10%**	**2.00%**	**0.15%**	**0.01%**
Design Failures Count	**3**	**6**	**4**	**6**	**0**	**1**

The Table 4-8 shows the performance of the six components on the whole network. Three structures, conductors & insulators; performed good well (80%-120%) and the other three jumpers, transformers & isolators, performed badly (>160%). This data will be included in the annexure at the end of the document.

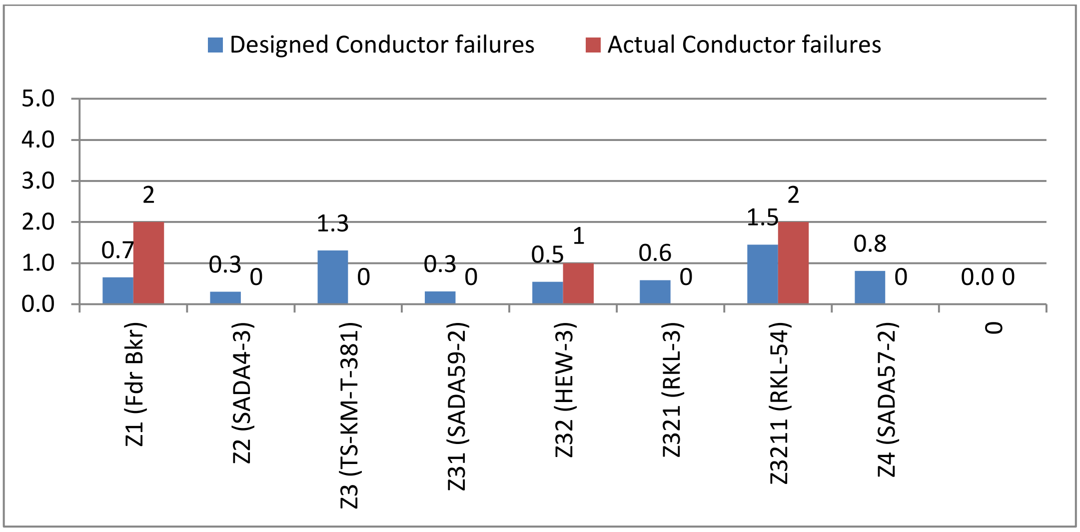


Figure 4-48: Conductor Failure Rates

4.23 Summary of the types of simulation studies:

Table 4-9: Summarizes the types of simulation studies

Simulation Type	Description/Purpose	Potential issues detected	Data Required
Load Flow	Load flow analysis checks that a generator can produce any level of power during any feasible loading condition placed on the power system, without being constrained by the operating limits of the power system. Contingency events such as the planned or unplanned outage of major electrical equipment are studied comprehensively to check what generation operating constraints will apply during the contingency	• Over/under voltages. • Overloading. • Adequate active and reactive power reserves. • Operational constraints/precautions required	Single-line diagram showing major transformers, bus names, voltage levels, lines/cables/other electrical equipment and point of connection to transmission system, as well as local network. Resistance and reactance data for all major equipment in the modelled network. This includes line lengths. Size of generator(s) and operating limits. Rated current, voltage range of existing and proposed electrical equipment. Load size in active and reactive power. Information on voltage and tapping control.
Short Circuit	Short-circuit analysis serves the following purposes: • Allowing the current trigger level of protection relays to be accurately set. • Ensuring electrical equipment is adequately rated to handle fault current. • Providing information required to	• Fault rating of connected equipment exceeded.	Complete set of load flow data. Zero sequence impedance for all equipment (necessary for earth faults). Generation and load sub-transient reactance values. Earthing details for transformers, generators and other miscellaneous electrical equipment.

Simulation Type	Description/Purpose	Potential issues detected	Data Required
	design the earthing system.		
Stability Studies	Stability studies look at how a power system operates during disturbances. A common objective is to see how long a protection device can take to clear a fault before the generator (and possibly the surrounding power system) becomes unstable. Stability studies also aid in fine-tuning the generation control systems that manage power transfer.	• Insufficient time to clear a fault. • Frequent interruptions to power transfer caused by unplanned generator/equipment outage. • Unwanted or poorly damped power transfer fluctuations and oscillations arising from control system conflicts. • Excessive frequency variations. • Insufficient voltage recovery after transient events.	Complete set of data including: Load Flow and Fault Level Data. Generation and load sub-transient reactance values and time constants, and other modelling parameters. Mechanical constants and physical properties for the generator and loads. Block diagram outlining the logic used to control the generator's real and reactive power output. A model of the generator and control scheme suitable for operating on any PSA software.

During the load flow analysis it was found that the power produced by the two generators increases the voltages, fault levels and positive effect on the transient stability of the system. It is critical that the fault level and voltages are below the allowable limits stipulated in the NRS 048-2 Standard. The equipment's fault current rating limit must be adhered to in order to ensure that the electrical equipment is adequately rated to handle fault current. The stability studies have demonstrated how the system behaves when it is exposed to system faults. It further explained the applicability of small STATCOM to recover the system during contingency. The stability studies also helped in fine-tuning the generation reactive power control and the amount of power transfer.

Connecting generators to a utility network have huge impact on the performance and operation of the network. The impact of the generators depends on the characteristics of the generator, the size of the generator and the location where the generator is connected. When an increase in the thermal rating of main circuit equipment is required, a review of associated protection equipment is necessary to ensure that the desired rating is achieved.

Chapter 5. CONCLUSIONS and FUTURE RECOMMENDATIONS

5.1 Conclusion

This report discusses several key issues regarding the development and integrating small Hydro Power plant into the existing electrical utility distribution unbalanced system with a focus on the instability and the quality of supply problems.

With the power flow analysis and study done it can be concluded that the customers taking LV supply can connect generators up to 350kW. Customers with generator sizes > 350 kW shall take supply at MV or HV. This is due to the very low fault levels on the LV network and the conductor sizes used.

With the studies done in this paper, all the small potential IPPs can be accommodated after the strengthening of the MV network. It has been evident (Figure 4-30 and Figure 4-33) that the more generators on the network the better the voltage unbalance and the voltage stability as well as rapid voltage change. The existing Bulhoek network is limited to about additional 10MW. For any additional unknown generation, the option of building a new substation fed from the traction network would be feasible. Further network analysis is required.

Most of the findings from the simulations were consistent with what was expected when comparing with other literatures. From the simulation results it was seen that the performance of the variable speed generators were superior to that of the fixed speed generators during transient conditions. It was also seen that the weakness of the network had a negative effect on the stability of the system.

It is also noted that the stability studies are a necessity when connecting the generators to a network and that each case should be reviewed individually. The fundamental cause of voltage instability is identified as incapability of combined distribution and generation system to meet excessive load demand in either real power or reactive power form.

From the above Chapters, it can be concluded that the presence of small hydro generators on the distribution level will have a positive effect on the transient stability of the system.

It is important to note that the generation supplies loads that would otherwise be supplied by the utility network. From a voltage change perspective, it does not matter how much of the generation is consumed locally or fed back into the network. When the generation output changes, the loading in the utility network changes accordingly, as the utility network supplies loads that would have been supplied by the Hydro generator.

Islanding of the DG is not allowed in South Africa. In cases where the Hydro plant connects to a distribution network with low voltage problems or where voltage support becomes a problem during periods of high load demand, the generation could be used to assist in reactive power generation for voltage regulation.

Relay coordination analysis was done considering three phase faults, phase to phase faults and single phase to ground faults. Protection analysis was performed in DigSilent (PowerFactory) and manual calculations were done. The results show that the CBs and relay time settings are required to be changed to be able to detect and isolate the faulty section.

From the literature reviews it can also be concluded that not all the problems regarding the connection of distributed generation have been addressed completely. International research and Grid Code specifications are focussed on networks with strong interconnection and voltage support and these conditions might not be true for the South African grid.

The impact of generators connected to the grid depends on how the generating plant is designed, and how the design is influenced by the South African Grid Code requirements. Hence the impact will depend on the Grid Codes. More stringent Codes result in generators having less network impacts. In this way, most generators support the grid, rather than create problems for the grid. The minimum technical requirements for the generating plant are specified in the relevant codes.

Connecting generators to a utility network have huge impact on the performance and operation of the network. The impact of the generators depends on the characteristics of the generator, the size of the generator and the location where the generator is connected (a strong or a weak network).

Although it is unlikely that the existing hydropower potential in South Africa will be ever fully exploited, small decentralized hydro power stations could play a role in supplying electricity to Rural Areas. In a number of cases the basic infrastructure is already in place and the low ecological impact as well as the economic effects due to the possible large contribution of the South African industry would be speaking in favour of the development of the small hydro potential.

5.2 Future Development and Recommendations

The study original focused on connecting the small Hydro plants on the already unbalanced distribution networks with the traction network linked to it. In this case it is necessary to evaluate the impact of the movement of each train while the generation is also in service. The detailed study is still need to be conducted to determine the method that will alleviate voltage unbalance using a time based STATCOM. This remain a major challenge encountered by Eskom engineers as there are scarce skills of conducting quality of supply studies on traction lines.

The other challenge is that the traction loads on the existing 132kV traction system does not reflect the actual configuration on site. The first step for future investigation is to ensure that each traction substation’s phasing is correct. The modelling of the loads at each site will also need to be updated. The vectorgrapher voltage unbalance measuring tool is required to be installed so that accurate QOS indication can be archived. The data recording system and the protection schemes on various substations should be revamped.

The supply to Bulhoek substation need to be made firm to avoid the system switching to islanding mode. The Teebus Hydro project will contribute to sustainable development in South Africa through supporting the development of renewable energy in the country and support Eskom’s aspiration for renewable energy.

Chapter 6. LIST OF SOURCES AND REFERENCES

[1] W. J.K, “Small hydropower in Southern Africa – an overview of five countries in the region,” *Energy in Southern Africa*, 2013.

[2] B. Barta, “Renewable energy:Hydropower,” in *The Sustainable Energy Resource Handbook*, vol. Volume 2, Cape Town, Wetern Cape: Alive2green, 2011, pp. 139-139-151.

[3] W. J Klunne, Small hydropower in Southern Africa – an overview of five countries in the region, Johannesburg: CSIR, 2013.

[4] M. T. Joemat-Pettersson, “State of Renewable Energy,” Department of Energy, Pretoria, 2015.

[5] J. M. Solanki, “Voltage Stability,” in *Ph.D. Seminar*, Indian Institute of Technology, Bombay, 2013.

[6] W. K. J.G Slootweg, “Aggregated Modelling of Wind Parks in Power System Dynamic Simulations,” IEEE Power Tech Conference, Bologne, 2003.

[7] Slootweg J, “Impacts of Distributed Generation on Power System Transient Stability,” in *Power Engineering Society Summer Meeting*, IEEE 2002.

[8] M. M, “Line Distance Protection up to and Including 132kV,” Eskom, Johannesburg, Megga Watt, 2014.

[9] C. D.C, “Protecciones Eléctricas. Notas de Clase,” in *Universidad Industrial de Santander.*, Santander, 2007.

[10] H. X. Wenxia Liu, “Optimal Distributed Generator Allocation Method Considering Voltage Control Cost,” in *Small-scale distributed generation*, Beijing, China, 2016.

[11] L. Esser, “A global overview. Water Power & Dam Construction,” 2012.

[12] Eskom, “Eskom heritage: Electricity in South Africa – the early years.,” 2009. [Online]. Available: http://heritage.eskom.co.za/heritage/electricity_in_south_africa.htm (February 29, 2012)..

[13] Mckenzie M, “Existing Hydro Power In South Africa,” 22 Februay 2012. [Online]. Available: http://urbanearth.co.za/articles/existing-hydropower-south-africa.

[14] A. N. H Knudsen, “Modelling and transient stability of large wind farm,” vol. 25, no. 1, 2003.

[15] M. Rani, “An Improved Rotor PLL (R-PLL) for Enhanced Operation of Doubly Fed Induction Machine,” Kerala, India, 2015.

[16] R, Anagha, “Comparison of various Wind Turbine Generators,” *Multidisciplinary Journal of Research in Engineering and Technology*, vol. 1, no. 2, pp. 129-135, 2016.

[17] B. A., “Existing small hydro in South Africa,” 09 March 2012. [Online]. Available: http://urbanearth.co.za/articles/existing-small-hydro-south-africa. [Accessed 09 March 2012].

[18] K. Jia, “An Islanding Detection Method for Multi-DG Systems Based on High-Frequency Impedance Estimation,” *An Islanding Detection Method for Multi-DG Systems Based* , vol. 8, no. 1, p. 158, 2017.

[19] K. UN, “Distributed Generation and Power Quality,” 2009.

[20] J. A. Martin-Arnedo, “Impacts of Distributed Generation on Protection and Power Quality,” 2009.

[21] J. M. J.Holmes, “Protection of Electricity Distribution Networks,” in *Power and Energy Series 47.*, United Kingdom, 2004.

[22] C. A. G. P. B. M. Van Zyl SJ, “COMBINED SPECIFICATION FOR BUS COUPLER, MEDIUM VOLTAGE DISTRIBUTION FEEDER AND EMBEDDED GENERATOR INTERCONNECTION PROTECTION SCHEMES,” ESKOM, Johanneseburg, 2010.

[23] Q. B, “Specification for Transmission and Distribution protection Schemes: Transformer and Reators,” Eskom, Johannesburg, Megga Watt, 2014.

[24] M. CR, “The Art & Science of Protective Relaying,” in *GE Energy Industrial Solutions*, 2007.

[25] Dr Cater Brown, Baic Power System Protection, Johannesburg: Eskom Center of Excellence, 2001.

[26] R. R. Chiradeja, “An Approach to Quantify the Technical Benefits of Distributed Generation,” U.S, 2005.

[27] K. H. SALEH, "Transient Stability Improvement in multi-machine system with using power system stabilizer (PSS) and Static Var compensator (SVC)," in *17th International Conference, ICEESE 2015,* Istanbul , Turkey, 2015.

[28] P. G. Arunkumar, “Power System Stability Enhancement using FACTS Controllers,” IEEE, 2012.

[29] S. Zyl, “A GENERALISED APPROACH TO EVALUATING VOLTAGE RISE IN NETWORKS EQUIPPED WITH DISTRIBUTED GENERATION,” March 2004.

[30] K. W. Slootweg J, “ Impacts of Distributed Generation on Power System Transient Stability,” in *Power Engineering Society Summer Meeting IEEE*, 2002.

[31] M. Klopper, Stability Analysis of Distributed Wind Generation Operating on Weak Distribution Networks in the Presence of Hydro Generation, South Africa: University of Cape Town, 2011.

[32] K. P, “Future GB Power System Stability Challenges and Modelling,” *The Institition of Engineering and Technology,* p. 11, March 2015.

[33] J. Vu Van Thong, “Interconnection of Distributed Generators and Their Influences on Power System,” Katholieke Univeristeit Leuven, Belgium., 2004.

[34] D. Powerfactory, “Integrated Power Systems Analysis Software, Product Information,,” Digsilent, Gomaringen, September 2002.

[35] C. S. a. K. Manohar, “A Case Study on Power Quality Issues in the Indian Railway Traction Sub-Station,” in *Proceedings of7'h International Conference on Intelligent Systems and Control (ISCO 2013)*, India, 2013.

[36] R. B. a. R. N. Allan, “Reliability Evaluation of Power Systems,” London (New York), 1984.

[37] G. Gentles, “Provision of basic lighting in schools in non-electrified areas of South Africa,” in *Use of Electrical Energy Conference 1998*, 1998.

[38] M. J. Vittal E, “Wind Penetration Limited by Thermal Constraints and Frequency Stability,” in *Power Symposium*, 2007.

[39] B. A. L. S. Barta, “Renewable energy:Hydropower,” in *The Sustainable Energy Resource Handbook*, vol. Volume 2, Cape Town, Wetern Cape: Alive2green, 2011, pp. 139-139-151.

[40] C. A, “The power quality concern in railway electrification studies,” UniversitA di Roma “La Sapienza", ITALY, 2012.

6.1 ESKOM NATIONAL AND DIVISIONAL DOCUMENTS

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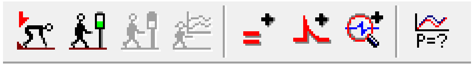
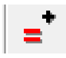
Table 6-1: Eskom national and divisional documents

	Document number	Document title	Preparer/author	Revision or date of issue
[41]	NRS 048-2	Electricity supply – quality of supply	NERSA	2006
[42]	NRS 097-2-1	Utility interface document for small scale generators	NERSA	Latest
[43]	34-1408	Network planning guideline for electrical motors	Eskom	Latest
[44]	34-542	Distribution voltage regulation and apportionment limits	Eskom	Latest
[45]	34-1765	Embedded generators interconnection guideline	Eskom	Latest
[46]	DST 240-46263934	Eskom standard on sharing Eskom Network Information for Generation grid integration	Eskom	Latest
[47]	Sep-32	Definition of Eskom documents	Eskom	Latest
[48]	DGL 34-618	Network Planning Guideline for Voltage Technology and Phasing	Eskom	Latest
[49]		South African renewable generation grid code	NERSA	Latest
[50]	Version 2.8	South African renewable generation grid code	Grid Code	Jul-14
[51]	DST 240-76613395	Planning standard for Distribution network Reliability to ensure Distribution network Code Compliance	Eskom	Feb-15
[52]	DST 240-82534300	Distribution Network Operations Planning (DNOP) Standard	Eskom	Feb-15
[53]	240-71905980	Advanced Distribution Automation Application Design Guide	Eskom	March-14

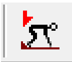
Appendix A - Conducting Transient Stability Studies

a) Conducting Transient Stability Steps

i. Locate RMS/EMT simulation button ranges 

ii. Define your variables/signals to be monitored from each element. 

iii. Setup your events (faults, parameter change etc) 

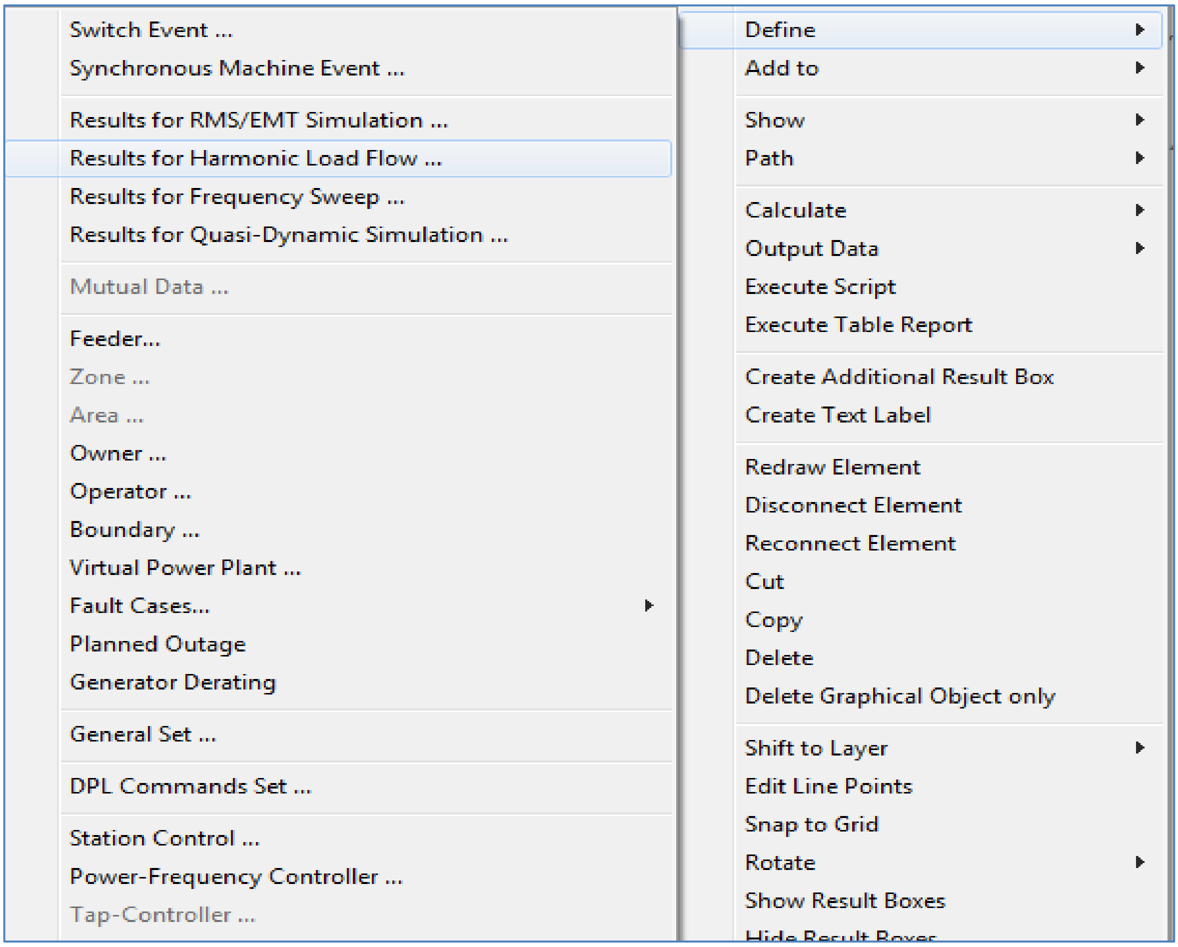
iv. Initialise the simulation 

v. Check the output window for messages

vi. Run simulation for pre-defined period 

vii. Visualise your results (create graphs/plots) 

b) Variable defination: PowerFactory defines some ‘default’ values



A.1 Defining the variables

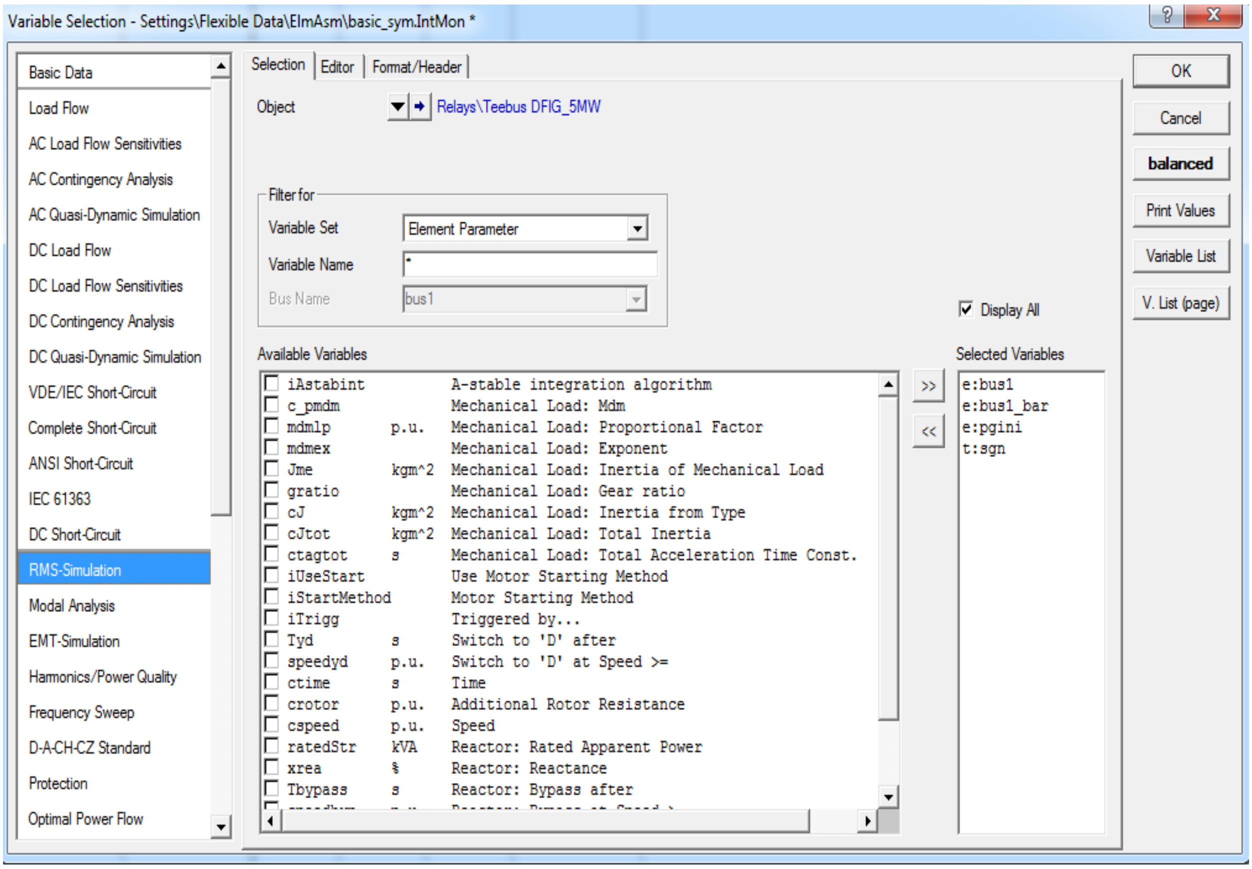
c) Variable defination using power factory default approach

