A voltage dip management program for Swaziland

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DECLARATION

I hereby declare that all the material incorporated in this dissertation is my own original unaided work except where specific reference is made by name or in the form of a numbered reference. The work herein has not been submitted for a degree at another university.

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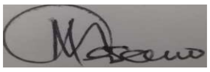

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ABSTRACT

The importance of Power Quality (PQ) is recognised by governments internationally to such an extent that in non-competitive electricity markets such as Southern Africa, it is required by law that the supplier of electricity must comply with a technical minimum standard. It is achieved in mostly, a similar approach in these countries by stipulating these requirements in the license agreement between the supplier of electricity and the energy regulator. The energy regulator normally operates under a government mandate to protect the economy, not only by price regulation, but also by protecting the needs of users in ensuring that the electricity is served at a minimum level in PQ and supply reliability.

The above requires that PQ parameters are continuously recorded and monitored for compliance to the minimum technical standards. A PQ monitoring system only presents the visibility on the performance level of the utility. It is the first step to what the energy regulator requires, namely the management of PQ. Data analysis is then needed for the assessment of recorded data. The information resulting is used for deployment in network operation. The latter is the ultimate goal, namely a voltage dip management program.

Voltage dips are generally the main focus of PQ. One major reason is that every voltage dip can represent a local outage to a user. A production process can shut down when voltage is reduced for a period within the technical definition of a voltage dip. This voltage dip is only recorded as a dip by the utility and not an outage. It can be that a utility reports high reliability but that the customer experiences a loss of production during every voltage dip. Voltage dips will in general occur much more frequently than interruption events as most of the root-causes (e.g. lightning and birds) are not within the direct control of the utility.

Voltage dips constitutes 50% of all PQ problems to be investigated by a utility [6]. Investigation requires finding the root-cause of each dip, the impact on the load, the penetration into the network and finally, the possibilities to mitigation. Most of the voltage dips correlate to an interruption as a voltage dip is mostly the result of a short-circuit condition somewhere in the network. A fault current will normally be interrupted after a period dictated by the trip setting of protection equipment.

During the time that the fault current flows, voltage drops over the impedances towards the location of the fault, dictated as the loss of voltage at the point of measurement. A lesser number of voltage dips are expected to be due to three phase - phase load action such as the energisation of transformers and the online starting of rotating loads. These types of voltage dips are expected to be due to a balanced loss of voltage between phases. Most of the voltage dips are therefore unbalanced between the phases.

At present, more than 70% of Power Quality customer complaints received by Swaziland Electricity Company are dip related hence the need to develop a voltage dip management program. In this dissertation, the root-causes of the dips, ownership, its impact on customer loads and dip mitigation measures will be discussed in order to formulate an effect voltage dip management program for SEC.

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LIST OF ABBREVIATIONS

EDM – Electricidade De Mocambique

EHV – Extra High Voltage

ESKOM – Electrical Supply Commission

HV – High Voltage

IEC – International Electrotechnical Commission

IPCC – Internal Points of Common Coupling

IUMOU - Inter-Utility Memorandum of Understanding

KPI – Key Performance Indicators

LV – Low Voltage

MV – Medium Voltage

NCC – National Control Centre

NRS – National Regulatory Standards

PCC – Point of Common Coupling

PQ – Power Quality

PQM – Power Quality Monitoring

QA – Quality Assurance

QoS – Quality of Supply

QoSWG – Quality of Supply Working Group

RMS – Root Mean Square

SA – South Africa

SADC – Southern African Development Community

SANS – South African National Standard

SAPP – Southern African Power Pool

SCADA – Supervisory Control and Data Acquisition

SEC – Swaziland Electricity Company

SERA - Swaziland Electricity Regulator Association

SZNS – Swaziland National Standard

THD – Total Harmonic Distortion

DEFINITION OF TERMS

Declared Voltage – This is the set operating voltage of a network which must have less deviation from the nominal voltage.

Event – This is the occurrence of an abnormal or normal condition in the network involving either one or more state changes relating to an incident in the network.

Power Quality – Is defined as a steady supply voltage that is within the limits specified in a Quality of Supply standard, e.g. NRS 048.

Residual Voltage – This is the remaining voltage after a disturbance in the network.

Root-cause – The primary cause resulting in the occurrence of an event in the network or loss of supply to a customer.

SAPP – This is a South African body which ensures that the electricity supply to customers which are members of the body is reliable and economically friendly. This must be consistent with the reasonable utilisation of natural resources.

State Change – This is a change in the condition of a network caused by the operation of an equipment.

Transient – This is a momentary variation of current, voltage or frequency.

KEYWORDS

Power quality

Power quality standards

Voltage dip definition

Voltage dip severity

Voltage dip characteristics

Voltage dip root causes

Voltage dip monitoring and management

Voltage dip ownership and mitigation

Impacts of voltage dips on loads

Verification and validation of voltage dip root causes

1 Introduction

The rationale for the research done is presented and the structure of the document is discussed.

1.1 Background

The operational application of electrical Power Quality (PQ) is to measure, analyse, benchmark and mitigate concerns related to the quality of electricity. It gained importance since the 1980s as electrical equipment in the supply industry became older whilst at the same time user equipment became more sensitive to supply variations due to the increased use of computerised control and power electronics [1], [2].

PQ, when both voltage and current parameters are considered, reveals the system technical performance and as such can be an important input to all aspects of power system operations. PQ can be managed by tracking the compliance to minimum technical requirements and mitigating concerns as and when identified. This requires understanding of the relation between cause and effect of poor PQ [2]. When PQ data supports system operations, then it becomes a support tool useful in containing operational risk at both the utility and the user.

An international PQ measurement standard, the IEC 61000-4-30 standard is used to harmonise the measurement of PQ. This standard previously qualified and quantified the measurement of voltage parameters and why PQ was historically also known as "Quality of Supply" (QoS) until recently.

The latest edition, being edition 3 published on 20 February 2015, addresses both the measurement of voltage and current PQ parameters. Two instrument classes are identified, namely Class S and Class A.

An instrument that complies with Class A standard will produce the same results regardless of the manufacturer of that instrument. Class S will not conform to the same strict metrological and signal processing requirements of Class A but can still be used for e.g. PQ statistical surveys.

If the PQ instrument makes use of an exact time reference such as GPS to time-stamp the PQ parameters, many additional advantages for power system operation can result. When time-stamping uncertainty compares to Phasor Measurement Unit (PMU) performance, namely better than 1 μs, it is possible to also include the synchrophasor measurement standard (IEEE C.37.118.1) resulting in numerous innovative and additional applications with PQ data [1]. PQ is normally composed of network reliability and Quality of Supply (QoS) as shown in Figure 1.1. It defines the quality of the waveform served to customers and how reliably it is done [3].

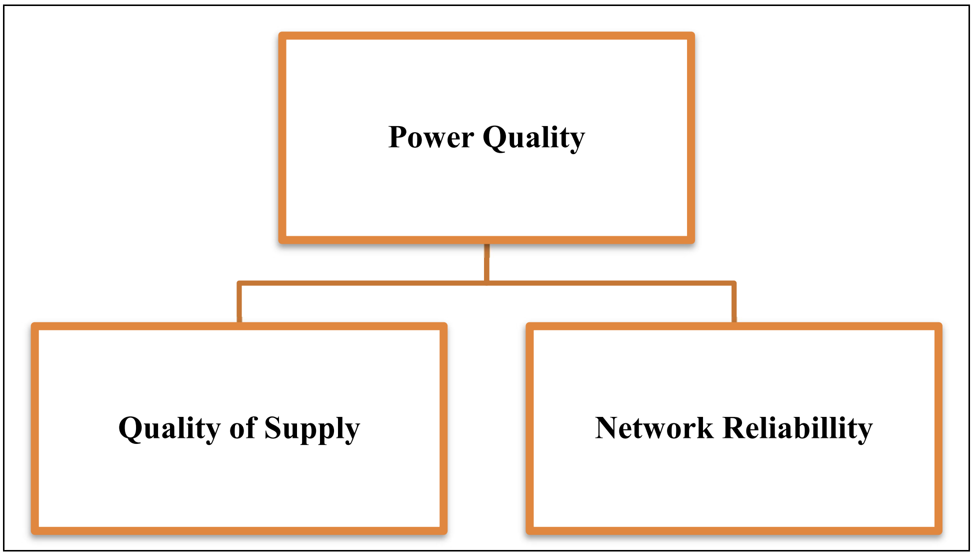

Figure 1.1: Components of Power Quality

QoS describes the technical parameters of the quality in electricity served to customers and the extent to which the needs of the customers are met. Minimum requirements are typically defined for QoS parameters in e.g. national specifications or standards. It focuses on voltage magnitude, voltage asymmetry, flicker, waveform distortion inclusive of individual harmonics and voltage waveform events such as voltage dips and swells.