Double click on the generator

	Name	Grid	Type TypSym	Terminal Substation	Terminal	Zone	Area	Out of Service	Par.no.
	11 kV 10MVA Hydro Mac	Relays	5 MVA Hydro SG		Teebus Hydr			☑	2
	50MVA Hydro Machine	Relays	Gariep Ruigtevalle		11kV LV			☐	1
	Gariep Ruigtevallei 2	Relays	Gariep Ruigtevalle		11kV LV(2)			☐	1
	Gariep Ruigtevallei 3	Relays	Gariep Ruigtevalle		11kV LV(3)			☐	1
	Gariep Ruigtevallei 4	Relays	Gariep Ruigtevalle		11kV LV(4)			☑	1
	teebus 11 kV 10MVA Hy	Relays	5 MVA Hydro SG		11kV LV(1)			☐	2

A.2 Checking the elements for the defined variables

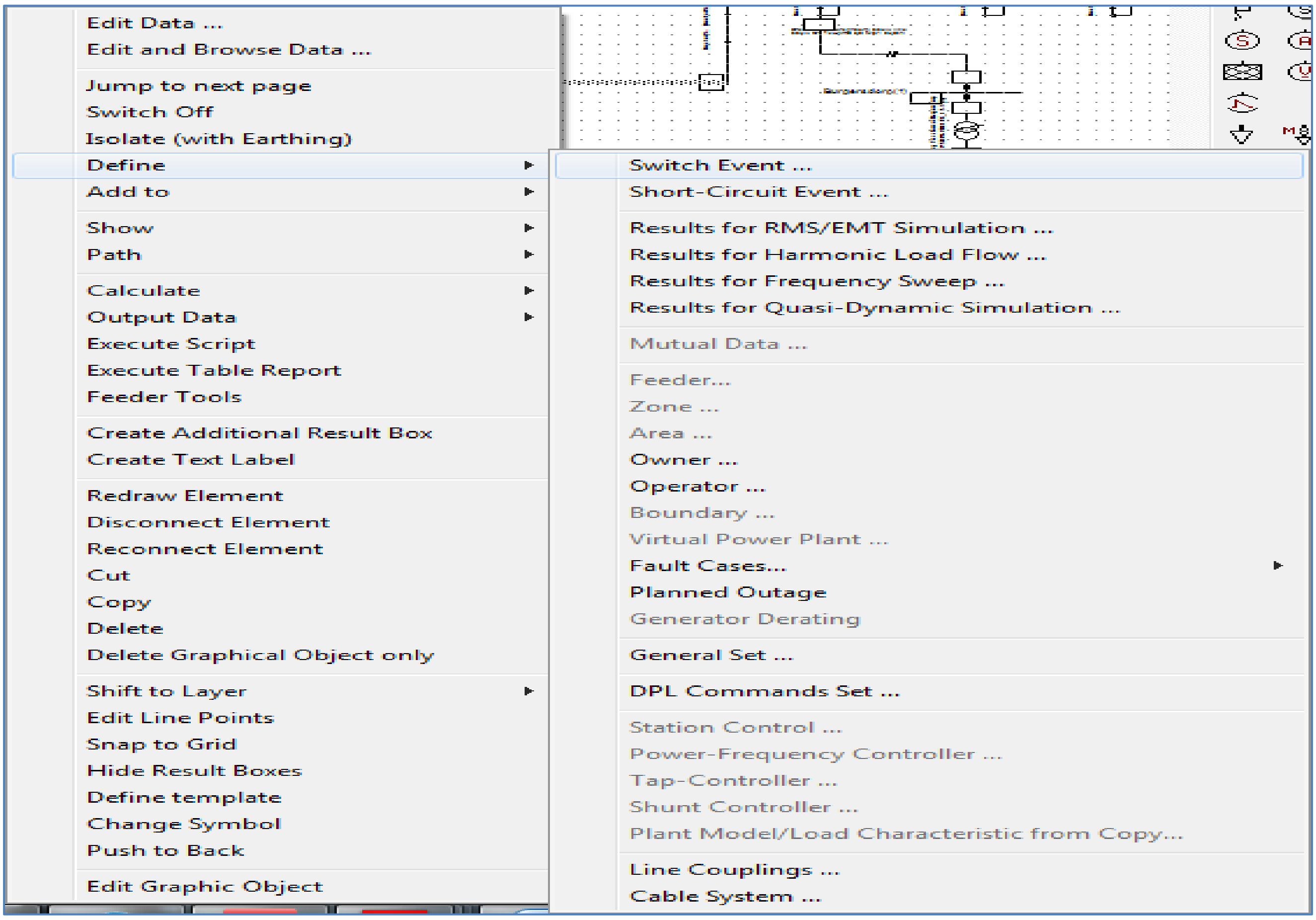
d) So that the appropriate variables can be selected as shown below



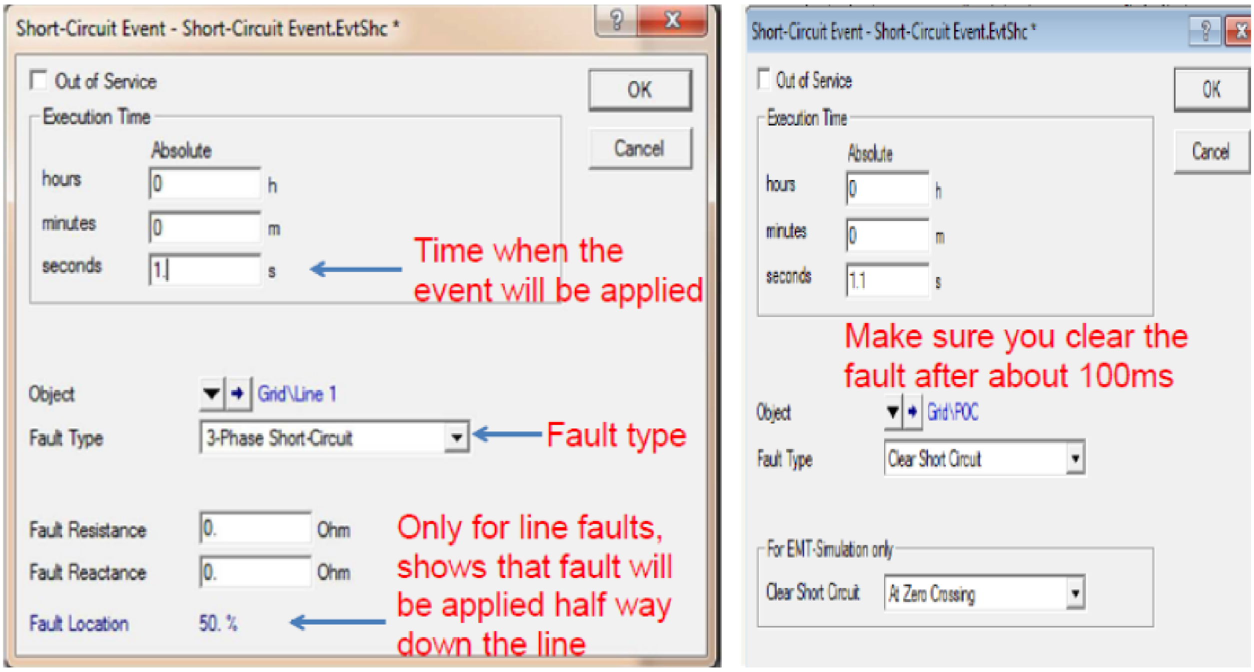
A.3 Checking and selecting the default defined variables by PowerFactory

e) Setting up your events (such as faults, tripping a line, parameter change etc)

i) Right-click on the element i.e. line that you want the event on and Select 'Define…' 'Short- Circuit Event'.
ii) Define a fault event e.g. apply a 3-phase fault, then allocate a time to start the fault
iii) Define another event to clear the fault, then allocate a time to clear the fault



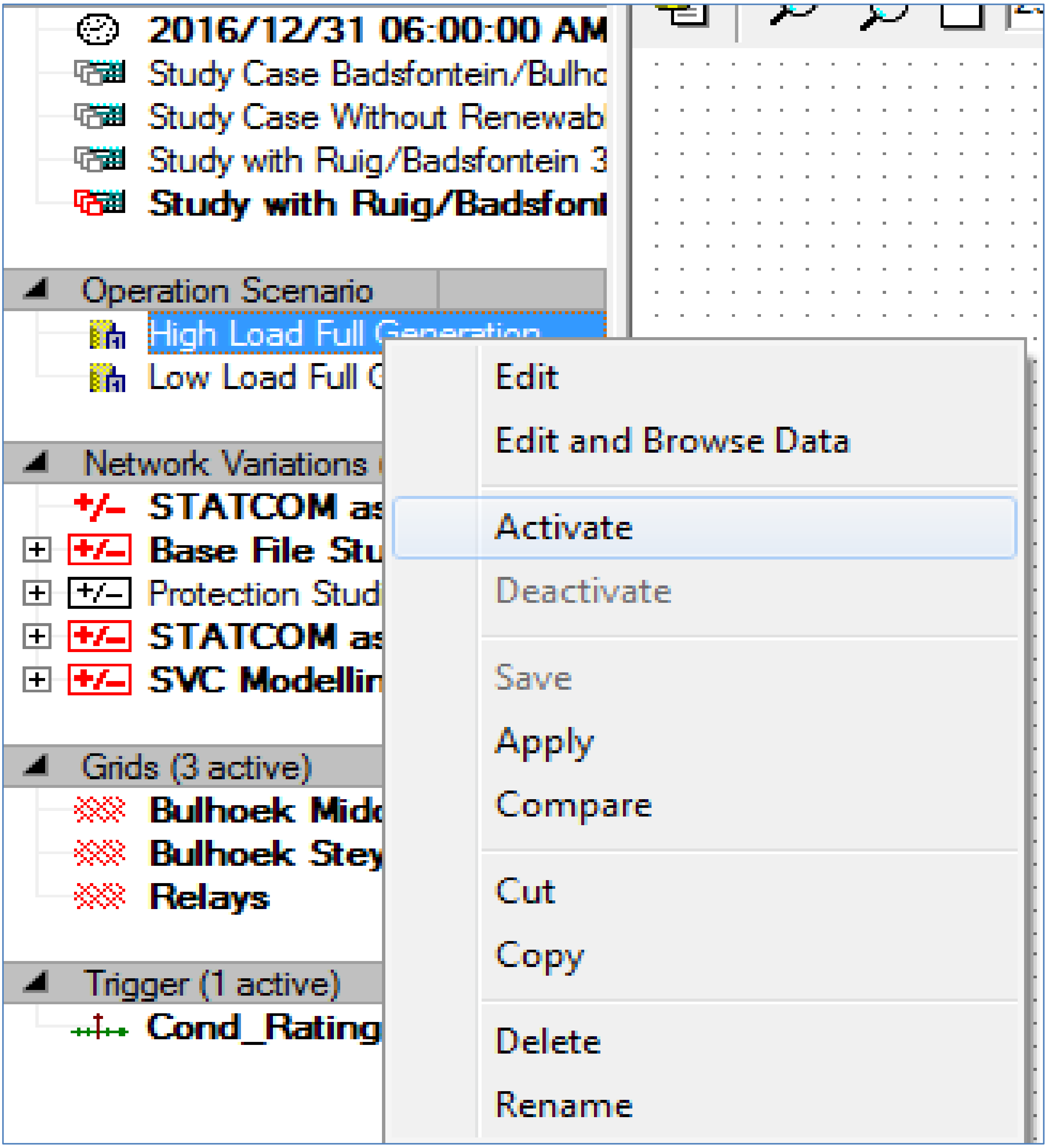
A.4 Defining and event on a line



A.5 Defining a fault event and clearing the fault events

Appendix B - Voltage variation tests in DigSilent PowerFactory

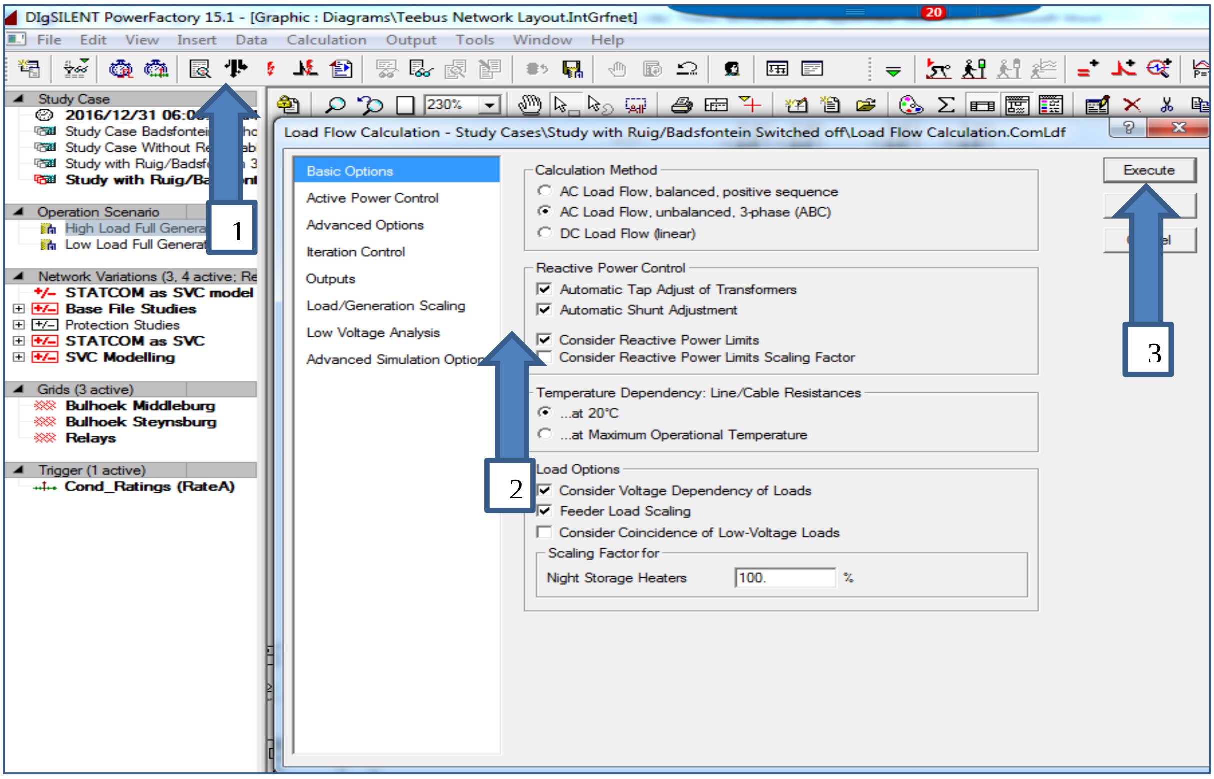
a) Ensure that the appropriate scenarios, i.e. High Load High Generation, Low Load High Generation, to be checked are active as shown below:



B.1 Activation of the High Load scenario

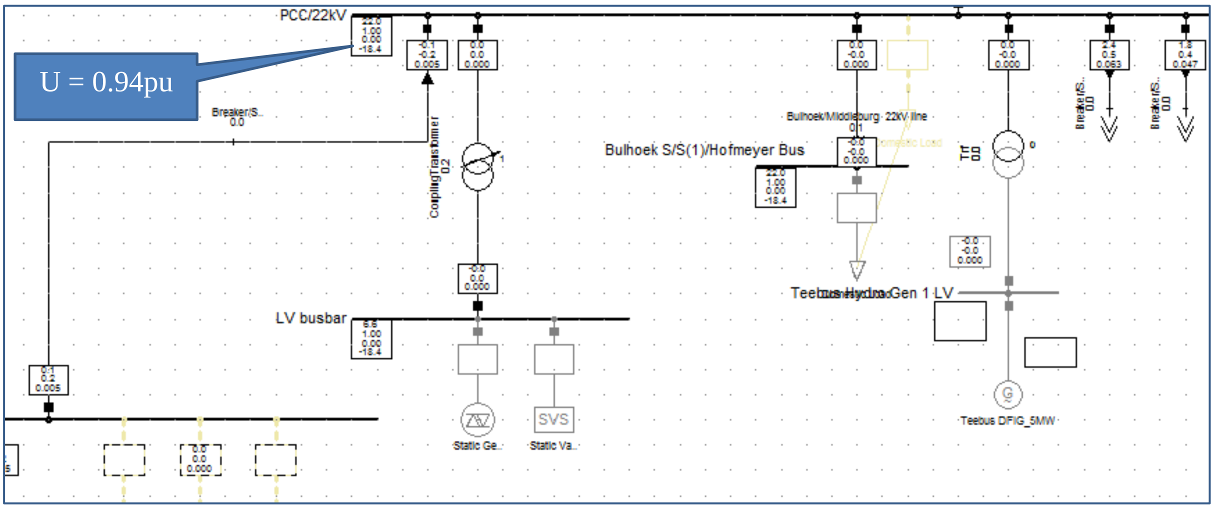
Illustration of activating the low load, high generation scenario during VVT tests

b) Run a load flow with the Automatic Tap Adjust of Transformers checked, as shown in below. Take note of the results.



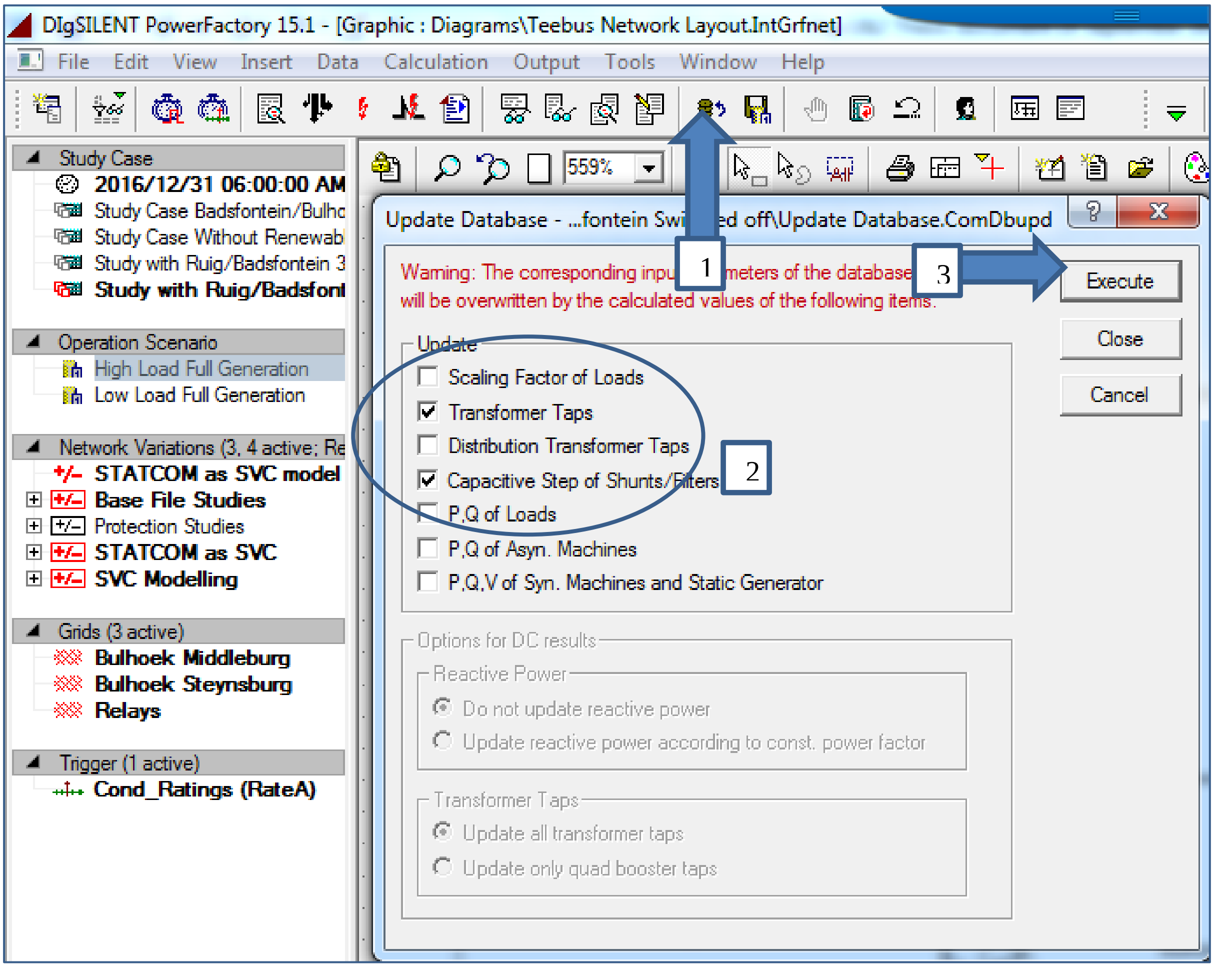
B.2 Illustration of running a load flow study during voltage variation tests

c) Check the current voltage level at the generator POC as shown in Figure B.3 below:



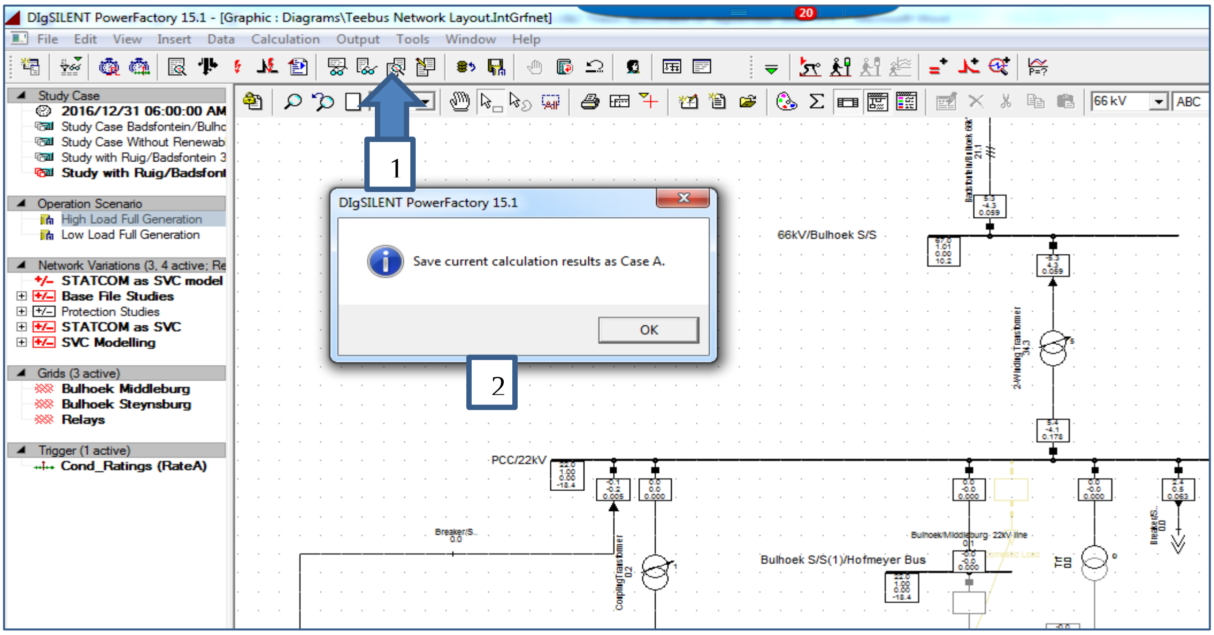
B.3 Illustration of the results at the POC during voltage variation tests

d) Update the database to store all tap settings as shown in Figure B.4 below:



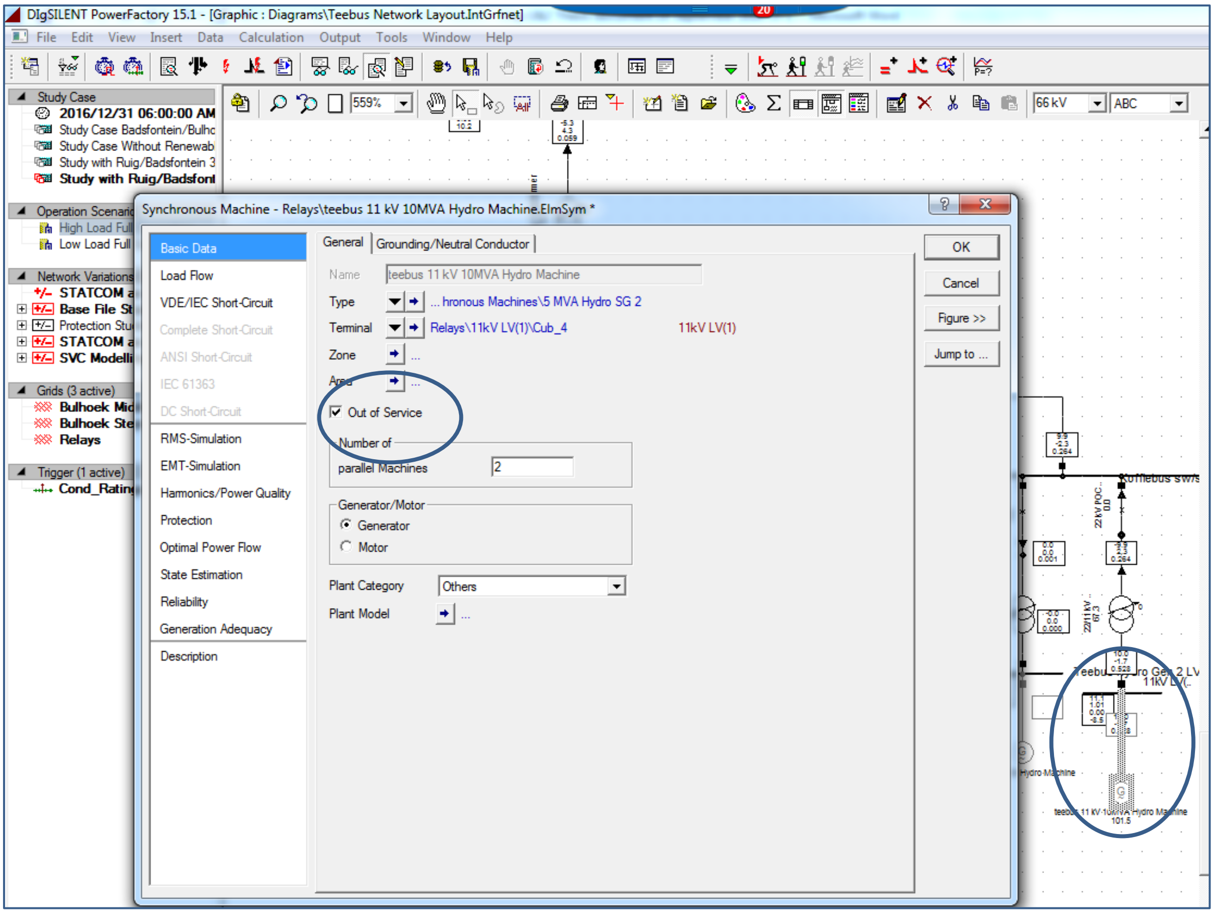
B.4 Illustration of saving tap settings during voltage variation tests

e) Set-up 'comparing of results' as shown in Figure B.5, in order to compare the percentage voltage change before and after the generator rejection.



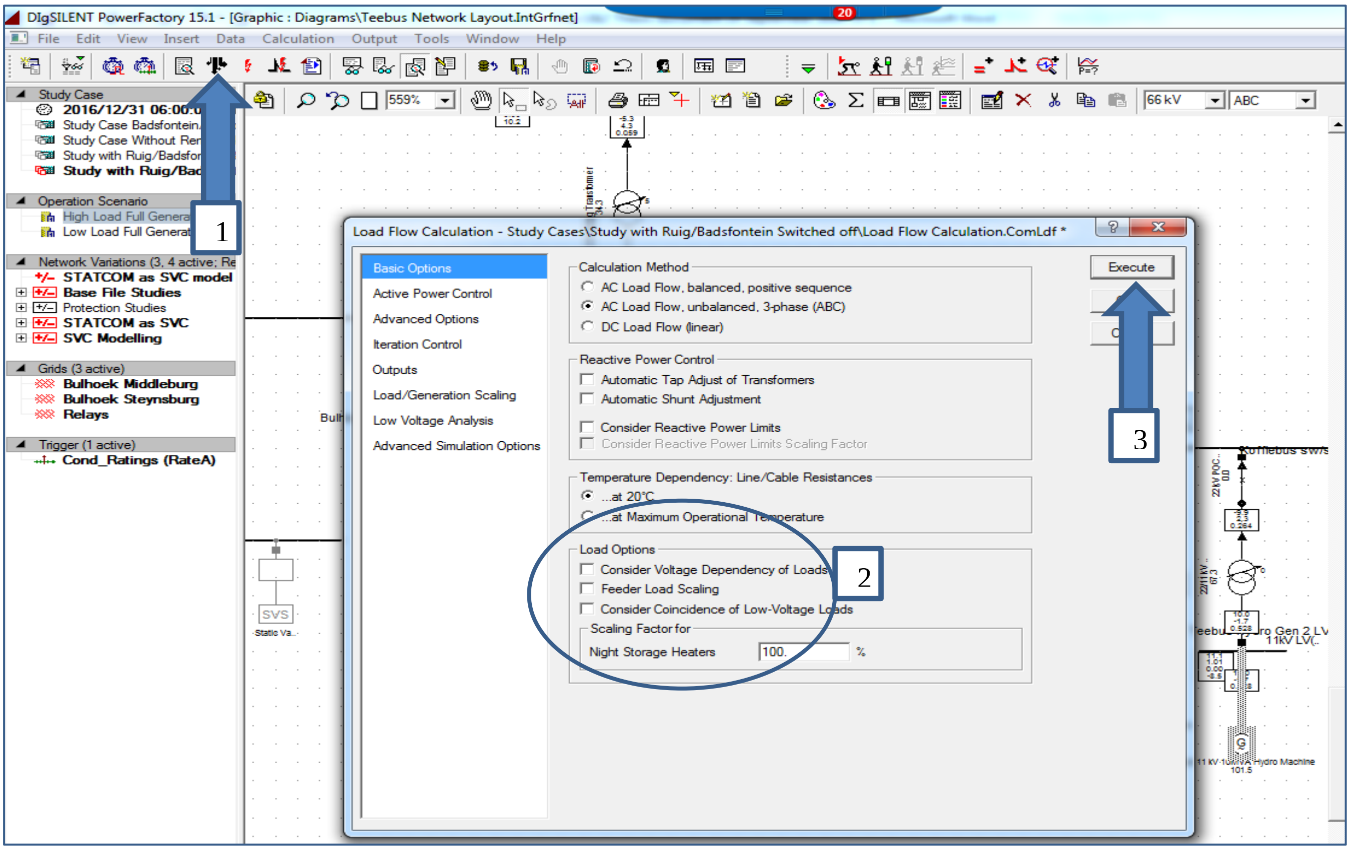
B.5 Illustration of setting up 'Comparing of Results' during voltage variation tests

f) Switch off the generator, as shown in Figure B.6 below:

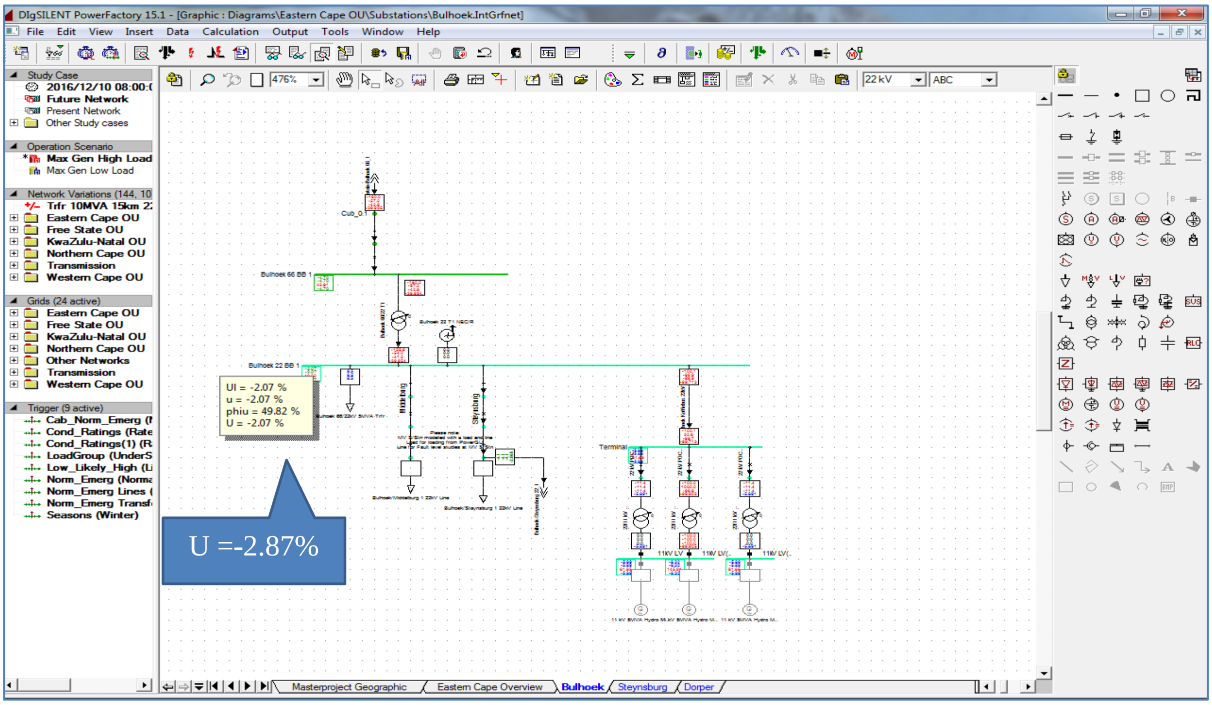


B.6 Illustration of switching off generator during voltage variation tests

g) Run a load flow, but make sure you uncheck the tap changer and reactive power limits and save the results afterwards.



B.7 Make sure you uncheck transformer and reactive power settings



B.8 Illustration of percentage voltage change at the POC during voltage variation tests

Appendix C – Data Collection

C.1 Load Forecast with all the surrounding substations

Substation	Transformer / Feeder	PF	Measured (MVA)			Forecast (MVA)					
			2012	2013	2014	2015	2017	2019	2021	2022	2025
Aberdeen	Aberdeen 5MVA 66/22kV trfr	0.99	2.50	2.76	2.66	2.67	2.70	2.73	2.76	2.77	2.81
	Aberdeen/Aberdeen Munic 1 22kV	0.98	1.94	2.01	1.95	2.2	1.98	1.99	2.01	2.02	2.05
	Aberdeen/Muller 22kV	0.99	0.83	1.02	0.99	1.1	1.01	1.03	1.05	1.06	1.08
Bosberg	Bosberg 2x10MVA 66/11kV trfrs	0.99	15.22	15.89	15.74	16.41	17.22	19.07	19.59	19.66	19.88
	Bosberg/Somerset East 1 & 2 11kV	0.99	15.22	15.89	15.74	16.41	17.22	19.07	19.59	19.66	19.88
Bulhoek	Bulhoek 5MVA 66/22kV trfr	0.98	4.48	4.48	5.48	5.49	4.73[1]	4.77	4.80	4.82	4.86
	Bulhoek/Middelburg 1 22kV	0.99	3.16	3.16	4.01	4.20	3.40	3.41	3.42	3.43	3.46
	Bulhoek/Steynsburg 1 22kV	0.98	1.91	1.91	2.09	2.09	2.11	2.12	2.13	2.14	2.16
Steynsburg	Steynsburg 5MVA 22/11kV trfr	0.98	1.68	1.73	1.78	1.79	1.80	1.82	1.83	1.84	1.86
	Steynsburg/Khyamnandi 1 11kV	0.99	0.90	0.99	1.01	1.0	1.02	1.03	1.04	1.05	1.06
	Steynsburg/Steynsburg Munic 1 11kV	0.96	0.84	0.85	0.85	0.85	0.85	0.86	0.86	0.86	0.87
Kwagga	Kwagga 10MVA 66/22kV trfr	0.97	8.45	4.56	4.57	4.59	3.963	3.99	4.01	4.02	4.05
	Kwagga/Tsolwana 1 22kV	0.97	4.12	4.57	4.57	4.59[2]	3.96	3.99	4.01	4.02	4.05
Skietkop	Skietkop 10MVA 66/22kV trfr	0.99	2.51	2.63	2.64	2.65	2.67	2.69	2.71	2.72	2.75
	Skietkop/Klipplaat 1 22kV	0.99	2.51	2.63	2.64	1.9	2.67	2.69	2.71	2.72	2.75
Spandau	Spandau/Graaff Reinet 1 66kV	0.98	12.75	12.85	13.19	13.39	14.24	14.51	14.82	14.94	15.20
	Spandau 5MVA 66/22kV trfr	0.99	2.03	2.10	2.15	2.15	2.36	2.56	2.77	2.78	2.82
	Spandau/Nieu Bethesda 1 22kV	0.99	1.18	1.21	1.23	1.23	1.44	1.65	1.86	1.87	1.91
	Spandau/Suurberg 1 22kV	0.99	0.96	1.01	0.94	0.97	0.94	0.94	0.94	0.94	0.95
Zebra	Zebra 20MVA 132/22kV trfr	0.99	0.00	4.99	6.06	6.08	13.47	13.52	13.55	13.57	13.60
	Zebra/Ethanol 22kV	-	0.00	0.00	0.00	0.00	8.00[3]	8.00	8.00	8.00	8.00
	Zebra/Garslandskloof 1 22kV	0.99	0.00	0.73	0.80	0.80	0.81	0.81	0.81	0.81	0.81
	Zebra/Visrivier 1 22kV	0.99	0.00	4.47	5.39	6.7	5.50	5.55	5.58	5.60	5.63
	Zebra 2x20MVA 132/11kV trfrs	0.97	12.25	11.30	12.51	12.53	13.42	13.87	14.70	14.77	15.36
	Zebra/Cradock 1 & 2 11kV	0.98	8.69	8.34	8.57	8.58	9.47	9.92	10.74	10.81	11.38
	Zebra/Lingelihle 1 11kV	0.99	4.12	4.12	2.24	2.24	2.25	2.27	2.28	2.29	2.30
	Zebra/Lingelihle 2 11kV	0.99	0.00	0.00	2.24	2.24	2.25	2.27	2.28	2.29	2.30

C.2 Capacity Analysis for Bulhoek substation

NORMAL CONDITION - BUSBAR VOLTAGES (%)											
Substations	**Aberdeen**	**Bosberg**	**Bulhoek**	**Kwagga**	**Skietkop**	**Spandau**	**Zebra**	**Hangklip**		**Poseidon**	
Voltages (kV)	**66**	**66**	**66**	**66**	**66**	**66**	**132**	**66**	**132**	**66**	**132**
Normal Voltage Limits (%)	**93**	**93**	**93**	**93**	**93**	**93**	**93**	**93**	**93**	**93**	**93**
2014	101	98	95	102	102	100	100	103	100	103	103
2017	101	98	97	101	102	100	100	103	100	103	103
2020	100	97	97	101	101	98	98	103	100	103	103
2025	100	96	96	101	101	98	97	103	100	103	103

C.3 Available Capacity on Bulhoek 22kV feeders

Substation	Transformer /feeder	Network Class	Main Line Conductor Thermal Rating (MVA, 50°C TT)	Existing Load (MVA)	Loading (%)	Min Voltages (%)	Distributed Load Spare capacity (MVA)	Limiting Condition	
								Year Occurs	Comments
Aberdeen	Aberdeen Munic/Lotusville 22kV	C3	5.6	1.1	20	99	4.8	Beyond 2025	N/A
	Aberdeen Munic 22kV	C3	7.8	2.2	28	99	4.1	Beyond 2025	N/A
	Muller 22kV	C3	10.7	1.1	10	103	2.5	Beyond 2025	N/A
Bulhoek	Middelburg 22kV	C3	7.8	4.2	54	96	0.4	Beyond 2025	N/A
	Steynsburg 22kV	C3	10.7	2.1	20	97	1.6	Beyond 2025	N/A
Kwagga	Tsolwana 22kV	C3	10.7	4.6	43	94	1.1	Beyond 2025	N/A
Middleburg	Bulhoek 22kV	C3	7.8	2.4	31	93	0.3	Beyond 2025	N/A
Skietkop	Klipplaat 22kV	C3	7.2	1.9	26	96	1.0	Beyond 2025	N/A
Spandau	Nieu Bethesda 22kV	C3	7.8	1.2	15	97	0.8	Beyond 2025	N/A
	Suurberg 22kV	C3	10.7	1.0	9	102	2.4	Beyond 2025	N/A
Steynsburg	Khayamnandi 11kV	C3	2.8	1.0	36	99	1.0	Beyond 2025	N/A
Zebra	Lingelihle 1 11kV	C3	3.9	2.2	56	102	1.8	Beyond 2025	N/A
	Lingelihle 2 11kV	C3	3.9	2.2	56	102	1.9	Beyond 2025	N/A
	Cradock 1&2 11kV	C3	10.7	8.6	80	101	2.1	Beyond 2025	N/A
	Visrivier 22kV	C3	7.2	6.7	93	94	0.3	Beyond 2025	N/A
	Garslandskloof 22kV	C3	7.2	0.8	11	102	3.0	Beyond 2025	N/A

C.4 QOS

Substation	Aberdeen 66/22kV	Bosberg 66/11kV	Bulhoek 66/22kV	Steynsburg 22/11kV	Kwagga 66/22	Skietkop 66/22	Spandau 66/66kV	Zebra 132/11kV	Hangklip 132/66kV
Regulation Max	3.4	5.4	3.7	2.1	DNA	DNA	0.5	6.8	1.2
Regulation Min	-0.7	-2.2	-2.7	-2.9	DNA	DNA	-5.7	-3.1	-3.5
Unbalance	1.6	1.5	1.8	1.5	DNA	DNA	1.6	3.8	1.5
THD	7.9	4.8	5.1	5.2	DNA	DNA	4	5.5	3.7

C.5 Fault Levels Data

FAULT LEVELS AND BREAKER RUPTURING CAPACITY						
Substation	**Busbar (kV)**	**Ik (3-ph) Fault kA**	**Ik (1-ph) Fault kA**	**3*Sk (3-ph) Fault MVA**	**Ik (1-ph) Fault MVA**	**Breaker Rupturing Capacity kA**
Aberdeen	66	0.52	0.63	59.53	23.06	25
	22	0.81	0.27	30.86	3.39	25
Bosberg	66	1.71	1.97	195.42	74.98	13.1
	11 (BB1)	4.03	1.12	76.87	7.12	13.1
	11 (BB2)	4.03	1.12	76.87	7.12	13.1
Bulhoek	66	0.68	0.70	77.67	26.66	25
	22	0.84	0.31	32.04	3.99	20
Steynsburg	11	0.88	0.13	16.84	0.85	13.1
Kwagga	66	0.94	1.06	106.09	40.28	13.1
	22	1.46	0.54	55.65	6.79	25
Skietkop	66	0.72	0.89	82.83	34.26	18.4
	22	1.32	0.35	50.19	4.33	12.5
Spandau	66	0.98	1.04	112.49	39.54	25
	22	1.05	0.55	39.93	7.03	12.5
Zebra	132	2.39	2.66	545.52	202.78	40
	22	3.73	0.38	142.05	4.76	20
	11	12.35	0.78	235.38	4.97	20
Hangklip	132	1.29	1.20	294.86	91.63	31.5
	66 (BB1)	1.16	1.20	132.15	45.77	13.1
	66 (BB2)	1.41	1.67	160.70	63.46	18.4
Poseidon	132	7.65	7.12	1750.11	813.74	40
	66	8.79	9.23	669.66	351.64	25

C.6 Distribution MV feeders requiring Reinforcement

Substation	Feeder	Number of Customers	Line Length in km	Electrification	Total Customers	Back-feeding Capacity (MVA)	Feeder SAIDI (%) Contr to ECOU	Compliant to Reliability Standard	Year of Non-compliance			Limiting Condition	Comment
									Voltage	Thermal	Performance		
Aberdeen	Lotusville 22kV	49	2.9	0	49	0	0.03	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Aberdeen Munic 22kV	698	139	0	698	1.1	0	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Muller 22kV	149	566	0	149	0	0.01	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Bulhoek	Middelburg 22kV	118	208	0	118	0	0.02	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Steynsburg 22kV	30	96	0	30	0	0	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Kwagga	Tsolwana 22kV	187	276	0	187	2.2	0.02	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Middleburg	Bulhoek 22kV	135	379	0	135	0	0	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Skietkop	Klipplaat 22kV	1 129	256	0	1 129	0.5	0.08	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Spandau	Nieu Bethesda 22kV	883	460	0	883	0.5	0.06	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Suurberg 22kV	165	421	0	165	1.7	0.01	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Steynsburg	Munic 11kV	1	2.4	N/A	1	N/A	0	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Khayamnandi 11kV	1 920	10	0	1 920	N/A	0.14	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
Zebra	Lingelihle 1 11kV	2 508	8	0	2 508	1.5	0.02	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Lingelihle 2 11kV	2 172	10	0	2 172	2	0.02	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Cradock 1&2 11kV	1	2.7	N/A	1	N/A	0	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Visrivier 22kV	260	518	0	260	0.9	0.05	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	
	Garslandskloof 22kV	156	369	0	156	0	0.02	Yes	Beyond 2025	Beyond 2025	Beyond 2025	N/A	

C.7 Tap Change Protection

Tap Change Protection				
Substation	**Transformer**	**Protection Installed**	**Installation date**	**Status**
Aberdeen	Aberdeen 5MVA 66/22kV trfr 1	4TC5100	15/07/2010	Operating
Bosberg	Bosberg 10MVA 66/11kV trfr 1	Phase 1 Relays	01/01/1977	Operating
	Bosberg 10MVA 66/11kV trfr 2	Phase 1 Relays	01/01/1977	Operating
Bulhoek	Bulhoek 5MVA 66/22kV trfr 1	3TC2300	23/11/1997	Operating
Steynsburg	Steynsburg 5MVA 22/11kV trfr 1	4TC5100	16/10/2007	Operating
Kwagga	Kwagga 10MVA 66/22kV trfr 1	Phase 1 Relays	01/06/1983	Operating
Skietkop	Skietkop 10MVA 66/22kV trfr 1	4TC5100	22/09/2010	Operating
Spandau	Spandau 5MVA 66/22kV trfr 1	2TC0100	05/03/2006	Operating
Zebra	Zebra 20MVA 132/11kV trfr 1	4TC5100	20/01/2011	Operating
	Zebra 20MVA 132/11kV trfr 2	4TC5100	20/01/2011	Operating
	Zebra 20MVA 132/22kV trfr 4	4TC5100	06/11/2012	Operating
Hangklip	Hangklip 40MVA 132/66kV trfr 1	4TC2100	19/09/2004	Operating
	Hangklip 20MVA 66/66kV trfr 1	2TC1000	17/11/1999	Operating

C.8 Transformer Protection

Transformer Protection				
Substation	**Transformer**	**Protection Installed**	**Installation date**	**Status**
Aberdeen	Aberdeen 5MVA 66/22kV trfr 1	3TM5110	15/07/2010	Operating
Bosberg	Bosberg 10MVA 66/11kV trfr 1	Phase 1 Relays	01/01/1977	Operating
	Bosberg 10MVA 66/11kV trfr 2	Phase 1 Relays	01/01/1977	Operating
Bulhoek	Bulhoek 5MVA 66/22kV trfr 1	3TM2700	28/06/1999	Operating
Steynsburg	Steynsburg 5MVA 22/11kV trfr 1	3TM5110	11/11/2008	Operating
Kwagga	Kwagga 10MVA 66/22kV trfr 1	Phase 1 Relays	01/06/1983	Operating
Skietkop	Skietkop 10MVA 66/22kV trfr 1	3TM5110	22/09/2010	Operating
Spandau	Spandau 5MVA 66/22kV trfr 1	2TM0100	05/03/2006	Operating
Zebra	Zebra 20MVA 132/11kV trfr 1	3TM5110	20/01/2011	Operating
	Zebra 20MVA 132/11kV trfr 2	3TM5110	20/01/2011	Operating
	Zebra 20MVA 132/22kV trfr 4	3TM5110	06/11/2012	Operating
Hangklip	Hangklip 40MVA 132/66kV trfr 1	3TM5110	19/09/2004	Operating
	Hangklip 20MVA 66/66kV trfr 1	2TM1000	01/07/1989	Operating

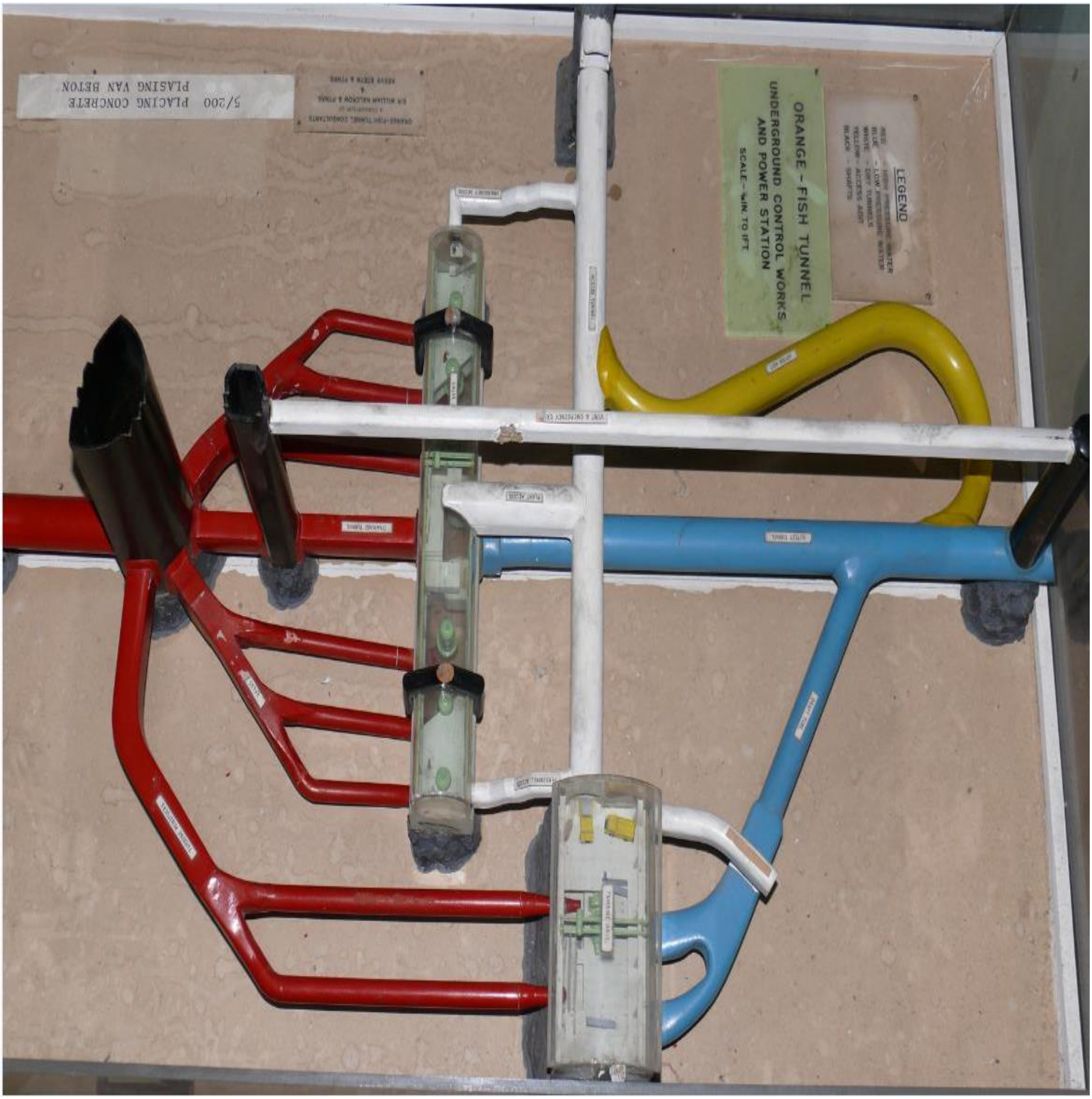
C.9 Distribution 22kV network status

Substation	Feeder	Protection Installed	Installation Date	Status
Aberdeen	Aberdeen/Aberdeen Munic 1 22kV	4RF5100	15/07/2010	Operating
	Aberdeen/Muller 22kV	4RF5100	15/07/2010	Operating
Bosberg	Bosberg/Somerset East 1 11kV	Part of Trfr 1		Operating
	Bosberg/Somerset East 2 11kV	Part of Trfr 2		Operating
Bulhoek	Bulhoek/Middelburg 1 22kV	4RF5100	02/07/2007	Operating
	Bulhoek/Steynsburg 1 22kV	3RF3100	03/07/2007	Operating
Steynsburg	Steynsburg/Khayamnandi 1 11kV	4RF5100	16/10/2007	Operating
	Steynsburg/Steynsburg Munic 1 11kV	4RF5100	Wrong date in Maximo	Operating
Kwagga	Kwagga/Tsolwana 1 22kV	Phase 1 Relays	14/09/1999	Operating
	Kwagga/Visrivier 1 22kV	Phase 1 Relays	01/06/1983	Operating
Skietkop	Skietkop/Klipplaat 1 22kV	4RF5100	22/09/2010	Operating
Spandau	Spandau/Nieu Bethesda 1 22kV	4RF5100	05/03/2006	Operating
	Spandau/Suurberg 1 22kV	4RF5101	05/03/2006	Operating
Zebra	Zebra/Ethanol 22kV	4RF5100	25/11/2012	Operating
	Zebra/Garslandskloof 1 22kV	4RF5100	25/11/2012	Operating
	Zebra/Kwagga 22kV Line	4RF5100	20/01/2011	Operating
	Zebra/Visrivier 1 22kV	4RF5100	20/01/2011	Operating
	Zebra/Cradock 1 11kV	Not yet in Maximo	Unknown	Operating
	Zebra/Cradock 2 11kV	Wrong in Maximo	20/01/2011	Operating
	Zebra/Lingelihle 1 11kV	4RF5100	20/01/2011	Operating
	Zebra/Lingelihle 2 11kV	4RF5100	20/01/2011	Operating

C.10 Telecontrol equipment

Telecontrol equipment			
Substation	**Type of RTU Installed**	**Installation date**	**Status**
Aberdeen	D20	30/06/2010	Commissioned and in-service
Bosberg	DRTU	2003/03/16	Commissioned and in-service
Bulhoek	DRTU	2004/01/04	Commissioned and in-service
Steynsburg	D20	2007/09/23	Commissioned and in-service
Kwagga	Micro-RTU	2004/01/04	Commissioned and in-service
Skietkop	D20	2003/03/16	Commissioned and in-service
Spandau	D20	2006/01/18	Commissioned and in-service
Zebra	D20	23/06/1995	Commissioned and in-service
Hanklip	ERTU	2004/08/01	Commissioned and inservice

Appendix D - Teebus Infrastructure

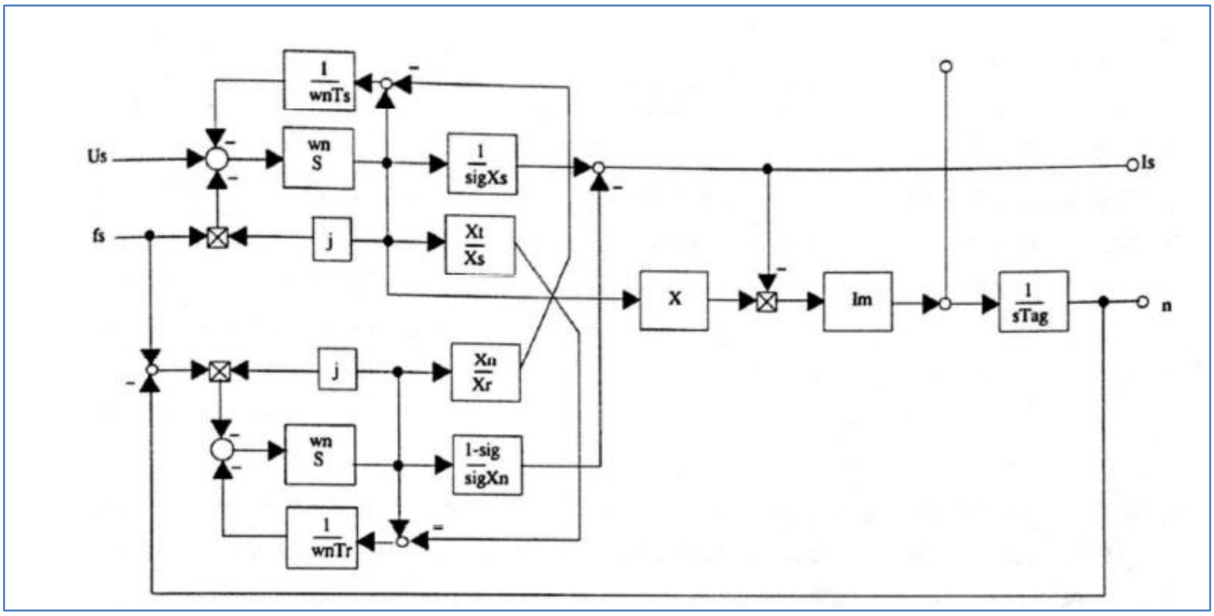


D.1 Teebus Orange Fish- Tunnel Layout

D.2 Existing 5MW Fransis Turbine

D.3 Space for a second 5MW Vertical Fransis Turbine

a) Induction generator



D.4 Standard Model for Induction Generators as used in DigSilent [31]

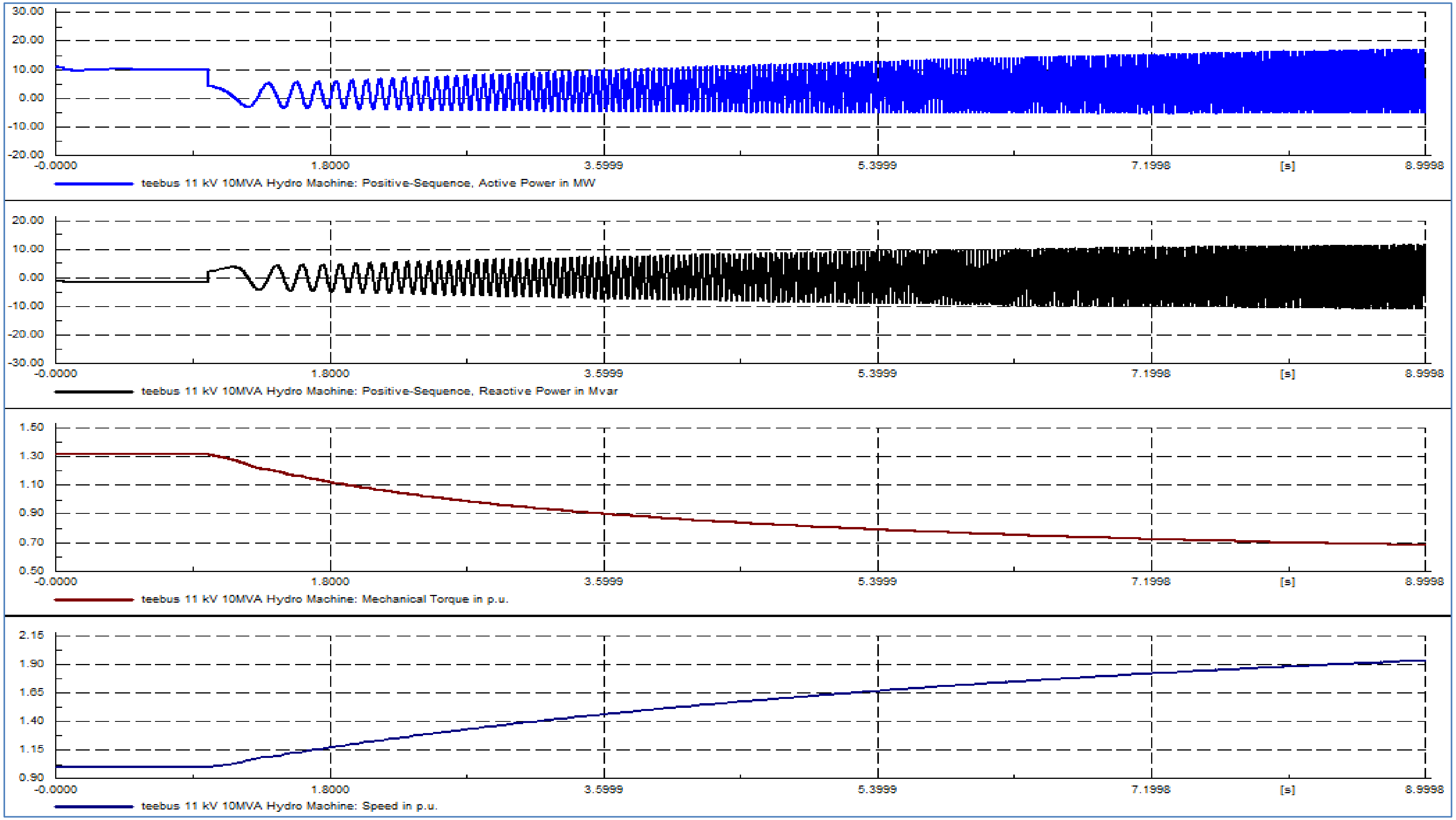
Rated Voltage	0.69	kv
Rated Apparent Power	3.65	MVA
Rated Mechanical Power	3.2	MW
Frequency	50	Hz
No. of Pole Pairs	2	
Connection	Y	
Zero Sequence Resistance	0.01	p.u
Zero Sequence Reactance	0.1	p.u
Stator Resistance	0.01	p.u
Magnitization Reactance	3.5	p.u
Stator Reactance	0.1	p.u
Rotor Resistance	0.01	p.u
Rotor Reactance	0.1	p.u
Locked Rotor Current	5.04527	p.u
Locked Rotor Torque	0.2718	p.u
R/X Locked Rotor	0.098617	
Torque at Staling Point	2.579885	p.u
Slip at Staling Point	0.05	