Network reliability deals with the duration and frequency of voltage interruptions, classified either as momentary or sustained [3].

1.2 Problem statement

The Kingdom of Swaziland set a strategic priority to stimulate economic growth. Electrical energy is one fundamental component to support this goal. Swaziland Electricity Company (SEC) is a parastatal company, supplying electricity to the entire country (Swaziland). Due to a non-competitive Electricity Supply Industry (ESI), a regulated QoS environment for the distribution of electrical energy is required by Swazi law and overseen by the Swaziland Energy Regulatory Authority (SERA). The goal for SEC in monitoring and managing PQ is to positively impact the Swazi economy. Monitoring of PQ must include the different aspects of the SEC business, being generation owned by SEC, from Independent Power Producers (IPP's), from Eskom and then the transmission[1] and distribution[2] of energy until it is delivered to the end-users.

A measurement strategy is needed to further ensure sufficient visibility of QoS performance at each of the contributors to the Swazi ESI. From a network operation point of view, 11 PQ instruments, monitoring 15 nodes were installed at infeed points and other strategic points within the network. These instruments comprise 7 Vecto IIs (monitoring voltage and current at one feeder each) and 4 Impedo-DUOs (monitoring voltage and current at two feeders each).

By far, most complaints received from customers involve voltage dips which results to the following undesirable effects:

- Customer dissatisfaction – Customers not happy with unreliable power.
- Closure of companies due to losses which are a result of voltage dips (A dip can significantly affect a process of a product, for instance, in a bakery company, frequent dip occurrence will result in an undesirable product which might require disposal).
- Disputes between SEC and customers due to equipment failure caused by voltage dips.

These are the push factors which led to the urgent need to improve service delivery (reducing / eliminating voltage dips) by formulating a voltage dip management programme for SEC. This will be achieved by:

- Assigning dip root-causes and
- Implementing mitigation measures.

The research and development of this management programme is therefore reported in this dissertation. Performance of the system (field data) with respect to dips is then validated by means of simulations conducted in a network model for optimal results.

Table 1.1 present details on where the PQ instruments are in the network. Data from the instruments, for the purpose of the research reported in this dissertation are used for assessment of the SEC network dip performance. Previously, voltage dips were not pro-actively managed and it is well-known that voltage dips are the main cause to economic consequences at users from a PQ perspective.

[1] Transmission voltage is between 66 kV – 400 kV

[2] Distribution voltage is between 230V – 11 kV. Medium voltage is only 11 kV

Table 1.1: Location of Power Quality instruments on SEC network

Location	Voltage level (kV)	Monitored feeder / transformer
Infeed points		
Nhlangano II Substation	132	Normandie - Nhlangano II
Edwaleni II Substation	400	Camden - Edwaleni II
Edwaleni II Substation	400	Maputo - Edwaleni II
Big Bend Substation	11	USL - Big Bend
Big Bend Substation	11	USL - Big Bend
Strategic points		
Hhelehhele Substation	66	Transformer 3
Ka-Langa Substation	66	Transformer 2
Matsapha Substation	66	Matsapha -Thompson
Nginamadvolo Substation	66	Nginamadvolo - Piggs Peak
Simunye Substation	66	Simunye - Mhlume
Sithobela Substation	66	Sithobela -Nhlangano
Stonehenge Substation	66	Transformer 1
Stonehenge Substation	132	Stonehenge -Mkinkomo
Nhlangano II Substation	11	Incomer
Sidvokodvo Substation	11	Incomer

The PQ instruments were configured to record additional data during a voltage dip to support understanding the root-cause of the voltage dip. The IEC 61000-4-30 measurement of a voltage dip is based on rms values of voltage.

Additional information (rms values for current, active and reactive power, voltage and current waveforms) helps to better understand the direction of the dip, whether upstream or downstream and to identify a possible cause such as a short-circuit condition in the supply network or the energisation of a motor.

The type of additional information required is discussed and motivated in section 2.3. Note that this research uses synchronous data (data at different points in the network is time-stamped to 1 μs uncertainty) as it improves the analysis of voltage waveform events.