D.5 Asynchronous Generator Parameters

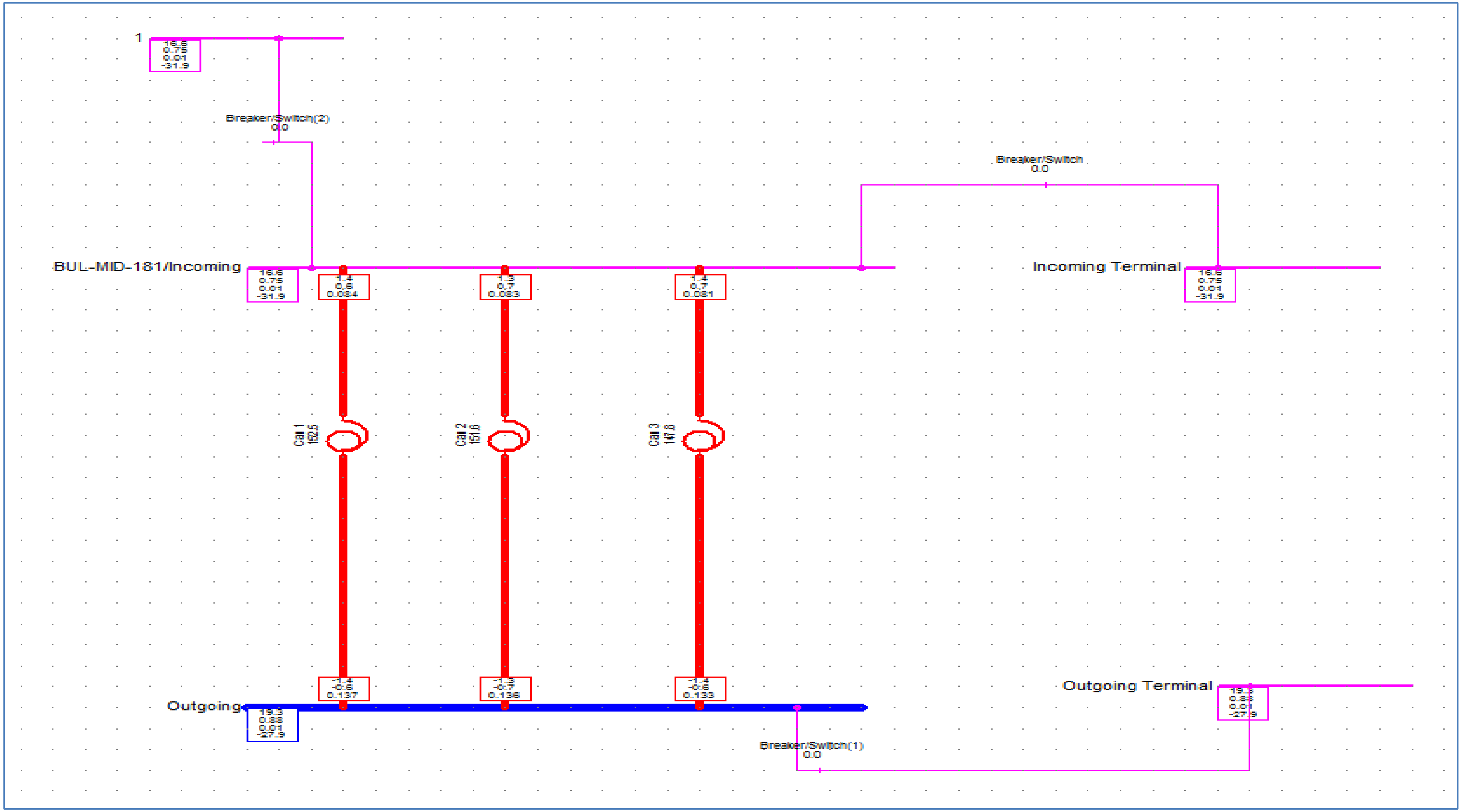
D.6 Entrance to Orange River Tunnel

D.7 Part of Sundays River System

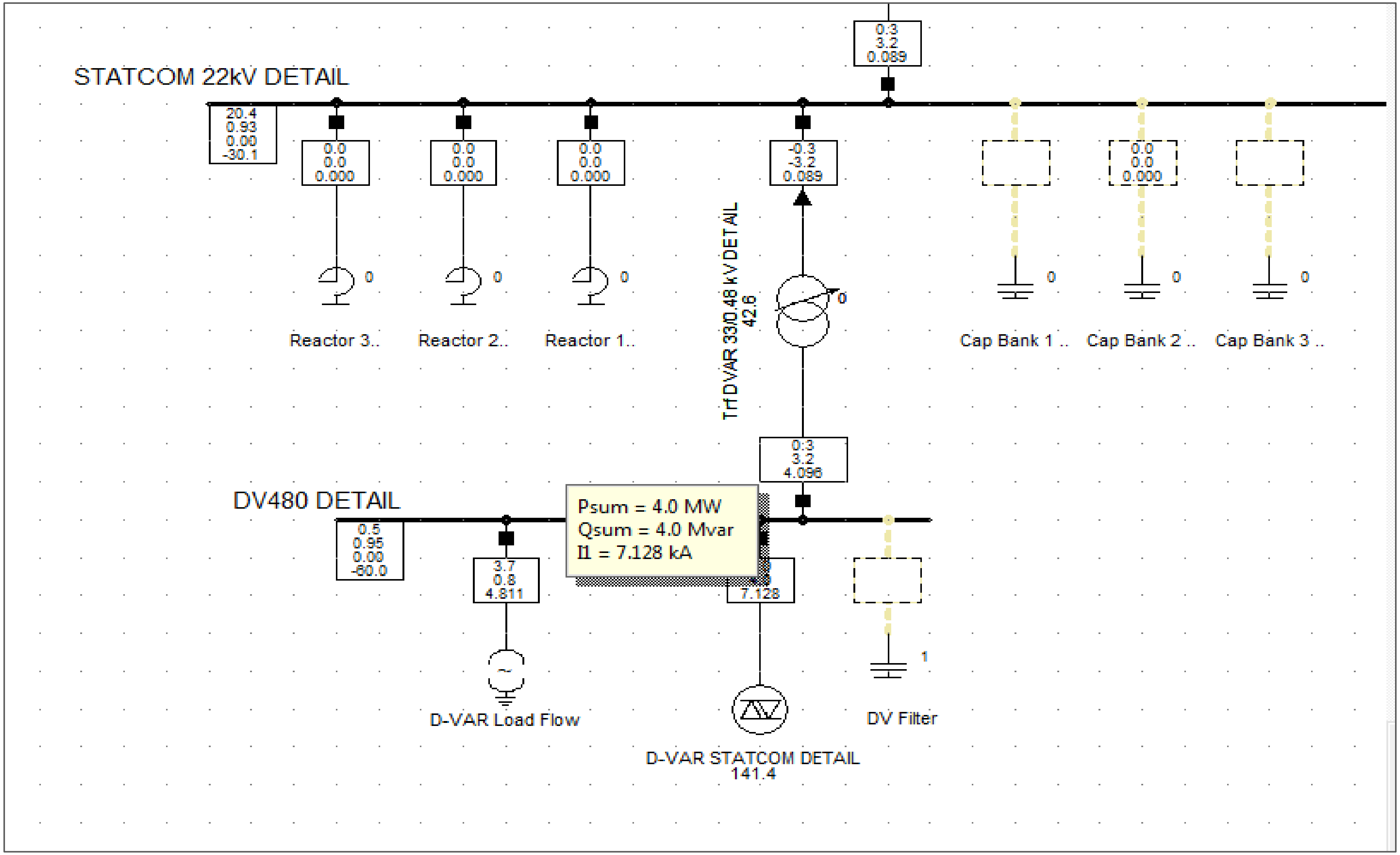
D.8 Network Control Support



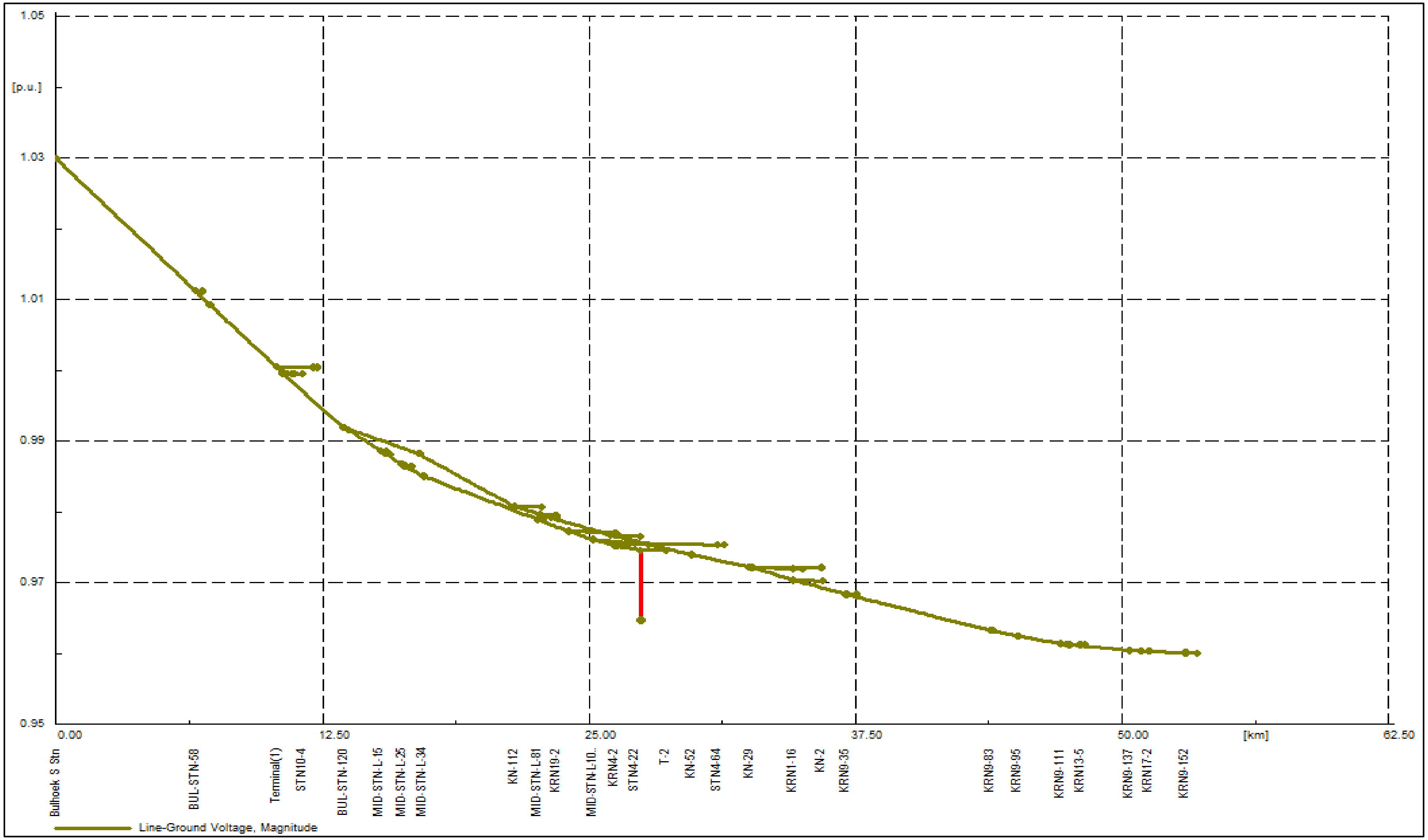
D.9 Stability Results without STATCOM



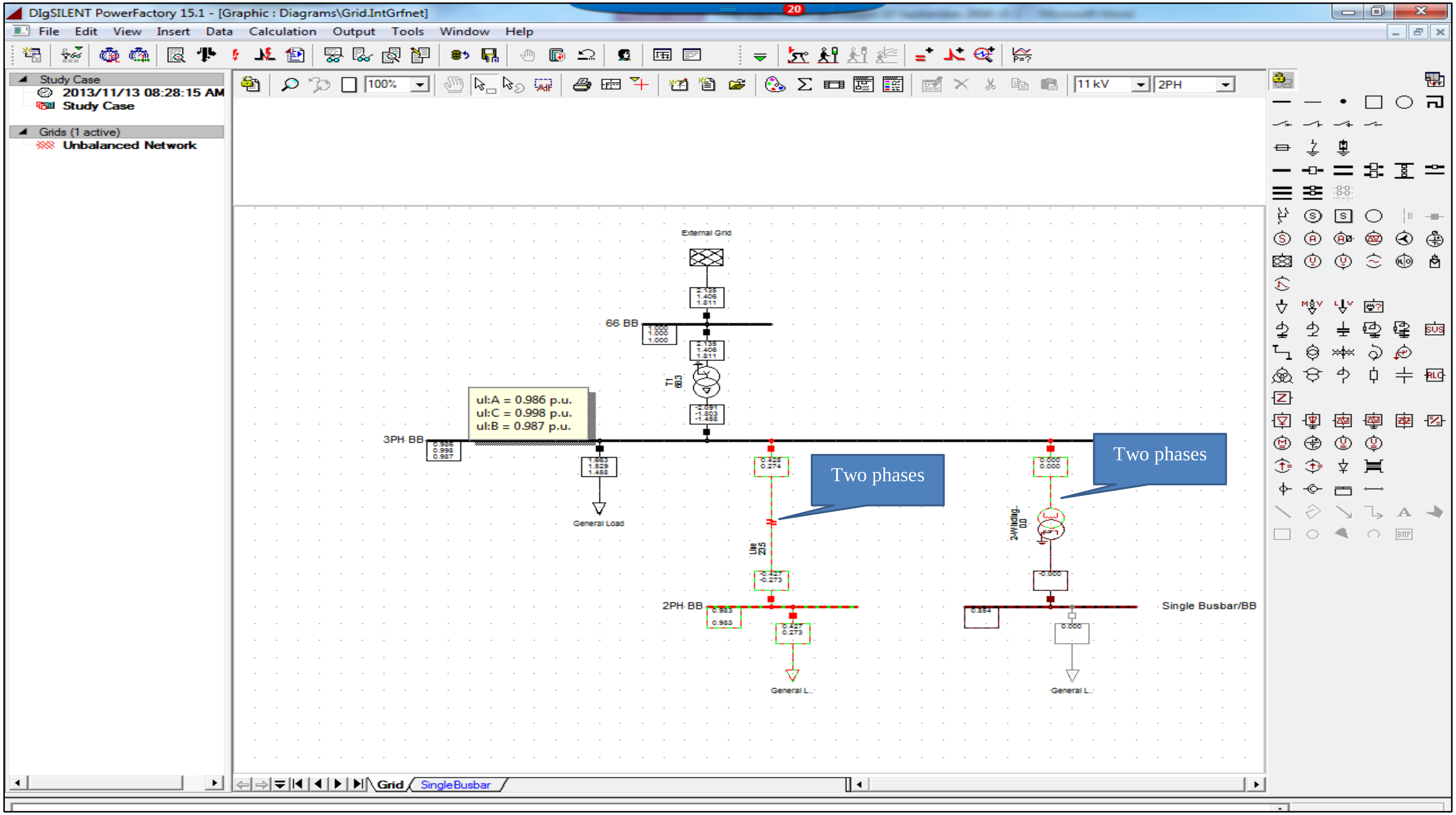
D.10 Closed Delta-three canned 22kV voltage regulator used in PowerFactory



D.11 22kV STATCOM modelled in DigSilent



D.12 Bulhoek/Steynesburg 22kV voltage profile



D.13 Bulhoek substation demonstrating the voltage unbalance on the 22kV feeder

Metering equipment					
Substation	**Feeder**	**Metering Installed Y/N**	**Type of Coms Installed**	**Metering comms or re-commended date**	**Status**
Bulhoek	Bulhoek/Middelburg 1 22kV	Y	N	19/06/2015	No comms
	Bulhoek/Steynsburg 1 22kV	Y	N	19/06/2015	No comms
Steynsburg	Steynsburg/Khyamnandi 1 11kV	Y	Y	Meter to be replaced - 2015	No project yet
	Steynsburg/Steynsburg Munic 1 11kV	Y	Y	Meter to be replaced - 2015	No project yet

D.14 Metering equipment data

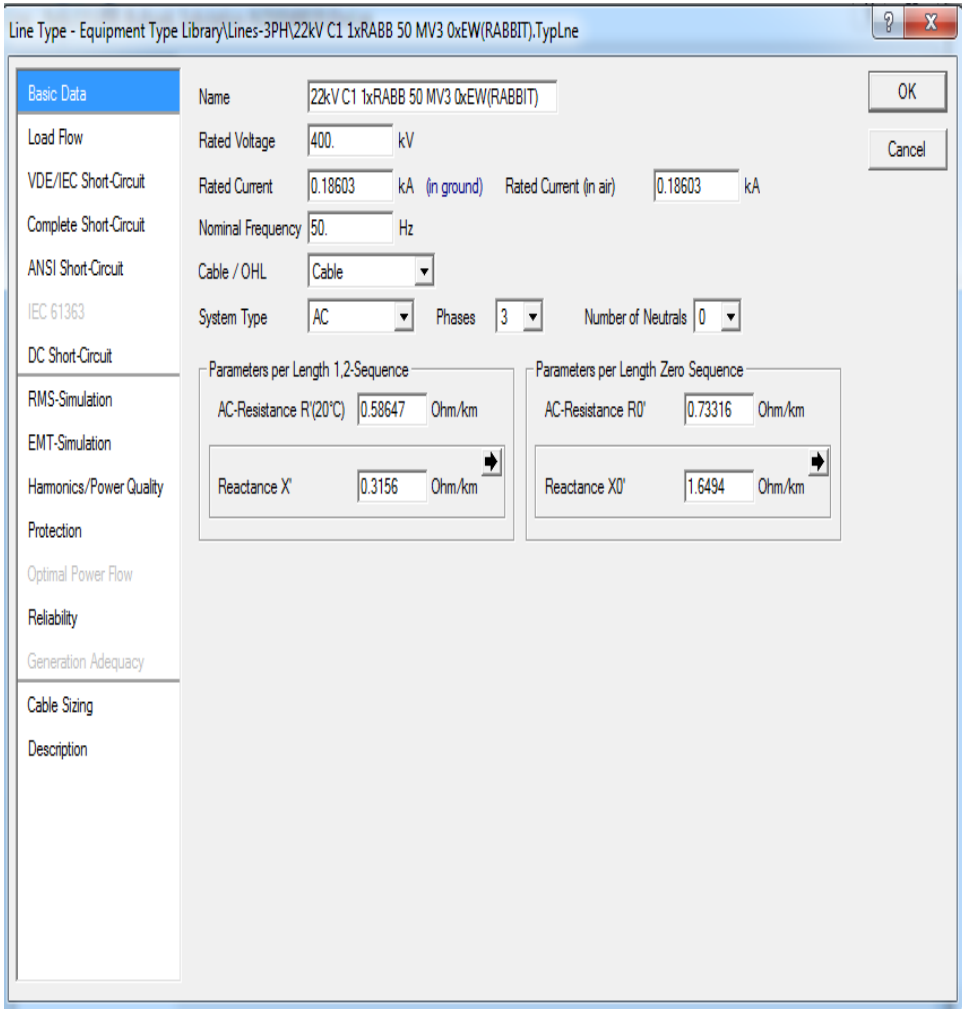
DC Systems			
Substation	**Battery Type Installed**	**Installation date**	**Status**
Bulhoek	Battery 110V 85 cell 18Ah, Nicad, ALCAD, L19P	2001/05/02	Operating
Steynsburg	Battery 110V 85 cell 71Ah, Nicad, ALCAD, VN71	1995/05/01	Operating

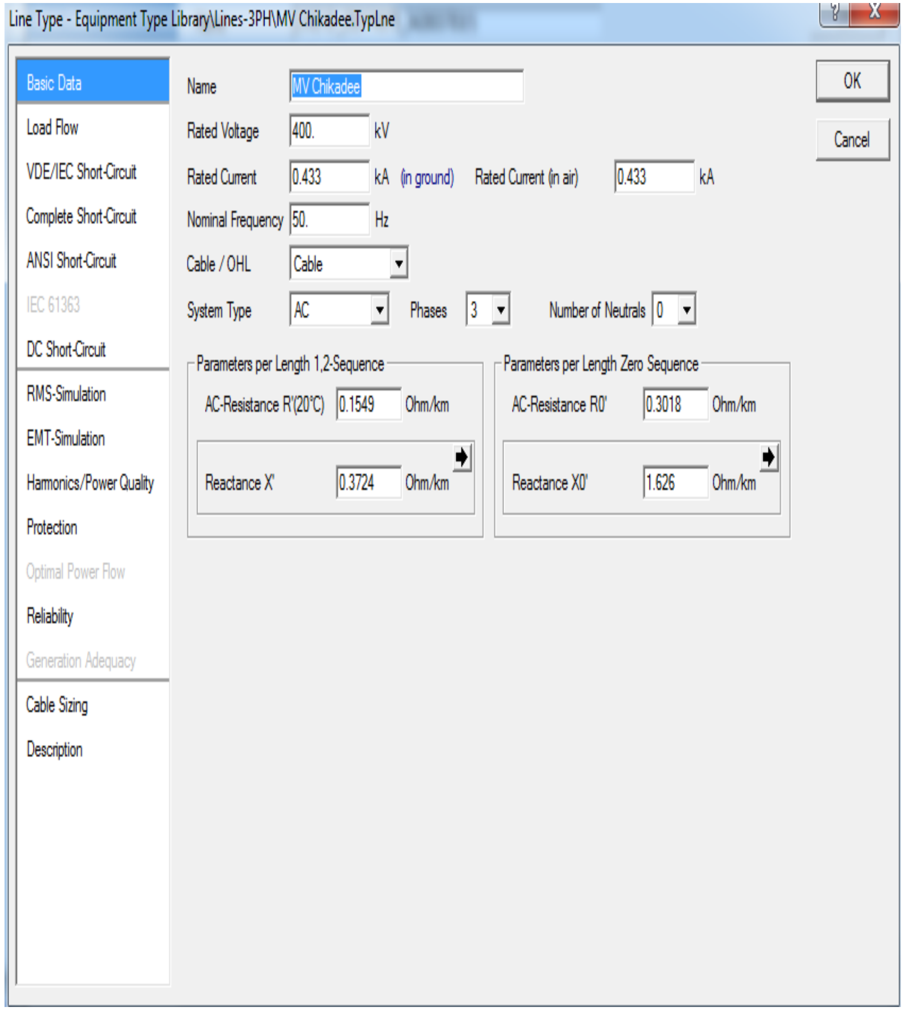
D.15 DC system information

Appendix E - Conductor parameters

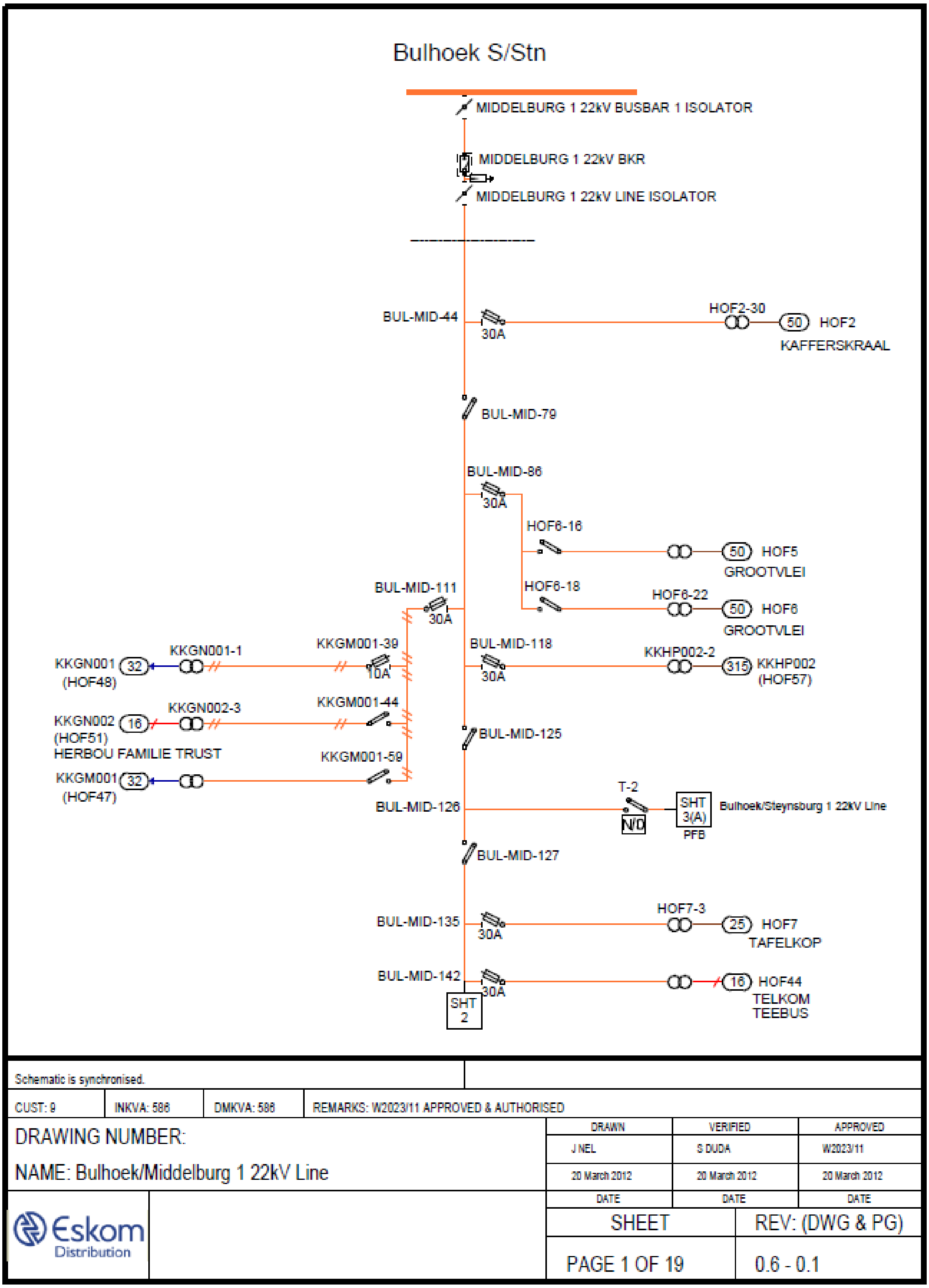
Voltage kV		Cond	Load Flow	Cond dimension		Cond	Cond	Typical constant per km in ohms and pu on 100 MVA base at 35°C							Ampacity (Thermal rating) in MVA						Ampacity (Thermal rating) in amps					
Un	Um	Code	Code	Alu Area	Ove Diam	Per	Type	R_1		X_1		B_1		R_0	TT 50°C		TT 60°C		TT 70°C		TT 50°C		TT 60°C		TT 70°C	
		Name	Name	mm²	mm	Phase		Ohm	pu	Ohm	pu	micm	pu	Ohm	Normal	Emergency	Normal	Emergency	Normal	Emergency	Normal	Emergency	Normal	Emergency	Normal	Emergency
11	12	SQUIRREL	1S11	20	6.3	1	ACSR	1.5500	1.2810	0.4500	0.3719	2.8000	0.000003	1.6600	2.0	2.7	2.3	3.1	2.6	3.5	104	143	122	165	138	183
		ACACIA	1A11	23.8	6.2	1	AAAC								2.1	2.9	2.5	3.4	2.8	3.7	108	153	129	176	145	194
		GOPHER	1G11	26	7.1	1	ACSR	1.0470	0.8653	0.4500	0.3719	2.8000	0.000003	1.1700	2.2	3.0	2.9	3.5	2.9	3.8	117	160	150	182	150	200
		FOX	1F11	37	8.4	1	ACSR	0.8600	0.7107	0.4500	0.3719	2.8000	0.000003	0.9500	2.8	3.9	3.3	4.5	3.7	4.9	148	203	173	234	196	258
		35	13511	42	8.3	1	AAAC								3.0	4.1	3.6	4.7	4.0	5.2	158	216	188	248	209	275
		RABBIT	1R11	53	10.1	1	ACSR	0.6800	0.5620	0.4450	0.3678	2.8500	0.000003	0.8150	3.6	4.9	4.4	5.7	4.8	6.5	190	255	230	300	250	340
		MINK	1M11	63	11	1	ACSR	0.5000	0.4132	0.4400	0.3636	2.9000	0.000004	0.6800	3.9	5.4	4.6	6.2	5.1	6.9	206	285	241	325	270	361
		PINE	1P11	71.6	10.8	1	AAAC								4.2	5.8	5.0	6.6	5.6	7.3	219	302	261	346	293	385
		HARE	1H11	105	14.2	1	ACSR	0.3200	0.2645	0.4100	0.3388	3.0000	0.000004	0.5100	5.3	7.5	6.4	8.5	7.2	9.5	280	392	335	448	376	496
		OAK	1O11	119	13.95	1	AAAC								5.7	7.9	6.7	9.1	7.4	10.1	297	417	350	479	391	530
		WOLF	1W11	158	18.1	1	ACSR	0.1950	0.1612	0.3240	0.2678	3.5500	0.000004	0.3420	6.9	10.1	8.5	11.5	9.5	12.8	363	528	444	605	498	671
		CHICADEE	1C11	201	18.9	1	ACSR								8.0	11.5	9.5	13.2	10.7	14.5	419	602	496	691	559	761
		MAGPIE	1MP22	10.6	6.3	1	ACSR								2.3	3.0	2.7	3.4	3.0	3.8	60	80	70	90	80	100
22	24	SQUIRREL	1S22	21	6.3	1	ACSR	1.5500	0.3202	0.4500	0.0930	2.8000	0.000014	1.6600	4.0	5.4	4.6	6.3	5.3	7.0	104	143	122	165	138	183
		ACACIA	1A22	23.8	6.2	1	AAAC								4.1	5.8	4.9	6.7	5.5	7.4	108	153	129	176	145	194
		GOPHER	1G22	26	7.1	1	ACSR	1.0470	0.2163	0.4500	0.0930	2.8000	0.000014	1.1700	4.5	6.1	5.7	6.9	5.7	7.6	117	160	150	182	150	200
		FOX	1F22	37	8.4	1	ACSR	0.8600	0.1777	0.4500	0.0930	2.8000	0.000014	0.9500	5.6	7.7	6.6	8.9	7.5	9.8	148	203	173	234	196	258
		35	13522	42	8.3	1	AAAC								6.0	8.2	7.2	9.5	8.0	10.5	158	216	188	248	209	275
		RABBIT	1R22	53	10.1	1	ACSR	0.6800	0.1405	0.4450	0.0919	2.8500	0.000014	0.8150	7.2	9.7	8.8	11.4	9.5	13.0	190	255	230	300	250	340
		MINK	1M22	63	11	1	ACSR	0.5000	0.1033	0.4400	0.0909	2.9000	0.000014	0.6800	7.8	10.9	9.2	12.4	10.3	13.8	206	285	241	325	270	361
		PINE	1PI22	71.6	10.8	1	AAAC								8.3	11.5	9.9	13.2	11.2	14.7	219	302	261	346	293	385
		HARE	1H22	105	14.2	1	ACSR	0.3200	0.0661	0.4100	0.0847	3.0700	0.000015	0.5100	10.7	14.9	12.8	17.1	14.3	18.9	280	392	335	448	376	496
		OAK	1O22	119	13.95	1	AAAC								11.3	15.9	13.3	18.3	14.9	20.2	297	417	350	479	391	530
		WOLF	1W22	158	18.1	1	ACSR	0.1950	0.0403	0.3550	0.0733	3.2400	0.000016	0.3420	13.8	20.1	16.9	23.1	19.0	25.6	363	528	444	605	498	671
		CHICADEE	1C22	201	18.9	1	ACSR	0.1450		0.3400		3.2600		0.2900	16.0	22.9	18.9	26.3	21.3	29.0	419	602	496	691	559	761
		PANTHER	1P22	212	21	1	ACSR	0.1460	0.0302	0.3440	0.0711	3.3000	0.000016	0.2930	16.8	24.5	20.4	28.1	23.1	31.2	441	642	536	737	606	818
66	72	RABBIT	1R66	53	10.1	1	ACSR	0.6800	0.015611	0.4870	0.011180	2.6280	0.000114	0.9250	21.7	29.2	26.3	34.3	28.6	38.9	190	255	230	300	250	340
		MINK	1M66	63	11	1	ACSR	0.5000	0.011478	0.4850	0.011134	2.6399	0.000115	0.7500	23.5	32.6	27.6	37.2	30.9	41.3	206	285	241	325	270	361
		PINE	1PI66	71.6	10.8	1	AAAC	0.4956	0.011377	0.3916	0.008989	2.9705	0.000129	0.8399	25.0	34.5	29.8	39.6	33.5	44.0	219	302	261	346	293	385
		RACCOON	1RC66	78	12.3	1	ACSR	0.3633	0.008340	0.4704	0.010799	2.7716	0.000121	0.6334	26.3	36.6	32.6	41.2	35.4	45.7	230	320	285	360	310	400
		HARE	1H66	105	14.2	1	ACSR	0.3200	0.007346	0.4530	0.010399	2.6530	0.000116	0.5760	32.0	44.8	38.3	51.2	43.0	56.7	280	392	335	448	376	496
		OAK	1O66	119	13.95	1	AAAC	0.2810	0.006451	0.4310	0.009894	2.6600	0.000116	0.6240	34.0	47.7	40.0	54.8	44.7	60.6	297	417	350	479	391	530
		RABBIT	2R66	53	10.1	2	ACSR	0.3130	0.007185	0.4300	0.009871	2.6850	0.000117	0.5110	43.4	58.3	52.6	68.6	57.2	77.7	380	510	460	600	500	680
		RACCOON	2RC66	78	12.3	2	ACSR	0.1870	0.004293	0.3280	0.007530	2.9150	0.000127	0.4640	52.6	73.2	65.2	82.3	70.9	91.5	460	640	570	720	620	800
		WOLF	1W66	158	18.1	1	ACSR	0.1880	0.004316	0.4180	0.009596	2.7600	0.000120	0.4730	41.5	60.4	50.8	69.2	56.9	76.7	363	528	444	605	498	671
		CHICADEE	1C66	201	18.9	1	ACSR	0.1466	0.003365	0.4076	0.009356	2.8730	0.000125	0.5074	47.9	68.8	56.7	79.0	63.9	87.0	419	602	496	691	559	761
		PANTHER	1P66	212	21	1	ACSR	0.1450	0.003329	0.4100	0.009412	2.8190	0.000123	0.4300	50.4	73.4	61.3	84.3	69.3	93.5	441	642	536	737	606	818
		BEAR	1B66	265	23.45	1	ACSR	0.1170	0.002686	0.4000	0.009183	2.8690	0.000125	0.4000	59.6	87.7	71.4	99.8	80.7	110.0	521	767	625	873	706	962
		ZEBRA	1Z66	429	28.62	1	ACSR	0.0820	0.001882	0.3960	0.009091	2.9380	0.000128	0.3670	81.2	116.8	95.1	132.7	107.2	146.9	710	1022	832	1161	938	1285
132	145	FOX	2F132	37	8.4	2	ACSR	0.3912	0.002245	0.2926	0.001679	3.8625	0.000673	0.5000	67.7	92.8	79.1	107.0	89.6	118.0	296	406	346	468	392	516

E.1 Conductor Parameters for MV and HV overhead conductors





E.2 Line Type – Equipment/Line parameters input



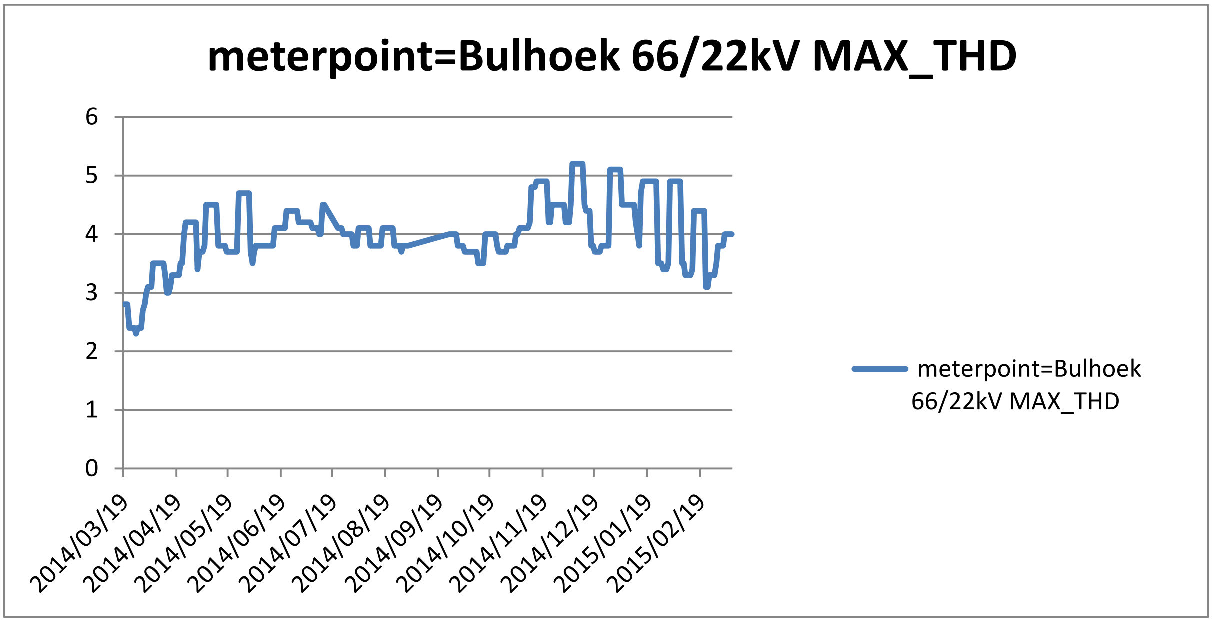
E.3 Single line diagram showing Bulhoek/Middleburg 22kV feeder.

Substation Name	Customer Description	Point of Supply Description	Customer Account No	NMD (kVA)
Aberdeen	Slabbert L.A.F 15	GRR15	EL-9239110825	50
	Slabbert L.A.F 5	GRR5	EL-00000001763	50
	Camdeboo Aberdeen Municipality	OBS43	EL-6502101957	1200
	FARM KARIEGASFONTEIN	OOR22		50
Bosberg	MUNICIPALITY OF SOMERSET EAST	OBS31	EL-7866752403	8000
Bulhoek	Van der Kel Boerdery	HOF33	EL-9887746678	200
	Southey JOH	TS9	EL-8055297068	200
	Steyn C 49	KKJN001	EL-8283559752	100
	WPF Trust 58	KKMM002	EL-7148920557	100
	WPF Trust TS44	TS44	EL-6991993800	200
	Wolfaardt PJ	HOF11	EL-6229718889	100
	FARM TEEBUS	KKHP002	commissioned	315
	NITIQUE BOERDERY23	HOF23	EL-6430914937	200
	Fortbrak Boerdery 56	KKLL003	EL-7531152673	200
	Steyn C 2	TS1	EL-8283559752	200
	Steyn C 15	HOF15	EL-8283559752	100
	DE KUILEN	KKKM001	commissioned	100
	Steyn C 37	HOF37	EL-8283559752	200
	FARM DE KUILEN	KKKM003	commissioned	100
	Lord Robert Andrew36	TS36	EL-9605391931	315
	Nitique Boerdery 61	KKJP004	EL-6756808468	315
	Steyn C 36	HOF36	EL-8283559752	200
	PLAAS DE KUILEN	TS13	commissioned	100
	PLAAS HELPMEKAAR	KKLM008	commissioned	100
	Teebus Village DWA	unset	EL-8305294863	300
	Munic of Ukhahlamba	KKGR002	EL-6263012376	315
Kwagga	Plaas Kareebosche101	MTR101	EL-5764881669	100
	Michau PW 21	MTR21	EL-8676430972	100
	Cawood PF 98	MTR98	EL-8694874334	200
	Du Preez LJ 23	MTR23	EL-6731252660	200
	Moolman J.J. 50	LKGP001	EL-8730028808	100
	Marais AM 150	LKHP002	EL-9708250342	100
	Linde H	MTR29	EL-7234726618	315
	Linde H 207	LKHQ008	EL-6600111964	100
	Michau PW 153	LKGR003	EL-5177890979	315
	Sugarbeet Cradock	LKDN007	commissioned	500
	Sevenstone Inv. 105	LKJR003	EL-7934406764	100
	Le Roux JP 24	MTR24	EL-8338356273	200
	Marais AM 43	MTR43	EL-7581176872	100

E.4 Customer Base and the customer NMD on Bulhoek substation

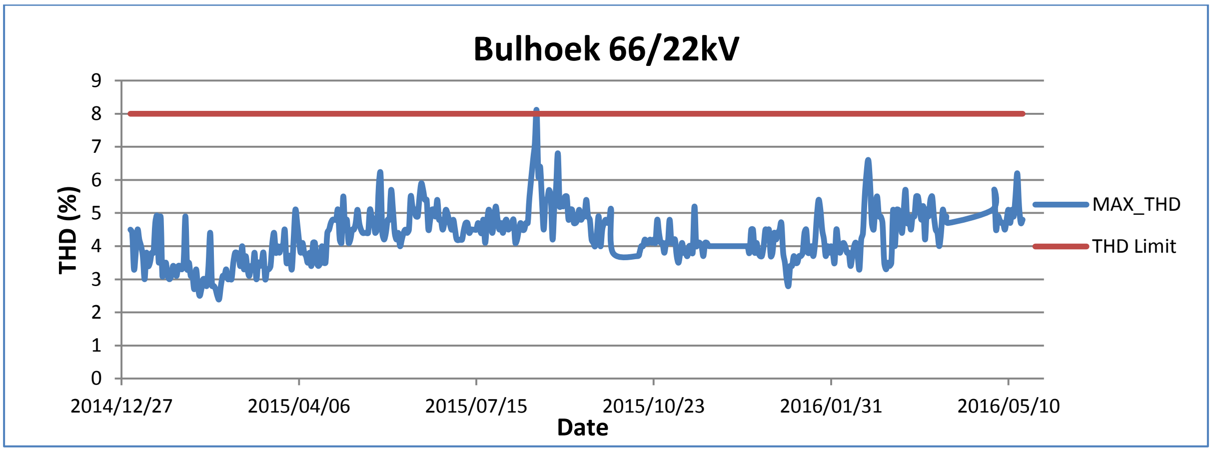
1	OHL Feeder Sub	Month	SAIDI - Year	SAIFI - Year	Saidi Ohd Year	Saidi Dpm Year	Saifi Ohd Year	Saifi Dpm Year
2	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	MAR2013	31.892	19.115	31.490	20.209	18.080	17.071
3	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	APR2013	32.115	19.522	31.712	20.432	18.487	17.478
4	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	MAY2013	31.255	19.451	30.852	19.572	18.416	17.407
5	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	JUN2013	31.126	19.381	30.723	19.443	18.345	17.336
6	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	JUL2013	31.126	19.381	30.723	19.443	18.345	17.336
7	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	AUG2013	31.559	18.876	31.156	19.876	17.841	16.832
8	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	SEP2013	18.294	16.204	17.892	17.892	15.168	15.168
9	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	OCT2013	17.969	14.442	17.566	17.566	13.407	13.407
10	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	NOV2013	20.696	15.272	20.293	20.293	14.237	14.237
11	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	DEC2013	17.924	16.582	17.521	17.521	15.547	15.547
12	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	JAN2014	27.959	19.779	27.556	27.556	18.743	18.743
13	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	FEB2014	29.381	19.879	29.381	29.381	19.879	19.879
14	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	MAR2014	24.599	16.130	24.599	24.599	16.130	16.130
15	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	APR2014	42.830	17.732	42.830	42.830	17.732	17.732
16	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	MAY2014	42.807	17.723	42.807	42.807	17.723	17.723
17	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	JUN2014	42.931	17.767	42.931	42.931	17.767	17.767
18	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	JUL2014	43.328	18.024	43.328	43.328	18.024	18.024
19	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	AUG2014	43.102	17.920	43.102	43.102	17.920	17.920
20	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	SEP2014	55.950	19.759	55.950	55.950	19.759	19.759
21	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	OCT2014	61.637	24.600	61.637	61.637	24.600	24.600
22	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	NOV2014	67.496	26.735	61.545	61.545	23.761	23.761
23	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	DEC2014	77.436	27.584	58.458	58.458	19.611	19.611
24	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	JAN2015	75.072	27.326	52.700	52.700	17.352	17.352
25	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	FEB2015	73.202	25.996	50.830	50.830	16.022	16.022
26	Bulhoek/Middelburg 1 22kV Overhead Line(293281880)	MAR2015	74.123	26.037	49.765	49.765	15.063	15.063

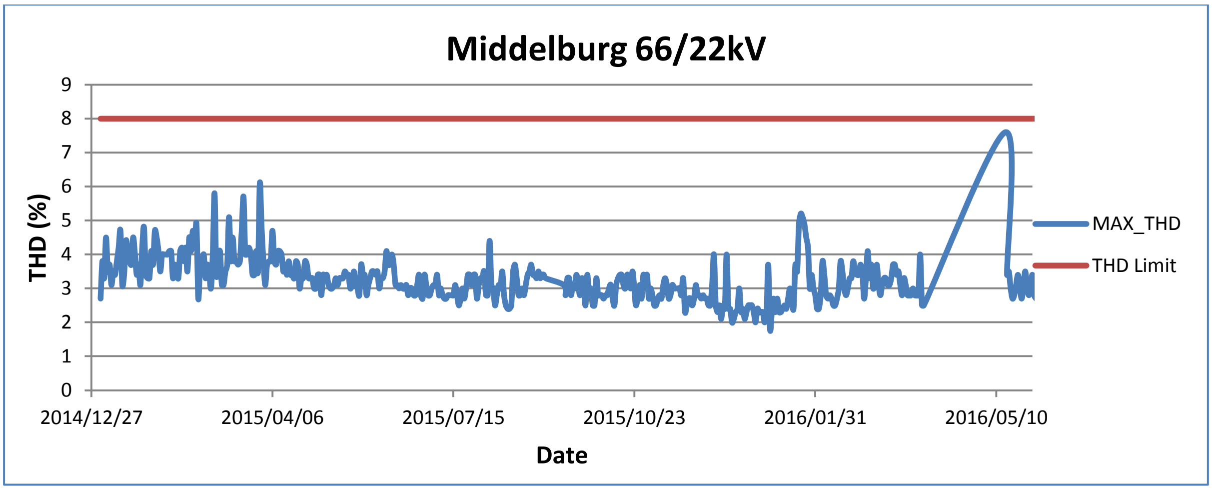
E.5 Bulhoek 22kV SAIDI and SAIFI Data



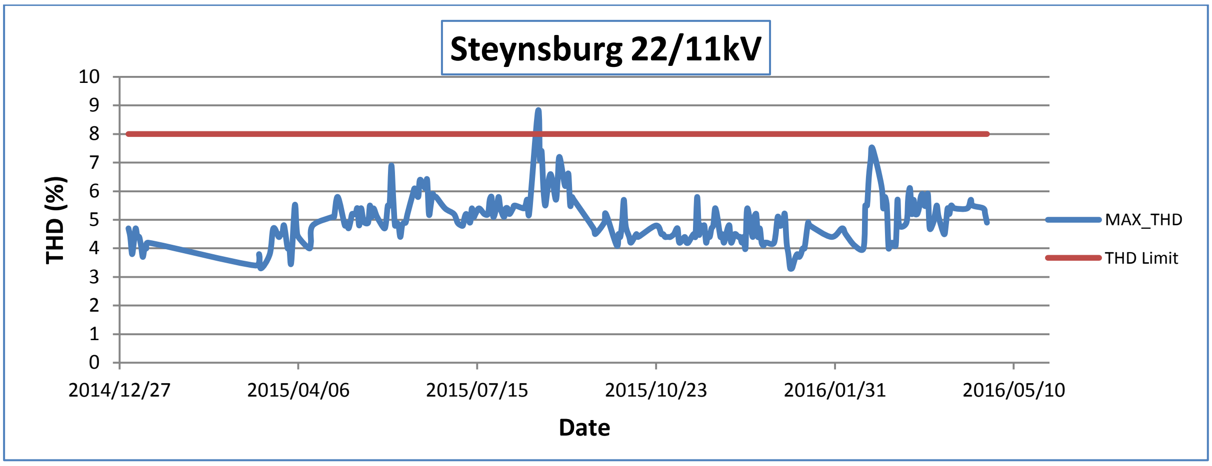
E.6 Network Performance and THD levels

Based on the graph in Figure below, it is found that the THD (%) is within limits except for the day 2015/08/18 where it is above limit.





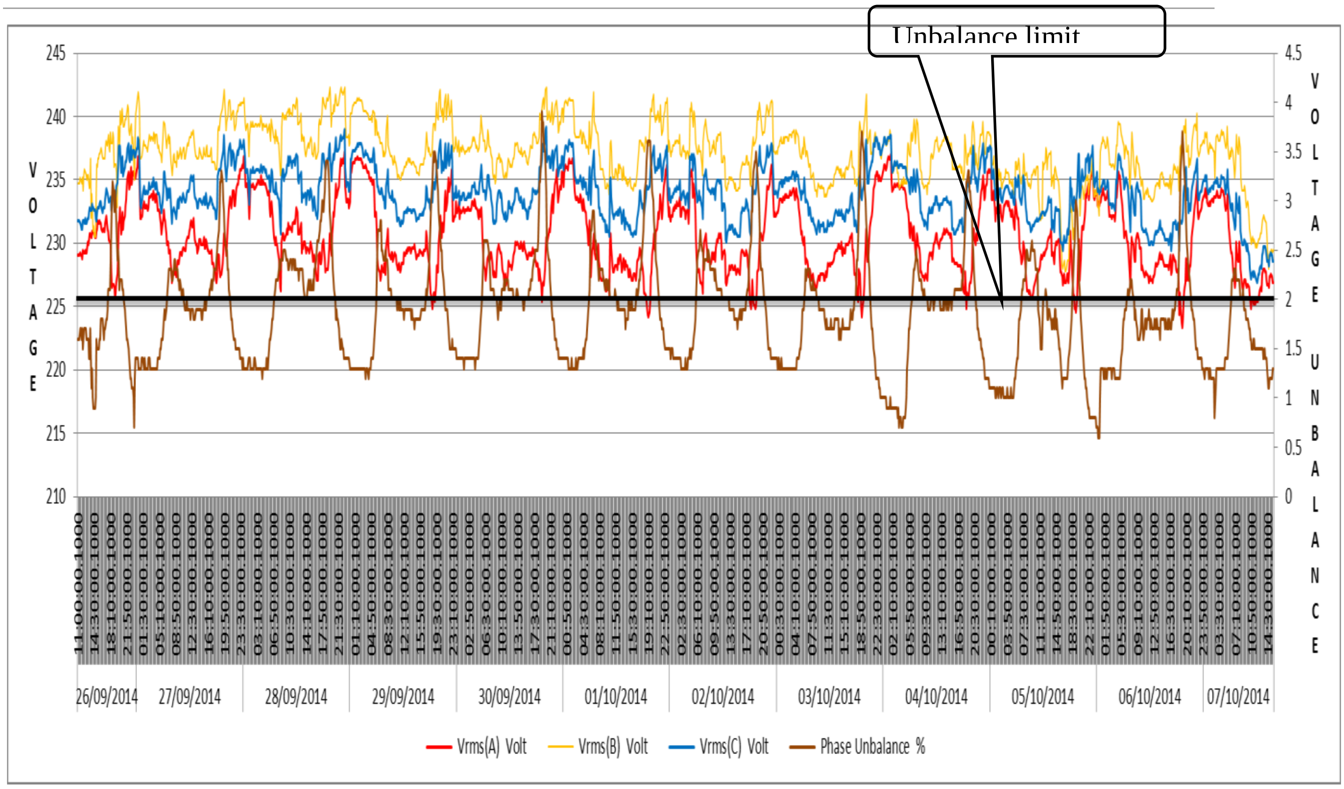
Based on the graph in figure above, it is found that the THD (%) is within limits.



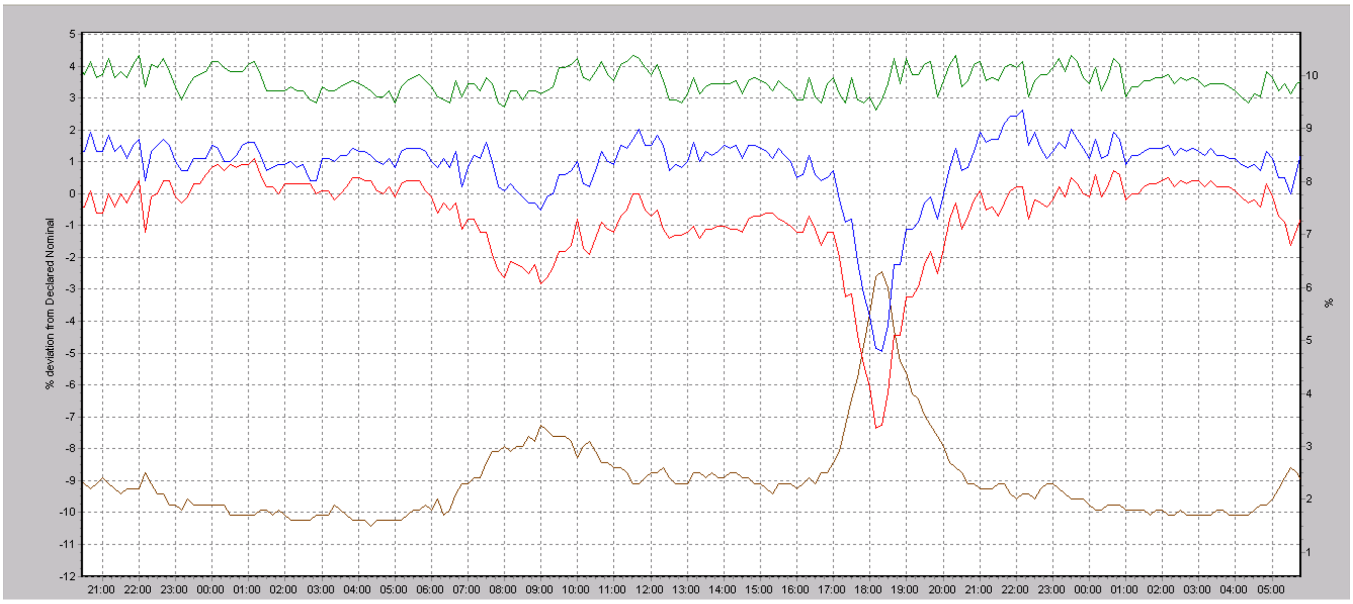
Based on the graph in figure above, it is found that the THD is within limits except on the 2015/08/18 where it is above limit.