This additional information is what is considered in this dissertation as “forensic” dip data because it helps the PQ manager to identify the root-cause of a voltage dip. Eskom refers to it as “dip to trip” analysis as during almost every voltage dip, a specific breaker would have tripped to clear the fault condition that has caused the voltage dip.

The SEC PQ instruments continuously ‘push’ data to a central database (known as a PQ-Portal) via the Internet. PQ reporting can therefore be done from this database to not only assess the compliance of a single site to PQ standards, but importantly for the research reported in this dissertation, how the coherent data at different points in the network is deployed in root-cause analysis.

1.3 Focus and research methodology

The focus of the research was on the development of a voltage dip management program for SEC. Assigning ownership and cause is needed to identify the opportunity for mitigation. Features of the voltage dip management program for SEC and the data used in the validation of the research was realised by the following:

- Record QoS data coherently at all SEC interconnectors and strategic points in the network for a period of at least 365 days, January – December 2016 was used as reference. 365 days reflects not only daily and monthly variations, but also seasonal impact of weather on dip performance.
- Coherent measurements were realised by GPS time-stamping with a time-uncertainty of better than 1 μs.
- The data from all PQ instruments were continuously "pushed" to an Oracle database via the Internet.
- Voltage dip events occurring at several sites during the same time were grouped to a single voltage dip incident by means of automatic time-aggregation. It is possible that a single short-circuit condition can result in several PQ instruments recording a voltage dip during the same time.
- Impedance (distance) between the different points where the instruments are located, determine depth of the voltage dips. With increasing distance between a PQ instrument and where the dip occurred, it can be that the voltage at the PQ instrument point does not sag below the dip threshold.
- PQ reports are based on the National (SZNS 027-2:2012) and South African PQ standards (NRS 048-2:2007).
- Root-cause analysis for each event requires continuous research on the reasons why a dip has occurred. Technicians, who dealt with the interruption, must be consulted. These reasons are not necessarily comprehensively recorded in a network control room. Knowledge on the root-cause is a fundamental requirement of a successful voltage dip management program.
- A comprehensive analysis of all dip events was done at least once a week.
- Common causes (e.g. conductor related fault or faulty equipment) to internal dips (within SEC network) were used to group dips into different categories. Choice of the root-cause categories is motivated in Chapter 2.
- Direction from where the event originates was used to assign ownership to the network owner, for instance SEC or Eskom.
- Simulating fault conditions in DigSILENT as found by the analysis of field data, was finally done in order to verify and validate the root-cause information. It aimed to confirm that the recorded dip was indeed the result of a specific root-cause. This approach tested the accuracy of the root-cause analysis approach developed for SEC during this research. Results of the simulations are presented in Chapter 4.
- Voltage dip data were disseminated in near-real-time (e-mail and sms notification) to relevant SEC operational departments, IPP's, own generation plants, and possible SVC installations to support the timeous intervention (if possible) and collection of forensic data needed in the root-cause analysis (dip-to-trip matching).
- Mitigation measures as means to improve dip performance are presented in chapter 5 and a voltage dip management program formulated and implemented within SEC.

1.4 Structure of dissertation

Chapter 1: Presents the rationale and methodology of the research.

Chapter 2: Presents a literature study on the theoretical principles of PQ with emphasis on voltage dips and its analysis.

Chapter 3: Field results of voltage dips recorded over a period of 365 days are analysed and discussed in detail. Correlation of system interruption performance with dip events is done to determine and categorise root-cause.

Chapter 4: An SEC network model in DigSILENT^{TM} PowerFactory was formulated and used to emulate voltage dip events. Field data was verified and validated in the model (simulation of the root-causes) in order to ascertain the accuracy of the root-causes and the dip-to-trip matching exercise.

Chapter 5: Opportunities for the mitigation of voltage dips by firstly mitigating the root-causes and discussion of how the projects in the SEC master plan will help improve and reduce the occurrence of dips in the future.

Chapter 6: Presents the conclusion and recommendations of future work to better improve the quality of supply to customers.

2 Theoretical principles of electrical PQ

The chapter analyse literature that focus on voltage dips within the wider Power Quality (PQ) field of study. Applicable PQ specifications and standards are firstly discussed and interpreted against the regulatory environment pertaining.

Next, the monitoring and reporting of PQ parameters are analysed with a focus on voltage dips. Lastly, the root-cause of voltage dips, the impact on customer loads and possible mitigation measures currently implemented by other utilities and customers are discussed.