Line	Length of network	Woodpole class 3 and 4	Condition of harware	Condition of conductor	Condition of structures	Suggestions
Collett/Genoegsaam 1 132kV Overhead Line	30	0	Steel structure, white phase insulator	Ok	OK	Normal maintenance
Collett/SATS 1 132kV Overhead Line		0	Steel structure, white phase insulator polluted	Ok	Ok	Normal maintenance
Cradock/SATS 1 132kV Overhead Line		0	N/A	N/A	N/A	N/A
Cradock/SATS 2 132kV Overhead Line		0	N/A	N/A	N/A	N/A
Cradock/Zebra 1 132kV Overhead Line	11	0	Steel structure, white phase insulator	Ok	OK	None, maintenance up to date
Dobbin/Cradock 1 132kV Overhead Line	27	0	N/A	N/A	N/A	N/A
Dobbin/SATS 1 132kV Overhead Line		0	Steel structure, white phase insulator	Ok	Ok	None, maintenance up to date
Drennan/EL&P 1 132kV Overhead Line		0	Steel structure, white phase insulator	Ok	Ok	None, maintenance up to date
Drennan/Klipfontein 1 132kV Overhead Line	26	0	N/A	N/A	N/A	N/A
Drennan/SATS 1 132kV Overhead Line		0	N/A	N/A	N/A	N/A
Drennan/Zebra 1 132kV Overhead Line	33	0	Steel structure, white phase insulator	Ok	Ok	None, maintenance up to date
Genoegsaam/Dobbin 1 132kV Overhead Line	26	0	N/A	N/A	N/A	N/A
Genoegsaam/EL&P 1 132kV Overhead Line		0	Steel structure, white phase insulator	Ok	Ok	None, maintenance up to date
Genoegsaam/SATS 1 132kV Overhead Line		0	N/A	N/A	N/A	N/A
Klipfontein/Poseidon 1 132kV Overhead Line	24	0	Steel structure,	Ok	Ok	Ok
Klipfontein/SATS 1 132kV Overhead Line		0	40 years old,	Dameged	40 years, 5 pole	Need replacement
Ludlow/Collett 1 132kV Overhead Line	28	0	Ok	Ok	Ok	Normal maintenance
Ludlow/SATS 1 132kV Overhead Line		0	Old 35	Mixed	35 Years	Need replacement
Newgate/Ludlow 1 132kV Overhead Line (Cradock CNC section)	6	0	Wishbone with shield	OK	OK	Ok
Badsfontein/Bulhoek 1 66kV Overhead Line (Cradock CNC section)	7	2	OK	Ok	Ok	Ok
Poseidon/Kwagga 1 66kV Overhead Line	73	0	OK	OK	OK	None, maintenance up to date
Bulhoek/Middelburg 1 22kV Overhead Line	210	0	Mixed	Fair	Fair	None, maintenance up to date
Bulhoek/Steynsburg 1 22kV Overhead Line	96	12	OK	OK	OK	None, maintenance up to date
Hofmeyr/Luxolweni 1 11kV Overhead Line	3	3	OK	OK	OK	None, maintenance up to date

E.7 Network Condition around Cradock areas



E.8 Voltage unbalance



E.9 Loading over a sample of one day

E.10 Existing Bulhoek substation

Appendix B – Cofference Paper

Impact of intergrating Teebus hydro power on the unbalanced distribution mv network

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***Abstract* — Small hydro power sources have been identified as one of the renewable energy technologies that the South African government is focusing on in order to generate more electricity from renewable/independent resources. Due to the low carbon output of most renewable energy technologies and the carbon intensive power generation technologies that are currently being used in South Africa e.g. Hydro, coal, gas, and etc. further pressure is increasing to incorporate cleaner forms of generation. In 2002 a study focusing on the hydropower potential was compiled providing an assessment according to conventional and unconventional possibilities for all the provinces [1].**

Eskom Distribution Eastern Cape Operating Unit (ECOU) was requested to investigate the feasibility of connecting a small hydro power scheme located in the Teebus area in the Eastern Cape. The Eastern Cape in particular, was identified as potentially the most productive area for small hydroelectric development in South Africa for both the grid connected and off grid applications.

Most of the findings from the simulations were consistent with what was expected when comparing with other literatures. From the simulation results it was seen that the performance of the variable speed generators were superior to that of the fixed speed generators during transient conditions. It was also seen that the weakness of the network had a negative effect on the stability of the system.

Keywords: Eastern Cape Operating Unit (ECOU), Eskom, Small HydroPower, Power Quality, Transient Stability, Protection Coordination, Volatge Unbalance, Teebus area, DigSilent (PowerFactory), and Distributed Generation.

I. INTRODUCTION

One of the major concerns, particularly in the Teebus area is that the existing distribution network already contains the quality of supply issues due to the nature of the customers being agricultural load (irrigation for livestock). The integration of hydro generation into an existing unbalanced distribution network system has many impacts on the network, including amongst others, the power quality, network performance, voltage stability, voltage regulation and power protection. Further, unbalancing of the supply systems may distort the supply voltage at the point of common coupling (PCC).

The research indicates that voltage rise is likely to form a key constraint to the widespread application of small Hydro plants in South Africa and other African countries. The research will look at the investigation and analysis of the impact that integration of small hydropower may have on power quality, voltage regulation, voltage instability, network performance and frequency of the unbalance on the distribution network.

To support the development of small-scale Hydro resources, the South African government, through the Departments of Energy, Water and Sanitation and National Treasury, conducted a feasibility study in 2011 for small-scale hydropower at twenty-six dams; part of the National Water Resource Infrastructure under the Department of Water and Sanitation (DWS). The study identified 22 sites with high potential feasibility for development. Based on the study findings, policy to regulate the development of these resources is being augmented by the DWS (Joemat-Pettersson, 2015)

Figure 1: Areas with micro hydro potential in South Africa

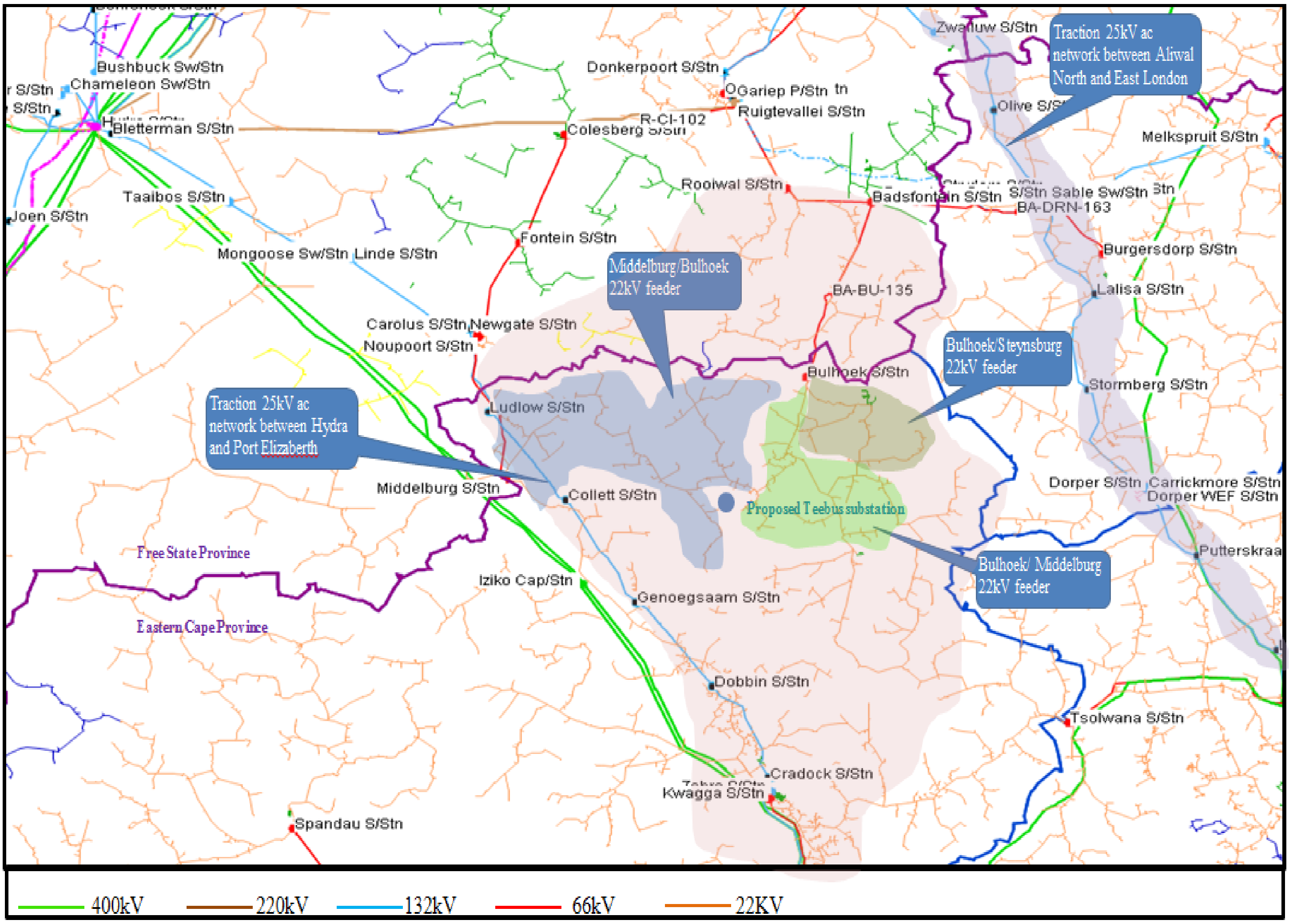


Figure 2: Areas with micro hydro potential in South Africa

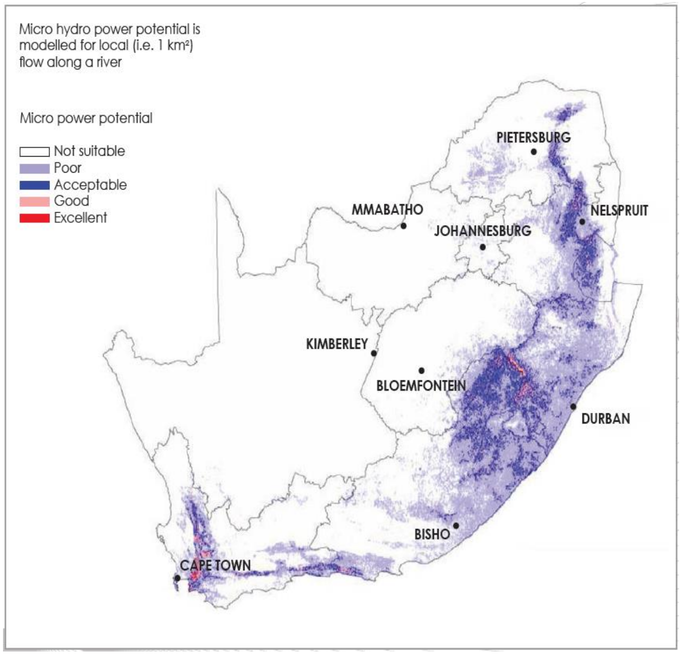


Figure 2 refers, the Teebus area is located about 30km away from Bulhoek substation and it falls within the Eastern Cape boarders on the Northern side. The 66kV line feeding Bulhoek 66/22kV, 5MVA substation is within the Free State Operating Unit (FSOU). Bulhoek substation is situated in the Eastern Cape and supplies two MV feeders, namely: Middleburg and Steynsburg 22kV feeders with approximately 900 agricultural and 1100 residential customers. The 22kV network stretches from Bulhoek substation towards the Teebus area where potential small hydro electrics are situated.

The majority of the Bulhoek customers are industrial and agricultural (farmers - irrigation to feed livestock) customers, therefore, possibility of voltage unbalance on the distribution networks relatively exist. Voltage unbalance is worsened by integrating a single phase generator, i.e. distributed generation based on small hydro power units, and moreover voltage unbalance is caused by the 132kV infeed from the traction system. The voltage unbalance becomes more noticeable as more and more single phase DG units are introduced into the distribution system. The Bulhoek substation and the 66kV line are due for refurbishment but instead of refurbishing the substation the current load at Bulhoek s/s will be transferred to the new Teebus substation in future.

II. SMALL HYDRO IN SOUTH AFRICA

Although South Africa is classified as a water-scarce country it is believed that substantial hydropower development is possible. It has been shown in an assessment conducted by the DME (2002), that there is a significant potential for development of all categories of hydropower in the short- and medium-term in specific areas of the country. Figure 2 shows all areas with hydro potential in South Africa. For example, the Eastern Cape and KwaZulu-Natal provinces are endowed with the best potential for the development of small (i.e. < 10 MW) hydropower plants. Previous research identified the Eastern Cape Province (particularly the area of the former Transkei) and the Lower Orange River as potentially the most productive areas for macro hydroelectric development in South Africa (W. J Klunne, 2013).

ECOU was requested to investigate the feasibility of connecting a small hydro power scheme located in the Teebus area in the Eastern Cape. The main purpose of the Teebus tunnel is to transfer water from Gariep Dam via an underground pipe and feed to the Eastern Cape for irrigation, urban and industrial use. A small hydro power plant of approximately 600kW was installed almost 40 years ago but has never been in operation due to switchgear damage just after commissioning. The waterways exist and all the major infrastructure investments have been done long ago. Based on the available hydraulic data for 40 years a preliminary study showed that with the available head and flow a configuration with two horizontal shaft turbines, each with 3.5 MW is possible. There is a plan to rehabilitate the Teebus Hydro station. According to ‘‘Hydro Power Station Phase 2 report’’ the prefeasibility study was concluded in August 2014 and the study investigated at concept level of the detail possible turbine and generator configuration that could be retrofitted within the existing turbine hall with minimal breaking of the cavern. The existing generators will be replaced with 2 x 5.64MW vertical Francis turbines. The project will contribute to sustainable development in South Africa through supporting the development of renewable energy in the country and support Eskom’s aspirations for Renewables Energy. In this paper the upper limit of 10MW installed capacity is used when referring to small hydro and this is all grid-connected. At this stage no internationally agreed definitions of the different hydro sizes exist. Within the range of small hydro, distinction can be made between the following (W. J Klunne, 2013):

- Mini ≤ 1MW
- 300kW ≥ Micro ≥ 100kW
- 20kW ≥ Pico ≥ 5kW

Micro and pico hydro installations are mostly found in developing countries for energy provision to isolated communities where the national electricity grid is not available, whereas mini hydro tends to be grid connected. Small hydro power plants less than 10MW can provide electricity in remote areas with minimal environmental impact and a lifespan of 30 years or more. The existing four ECOU small Hydro plant statuses are provided on Table 1 below:

Table 1: ECOU Existing Small Hydro Power Plants

Hydro Name	Installed Capacity	Position/Location
Collywobbles/Mbashe	3 x14MW units	Collywobbles on the Mbashe river system approximately 30km east of Idutywa. Provision for a future fourth machine
First Falls	3MW	First Falls on the Mthatha river situated approximately 5km east of Mthatha
Second Falls	5.5MW	Second Falls on the Mthatha River locate approximately 15km down the stream from First falls.
Ncora	1.6MW	Ncora on the Tsomo River located at about 50km west of Engcobo in the North.

III. IMPACT OF DISTRIBUTED GENERATION ON DISTRIBUTION NETWORKS

The integration of the Small Hydro power plant into the distribution grid (22kV) is something that impacts a lot of stakeholders; network companies (both distribution and transmission), the owners and operators (developers) of the distribution generation units, other end-users of the power grid (including normal consumers) and not in the least policy makers and regulators

The effects of connecting distribution generators onto the unbalance distribution system is well documented and include amongst others, the power quality, network performance, voltage stability, voltage regulation and power protection. Further, unbalancing of the supply systems may distort the supply voltage at the point of common coupling (PCC). One of the major concerns, particularly in the Teebus area is that the existing distribution network already contains the quality of supply issues due to the nature of the customers being agricultural load (irrigation for livestock- uses single phase motors).

A. Voltage regulation and network instability

The integration of the small hydro could affect voltage regulation and cause over voltages due to too much injection of active and reactive power.

B. Network performance, protection and reliability of power supply

The connection of hydro generation will impact the network stability and further interrupt the demand side, therefore, affect the utility's SAIDI and SAIFI monthly targets (J.G Slootweg, 2003), (Slootweg J, IEEE 2002). Short circuit power of a distribution network changes when its state changes.

C. Voltage Unbalance on the existing MV and LV Networks [15]

The MV standard voltages refers to 11kV, 22kV and 33kV, the standard LV voltage is 230 phase to neutral i.e. 400V phase to phase for three phase and 460V phase to phase for dual phase supplies. In Eskom Distribution MV and LV distribution networks the primary cause of voltage unbalance is unequally loaded three phase backbones, where the load imbalance is caused by the connection of non-three phase loads and network technologies e.g. phase to phase laterals and single phase transformers. The magnitude of the load imbalance is dependent on the phase connections used.

A real test system with two generators that are already approved and three future potential hydro generating units will be set up to examine their dynamic and steady state performance using the PowerFactory tool.

The following scenarios were modelled in PowerFactory:

- Case 1: Impact to customers when one critical infeed losses power (N-1 scenario).
- Case 2: Voltage variation test at the PCC when small hydro generator is switched on and off (before the adjustment of tap changers)
- Case 3: Impact of the two generators during high and low load on the network.
- Case 4: The behaviour of the grid when the generator continues to energize a portion of the utility system that has been separated from the main utility system [islanding (not allowed in the Grid Code)].

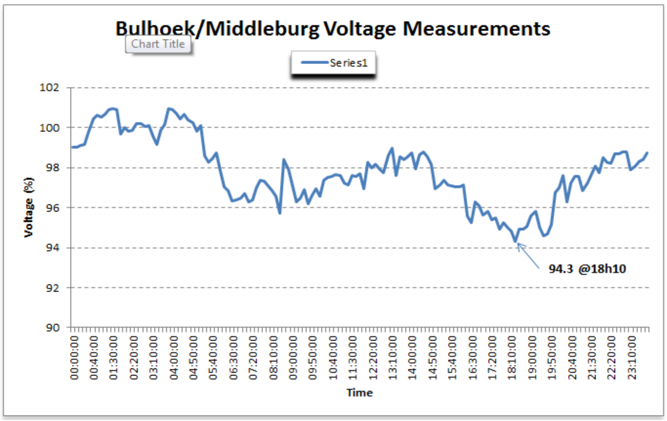
For use in this study, the voltage levels that are considered are 132kV, 66kV and 22kV.

IV. BULHOEK/MIDDLEBURG 22KV LINE INFORMATION

Bulhoek/Middelburg 22kV feeder mainline (backbone) conductor is Mink and it interconnects with Middelburg/Bulhoek, Bulhoek/Steynsburg and Tsolwana/Bulhoek Middelburg Tee 22kV feeders via normally open points. The

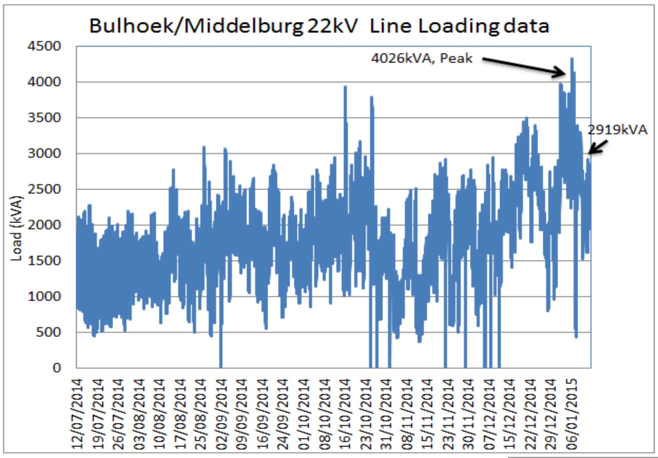
Figure ***3*** below show the voltage records for Bulhoek/Middleburg 22kv line, it can be noted that the lowest voltage of 94.3 is experience during peak between 18:00 and 20:00.

Figure 3: Voltage measurements for Bulhoek/Middleburg 22kV line



This is the C3 network class (93% voltage level limits), the MV source voltages are set at 103% and the minimum measured voltage is 94% (and simulated) of nominal voltage. According to the loading data (March 2014 to June 2014), provided by metering department (Eskom), the current peak load is 4.02MVA, with the Homier Munic load at 0.88MVA.

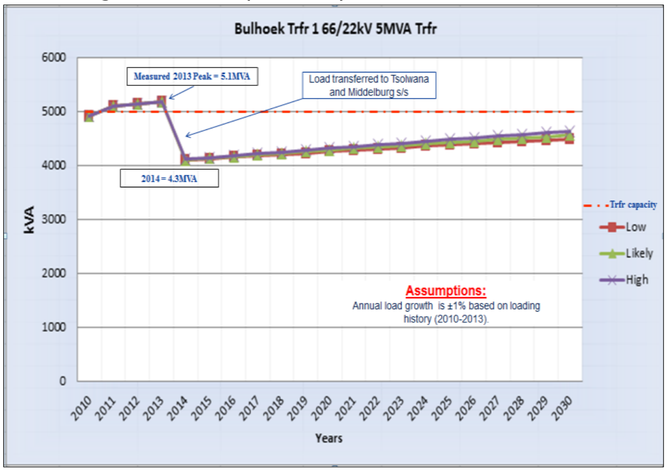
Figure 4: Load measurements for Bulhoek/Middleburg 22kV line



A. Load Forecast

The load forecast is extracted from the Geo-Based Load Forecast (PowerGLF) tool. The Figure 5 below shows the future load prediction for the 22kV feeders fed from Bulhoek s/s.

Figure 5: Load forecast for Bulhoek substation



The measured load (5.1MVA) in 2013 went above the transformer capacity and was reduced to 4.3MVA by shifting the load to the neighbouring MV feeders (Middleburg/Bulhoek 22kV feeder). The predicted load forecast shows that the load will not exceed the trfr limit for the next 20 years. The average load growth rate per annum for this feeder is approximately 1% based on the historical data and there are no known significant developments in the area. The measurement is taken from the most likely scenario as this is the most predicted growth. The connection of the small Hydro electrics will benefit largely the upstream network and the over-voltages on the MV network would be tested in the analysis. The future load growth in the area and the connection of small hydro generators will influence the selection the transformer sizes.

B. Distributed Generation

Much distributed generation (i.e. rotating generators connected to the distribution system) is unlikely to be stable after network faults due to its low inertia and the long protection clearing times of distribution networks. Distributed generators take a voltage and frequency reference from the power system and are not intended to operate in islanded mode. Distributed generators are fitted with Loss of Mains protection to detect islanding as operation is not permitted without a connection to the normally operating power system. Traditionally distributed generators have not been expected to support the power system in the event of disturbances in frequency and voltage but to trip as soon as a network disturbance is detected [19].

V. Power Quality

The main objective of this section is to monitor the full spectrum of deviation in quality of supply at the Bulhoek substation. The aim is also to ensure that excessively high levels of deviation are identified, action plans put in place so that they can be appropriately managed. The data was downloaded from the quality of supply recorders at Bulhoek substation. Note that the data also does not include the traction voltage unbalance.

Figure 6: Bulhoek 22kV Voltage unbalance - RMS Values

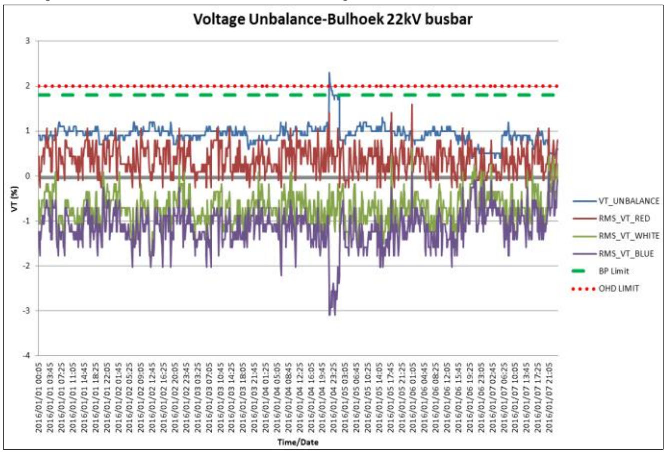


Figure 6 shows the measured trended values recorded by a power quality (PQ) recorder at the Bulhoek 22kV busbar for approximately a year. These compatibility values shown on Table 2 are minimum and maximum RMS values. The voltage profiles indicate that Eskom currently does not comply with the +-5% or with the +-7.5% standard limit prescribed by the NRS 048-02, the exceedances that happened on 04 January 2016. This trended values do not necessary mean the voltage unbalance limits are exceeded. The trended values (RMS) are not used only for reporting purposes but the CPF 95 values, where the 5% of the data has been filtered. Based on the graph above, it is found that the voltage unbalance is within the limits set by the National Electrical Regulator. It should be noted that the red and the blue phases are significantly loaded. It can be seen that the winter demand also possibly results in lowering the voltages. The white phase is shown to be relatively lightly loaded throughout the year [14].

A. *Voltage Unbalance Limits*

The maximum compatibility level of voltage unbalance as specified in NRS048-2 is 2%. In networks supplying predominantly single phase loads the compatibility level for voltage unbalance is 3%. Predominantly single phase loading is defined when both of the following criteria are met. Indicative planning limits for voltage unbalance are provided in Table 2 below for each and every system voltage levels.