2.1 What is PQ?

PQ refers to the quality of electrical energy supplied to customers. It manifests in the quality of the voltage applied to a load and that is why PQ is also referred to as Quality of Supply (QoS) [2].

Voltage is what the utility provides; current is the consequence of the customer using the supplied voltage to operate electrical equipment. It is the current withdrawal through supply line impedances that cause variations in the voltage, dictated by Ohm's law, and why less than perfect PQ is to be expected in real networks.

A qualitative assessment of parameters that reflect the level of PQ in a network under consideration is possible by means of a technical standard on how to measure and benchmark PQ against a norm. Different PQ parameters are used for this purpose and briefly introduced below.

When voltage is applied to an electrical network, the impedance of the network and the load dictates the flow of current. A perfectly sinusoidal voltage at a fixed frequency, when applied to a linear impedance, will result in a perfectly sinusoidal current waveform at the same fixed frequency. Figure 2.1 illustrates the relationship between the different PQ parameters.

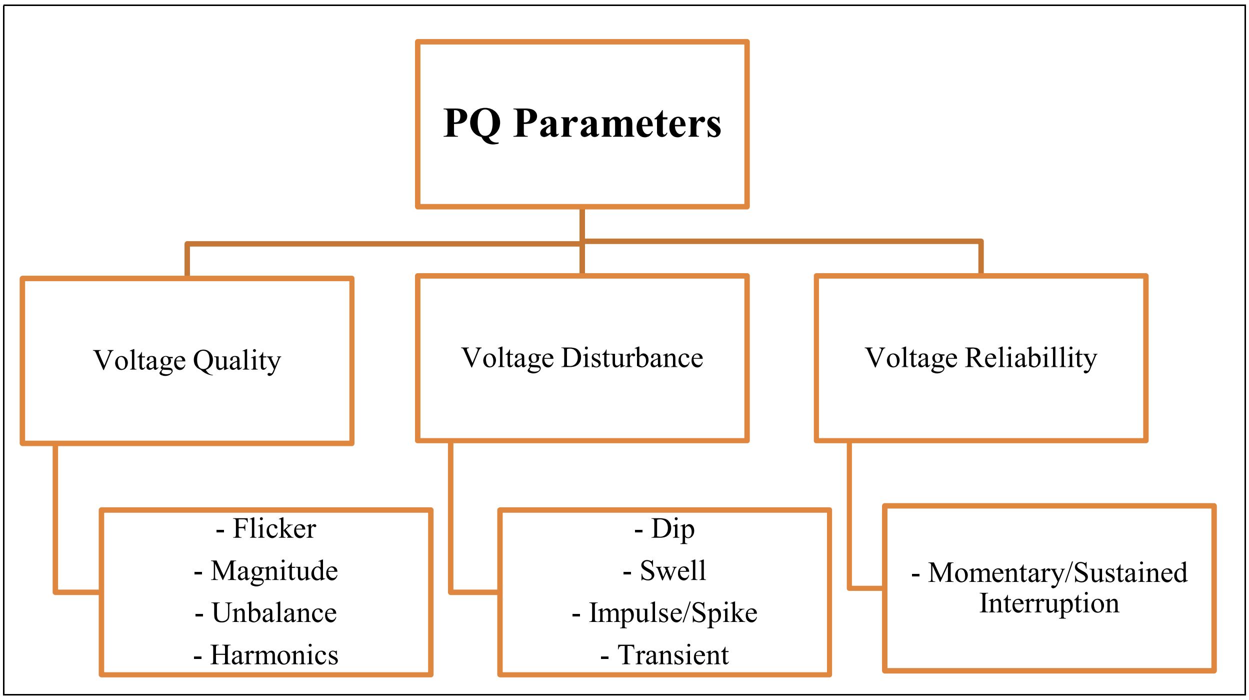

Figure 2.1: A block diagram of QoS technical parameters [30]

These parameters are discussed below with a focus on voltage dips.

2.1.1. Voltage magnitude

A voltage drop over the supply impedance towards the load terminals has to be within an acceptable level in order for electrical consumer equipment to function as designed.

Voltage can also rise over the supply impedance, resulting in a higher voltage at the receiving end than at the sending end due to reactive power injected into the line such as the distributed capacitance between line and earth or by power factor correction equipment. When loading increases and taking into account that most loads consume reactive power, voltage will be reduced.