Table 2: Indicative planning levels for voltage unbalance

System voltage	Voltage unbalance planning limit
EHV	0.8%
HV	1.4%
MV	1.8% (predominantly single phase loads 2.7%)
LV	2.0% (predominantly single phase loads 3.0%)

There are several formulas to calculate voltage unbalance [14]:

Voltage Unbalance formula 1

$$V_{Unbalance} = \left|\frac{V_{Negative\ sequence}}{V_{Positive\ Sequence}}\right| \times 100\% \quad \ldots(1)$$

Or

Voltage Unbalance formula 2

$$V_{Unbalance} = \frac{(V_{Max} - V_{Min})}{V_{Ave}} \quad \ldots(2)$$

Or

Voltage Unbalance formula 3

$$V_{Unbalance} = \frac{\text{Maximum measured V from Avarage}}{V_{Ave}} \times 100\% \qquad \ldots(3)$$

Or

Voltage Unbalance Equation formula 4

$$V_{Unbalance} = \frac{(|V_a - V_{ave}| + |V_b - V_{ave}| + |V_c - V_{ave}|)}{2 \times V_{ave}} \times 100\% \qquad \ldots(4)$$

Figure 7: Voltage unbalance of the existing network (with one generator connected)

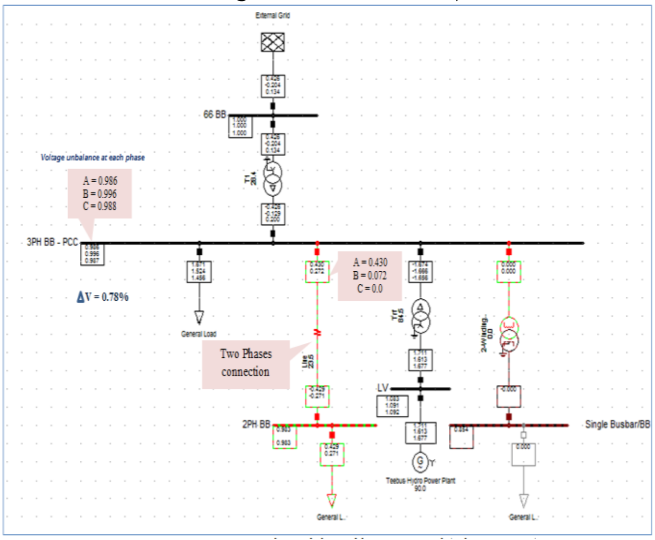


Figure 7 above shows voltage unbalance after the connection of the single planned generator. The red and green colours represent the technology on the existing system (two/three phase system). From the above results, negative sequence components is 0.007p.u and positive components = 0.974pu. Therefore,

Voltage unbalance with Gen connected can be calculated as follows:

- $V_{Unbalance} = \left|\frac{V_{Negative\ sequence}}{V_{Positive\ Sequence}}\right| \times 100 \qquad \ldots(5)$
- $= \frac{0.007}{0.974} \times 100\%$

$= 0.72\%$

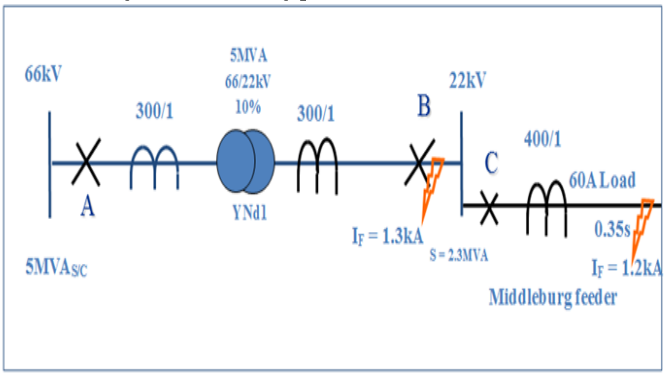
VI. PROTECTION COORDINATION

Power system simulation and modelling studies have shown that distributed generation causes several challenges to the protection of distribution networks. The existing Current Transformer ration at the secondary side of the transformer: CT ratio = 400/1A. The formula to determine Plug Setting Multiplier is as follows:

$$Current\ setting = \frac{Pick\ up\ current}{Rated\ secondary\ cuurent} \times 100\%$$

Note: Current setting for current relay generally ranges between 50% to 200%, in steps of 25% and for earth fault if ranges from 10 to 70%, in steps of 10%. Time Setting Multiple (TSM) ranges from 0.5 to 1pu in steps of 0.01pu or in steps of 0.05pu depending on the relay.

Figure 8: Existing protection coordination



Important data required for the coordination study [15]:

- Single Line diagram
- System voltage levels
- Incoming power supply data
  - Impedance and MVA data
  - X/R ratio
  - Existing protection including relay device numbers and settings, CT ratios and time-current characteristic curves
- Data on system under study
  - Generator ratings and impedance data
  - Motor ratings and impedance data
  - Protective devices ratings including momentary and interrupting duty as applicable
  - Time-current characteristic curves for protective devices
  - CT ratios, excitation curves and winding resistance
  - Thermal (I^2t) curves for cables and rotating machines.
  - Conductor sizes and approximate lengths
- Short circuit and current data

- Maximum and minimum momentary (5cycles and above) short circuit currents at major buses.
- Maximum load currents
- Motor starting currents
- Transformer protection points

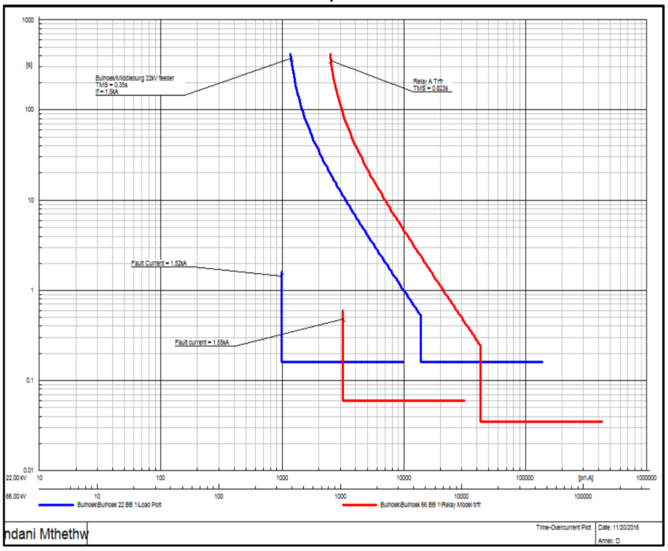
The above Figure 8 shows the proposed control plant (secondary equipment) plan in terms of the protection after connecting the Teebus Hydro Plant. This section will demonstrate the protection scheme used in this system. This is achieved by adding relays and their associated instruments transformers at the appropriate places within the network model. The 22kV feeders will be protected by the SEL-351S and the 66kV will protected by 4FZD 3920 three-pole distance/differential feeder protection scheme. This scheme offers distance/differential protection (RED670) and the directional back-up protection O/C and E/F (REF615). For 66kV buszone single busbar, a high impedance buszone protection scheme will be used since it consists of a F35 relay which offers two zone protection with a check zone for a single busbar with bus-section breaker. This will ensure fast selective protection for buszone faults.

A. Synchronism Check Protection for Generators

Where two network sections are switched in by control command or following a 3-pole auto-recloser, it must be ensured that both network sections are mutually synchronous. For this purpose, a synchronism-check function is provided. After verification of the network synchronism, the function releases the close command. At Synchro check mode the variables ΔV, Δf, $\Delta\alpha$ are checked. If they reach set values, a release command is issued for as long as all three conditions are met, but at least for a settable time [7].

The protection schemes shall be matched to provide the inter-tripping between Badsfontein and Bulhoek substation. Note: The islanding is not catered for; the protection is set in such a way that whenever the fault is experienced the generation will be curtailed or switched off completely. In terms of the protection, once the system goes to Islanding the protection will be able to disconnect the energised area with synch check mechanism [15].

Figure 9: Bulhoek/Middleburg 22kV line and Relay at the trfr



VII. Transient Stability studies

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on transmission facilities, loss of generation, or loss of a large load [17]. The stability studies look at how a power system operates during disturbances.

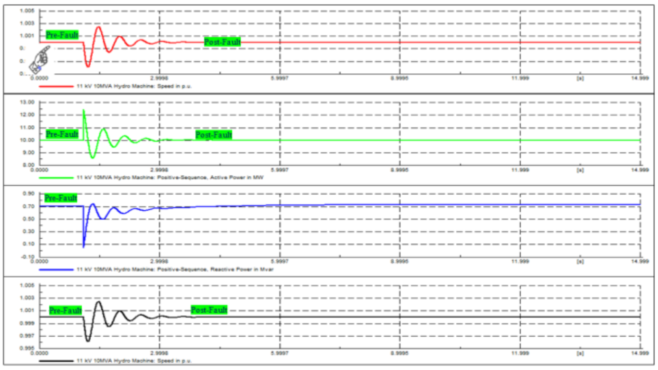
A common objective is to see how long the protection device can take to clear a fault before the generator becomes unstable. It can be observed that when there is insufficient time to clear a fault and excessive frequency variations, this poses an issue in stability.

The following planning scenarios were followed [17]:

- Peak load scenario
- Maximum output of the generating plant
- Low excitation voltage (absorbing Q)
- Minimum network strength i.e. low fault levels (single phase-ground faults level)
- Using a generator model with a tuned Automatic Voltage Regulator (AVR)

- No Power system stabilizer (PSS) in the generator model

Figure 10: Teebus Hydro Plant dynamic simulation plots with contingency 'Ruigtevallei/Badsfontein 66kV line'



Voltage stability analysis - 22kV system [18]:

- The X/R ratio does have an effect on the voltage stability of the system
- A lower X/R ratio had a negative effect on the voltage stability margin
- A higher X/R ratio had a positive effect on the voltage stability margin
- An increase in hydro power penetration increased the stability margin

On the simulation plot Figure 10 above, it can be noted that the fault is applied on Ruigtevallei/Badsfontein 66kV line (critical infeed lost power - case1). The system is fed via a Dreunberg/Badsfontein 66kV line as a reliability security. The faults simulation is set to stop at 15sec in order to clearly observe the behaviour of stability. The voltages and the thermals are below the allowable limits even during the fault; therefore, system is able to maintain the stability.

Figure 11: Guideline to determine the stability of the network [17]

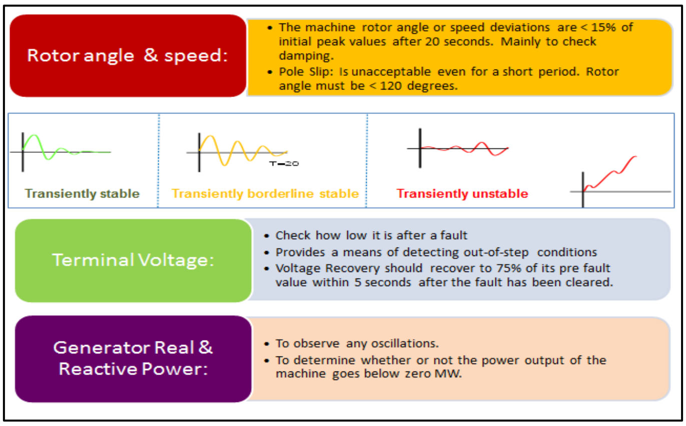
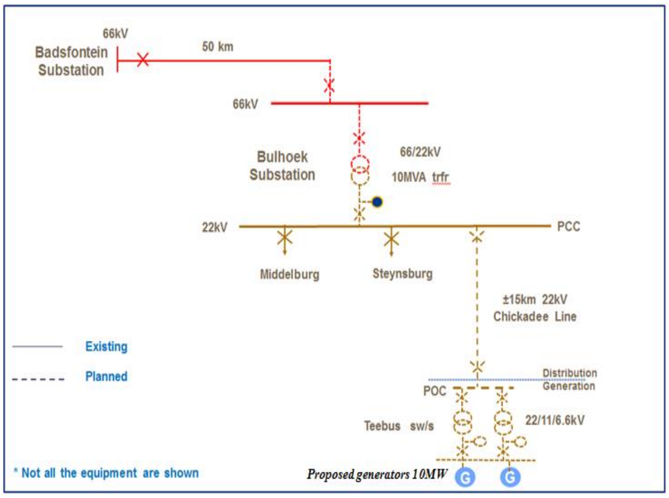


Figure 11 above is sourced from the SA Distribution Grid Code for Renewable Power Producers; this is used as a Standard guideline that should be adhered to when performing the analysis.

VIII. PROPOSED SOLUTION

Figure 12: SLD showing the Teebus switching station solution



The Figure 12 below shows a Bulhoek substation with the two planned generators. The high level scope of work to connect the Teebus Hydro is as follows:

- It is proposed to connect the Teebus Hydro Plant directly to the existing Bulhoek substation
- Construct ±15 km of 22kV Chicadee line from Teebus plant to Bulhoek s/s
- Upgrade the existing 66/22kV 5MVA trfr to 10MVA trfr and 22kV feeder bay
- Build a new switching station to connect the two generators

- Build new control room and extend the existing substation to be able to fit the new protection schemes

Figure 13: Bulhoek/Middleburg 22kV voltage profile simulated from DigSilent

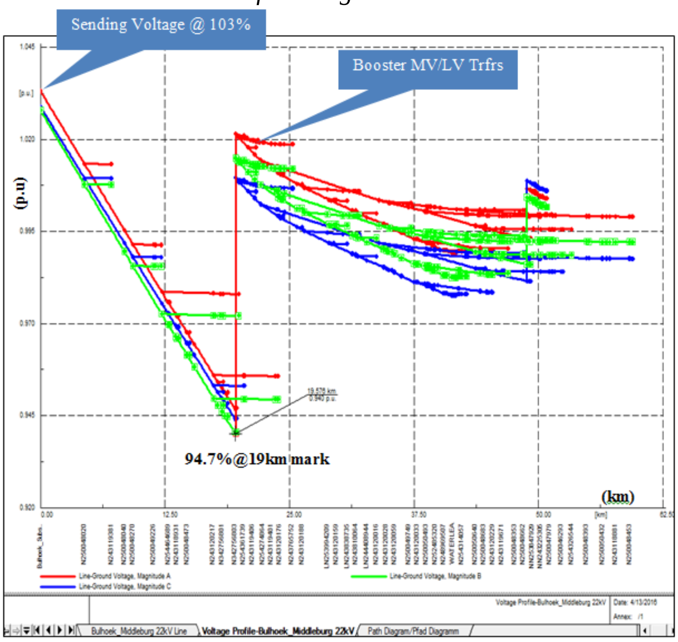
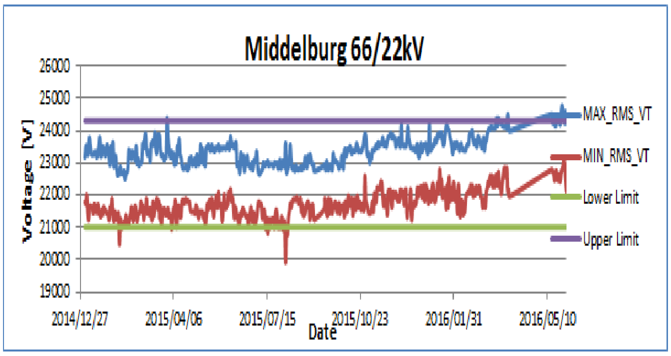


Figure 13 above shows the voltage profile of the existing network status for Bulhoek-Middleburg 22kV feeder. It can be noted that the simulated results shown on this profile matches the measured minimum voltage of 94% of the nominal voltage taken from the MV-90 tool. The voltage profile illustrated above also includes the MV/LV booster transformers (dashed lines). It can also be noted that the voltage regulator location is such that it has an impact on per unit voltages downstream.

Figure 14: Bulhoek/Middleburg 22kV feeder RMS voltages

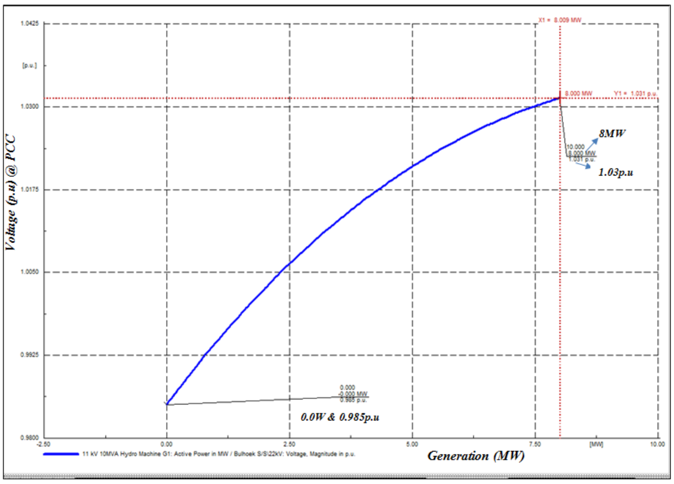


Based on the graph in Figure 14 above, it is found that the voltage regulation is within limits; except for 2015/02/07 and 2015/08/06 where the voltage is below the lower limit. The voltage is above the upper limit on 2015/03/30 and from 2016/03/24 to 2016/05/15. This was due to the outage that took place during this period where some of the load was transferred to this feeder. The outage information was captured from the field service Engineer for the area where Teebus Hydro is located. The Steynsburg 11kV feeder is also dispatching from a step down transformer from Bulhoek/Steynsburg 22kV feeder.

A. Voltage Variation Test (VVT) (Case 3)

The VVT study was carried out with the generators generating at maximum output. For any stable generation plants, such as concentrated Solar Power Plant (CSP) and Hydro Plant (which seldom trips), a VVT limit value of 5% is specified because rapid output changes and tripping of plant occurs infrequently.

Figure 15: Generator Power (MW) vs Busbar Voltage at Bulhoek S/S



A PV curve on Figure 15 above shows the voltage trend as the generation power (MW) increases. It can be seen that the more power generated to the system causes the voltage to rise gradually. In this PV curve the maximum power of 10MW was generated and the voltage at Bulhoek 22kV busbar increased to 1.03pu as shown on Figure 15. The Table 3 below shows the generation output and the voltages simulated at the PCC (Bulhoek S/S busbar) in a table format.

Table 3: Generator Power (MW) vs Simulated Voltages

Generation (MW)	Voltages (p.u)
0.00	94.3
2.50	99.3
5.00	1.01
7.50	1.02
8.00	1.03
10.00	1.03

IX. CONCLUSIONS

This report discusses several key issues regarding the development and integrating small Hydro Power plant into the existing electrical utility distribution unbalanced system with a focus on the instability and the quality of supply problems.

With the power flow analysis and study done it can be concluded that the customers taking LV supply can connect generators up to 350kW. Customers with generator sizes > 350 kW shall take supply at MV or HV. This is due to the very low fault levels on the LV network and the conductor sizes used.

With the studies done in this paper, all the small potential IPPs can be accommodated after the strengthening of the MV network. It has been evident (

*Figure **10***) that the more generators on the network the better the voltage unbalance and the voltage stability as well as rapid voltage change. The existing Bulhoek network is limited to about additional 10MW. For any additional unknown generation, the option of building a new substation fed from the traction network would be feasible. Further network analysis is required.

Most of the findings from the simulations were consistent with what was expected when comparing with other literatures. From the simulation results it was seen that the performance of the variable speed generators were superior to that of the fixed speed generators during transient conditions. It was also seen that the weakness of the network had a negative effect on the stability of the system.

It is also noted that the stability studies are a necessity when connecting the generators to a network and that each case should be reviewed individually. The fundamental cause of voltage instability is identified as incapability of combined distribution and generation system to meet excessive load demand in either real power or reactive power form.

From the above Chapters, it can be concluded that the presence of small hydro generators on the distribution level will have a positive effect on the transient stability of the system.

It is important to note that the generation supplies loads that would otherwise be supplied by the utility network. From a voltage change perspective, it does not matter how much of the generation is consumed locally or fed back into the network. When the generation output changes, the loading in the utility network changes accordingly, as the utility network supplies loads that would have been supplied by the Hydro generator.

Islanding of the DG is not allowed in South Africa. In cases where the Hydro plant connects to a distribution network with low voltage problems or where voltage support becomes a problem during periods of high load demand, the generation could be used to assist in reactive power generation for voltage regulation.

Relay coordination analysis was done considering three phase faults, phase to phase faults and single phase to ground faults. Protection analysis was performed in DigSilent (PowerFactory) and manual calculations were done. The results show that the CBs and relay time settings are required to be changed to be able to detect and isolate the faulty section.

From the literature reviews it can also be concluded that not all the problems regarding the connection of distributed generation have been addressed completely. International research and Grid Code specifications are focused on networks with strong interconnection and voltage support and these conditions might not be true for the South African grid.

X. RECOMMENDATIONS

The study original focused on connecting the small Hydro plants on the already unbalanced distribution networks with the traction network linked to it. In this case it is necessary to evaluate the impact of the movement of each train while the generation is also in service. The detailed study is still need to be conducted to determine the method that will alleviate voltage unbalance using a time based STATCOM. This remain a major challenge encountered by Eskom engineers as there are scarce skills of conducting quality of supply studies on traction lines.

The other challenge is that the traction loads on the existing 132kV traction system does not reflect the actual configuration on site. The first step for future investigation is to ensure that each traction substation’s phasing is correct. The modelling of the loads at each site will also need to be updated. The vectorgrapher voltage unbalance measuring tool is required to be installed so that accurate QOS indication can be archived.

The data recording system and the protection schemes on various substations should be revamped.

The supply to Bulhoek substation need to be made firm to avoid the system switching to islanding mode. The Teebus Hydro project will contribute to sustainable development in South Africa through supporting the development of renewable energy in the country and support Eskom's aspiration for renewable energy.

XI. REFERENCES

[1] W. J.K, "Small hydropower in Southern Africa – an overview of five countries in the region," Energy in Southern Africa, 2013.

[3] W. J Klunne, Small hydropower in Southern Africa – an overview of five countries in the region, Johannesburg: CSIR, 2013.

[4] M. T. Joemat-Pettersson, "State of Renewable Energy," Department of Energy, Pretoria, 2015.

[5] W. K. J.G Slootweg, "Aggregated Modelling of Wind Parks in Power System Dynamic Simulations," IEEE Power Tech Conference, Bologne, 2003.

[6] Slootweg J, "Impacts of Distributed Generation on Power System Transient Stability," in Power Engineering Society Summer Meeting, IEEE 2002.

[7] M. M, "Line Distance Protection up to and Including 132kV," Eskom, Johannesburg, Megga Watt, 2014.

[8] C. D.C, "Protectione Eléctricas. Notas de Clase," in Universidad Industrial de Santander., Santander, 2007.

[9] L. Esser, "A global overview. Water Power & Dam Construction," 2012.

[10] Mckenzie M, "Existing Hydro Power In South Africa," 22 Februay 2012. [Online]. Available: http://urbanearth.co.za/articles/existing-hydropower-south-africa.

[11] A. N. H Knudsen, "Modelling and transient stability of large wind farm," vol. 25, no. 1, 2003.

[12] R, Anagha, "Comparison of various Wind Turbine Generators," Multidisciplinary Journal of Research in Engineering and Technology, vol. 1, no. 2, pp. 129-135, 2016.

[13] K. Jia, "An Islanding Detection Method for Multi-DG Systems Based on High-Frequency Impedance Estimation," An Islanding Detection Method for Multi-DG Systems Based , vol. 8, no. 1, p. 158, 2017.

[14] J. A. Martin-Arnedo, "Impacts of Distributed Generation on Protection and Power Quality," 2009.

[15] J. M. J.Holmes, "Protection of Electricity Distribution

[16] Dr Cater Brown, Baic Power System Protection, Johannesburg: Eskom Center of Excellence, 2001.

[17] K. H. SALEH, "Transient Stability Improvement in multi-machine system with using power system stabilizer (PSS) and Static Var compensator (SVC)," in 17th International Conference, ICEESE 2015, Istanbul , Turkey, 2015.

[18] P. G. Arunkumar, "Power System Stability Enhancement using FACTS Controllers," IEEE, 2012.

[19] K. W. Slootweg J, "Impacts of Distributed Generation on Power System Transient Stability," in Power Engineering Society Summer Meeting IEEE, 2002.

[20] M. Klopper, Stability Analysis of Distributed Wind Generation Operating on Weak Distribution Networks in the Presence of Hydro Generation, South Africa: University of Cape Town, 2011.