A variation in voltage at the load terminals, dictated by the flow of current, is expected and considered an important PQ parameter, namely voltage regulation.

- Voltage regulation at the Point of Connection (PoC) to the customer is the PQ concept used to assess if the variation in voltage between periods of low and high loading is within an acceptable norm.

NRS 048:2 sets voltage magnitude compatibility levels to be within ± 10% for voltages less than 500V and ± 5% for voltages greater than 500V with reference to the nominal voltage for 95% of the time. In addition, it is required that no more than 2 consecutive 10-min rms values allowed to be outside the stipulated boundaries [4]. It is defined for purposes of detecting the start and end of a voltage dip, interruption or a swell. Upper limits are also set in line with equipment voltage standards, such as IEC 60071.

Figure 2.2 shows an example of a voltage magnitude compliance assessment based on a 7-day sliding principle recorded over a period of 7 days derived from a trend of 10-minute values.

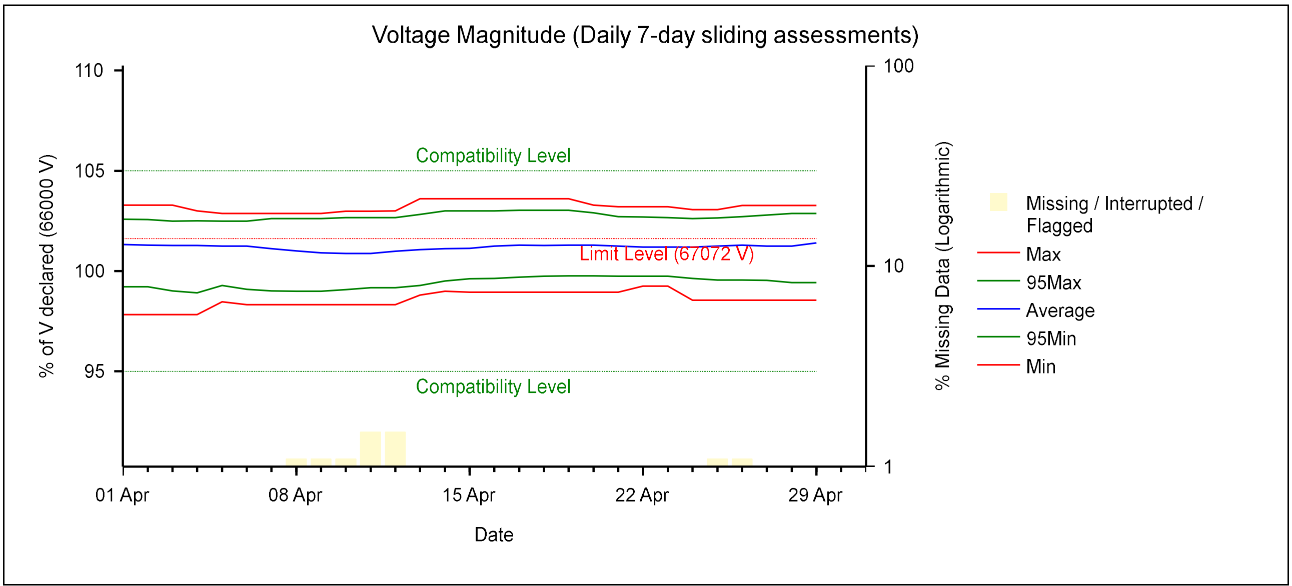

Figure 2.2: Voltage magnitude 7 day sliding assessment and 10-minute readings [31]

Causes of voltage magnitude fluctuation

Voltage fluctuations are due to variation in current causing a change in voltage drop in supply impedance towards the point of measurement. Sources of voltage magnitude variation can be categorised into two:

- Loads that cause separate voltage changes: These types of loads have a very short duty cycle, e.g. heating and cooling loads. Loads which have an electrical motor as a main power consumer are the worst due to high inrush currents during motor start-up (refrigerators and air conditioners) [27].
- Loads that cause voltage fluctuations: These types of loads results in continuous current changes, e.g. arc furnace, they have a high inrush currents which results in voltage changes.

Effects of voltage magnitude fluctuation

The effects of voltage magnitude fluctuations are [29]:

- Insulation failure due to over voltages. This is a long-term effect, not visible in the short term.
- Malfunctioning of induction motors: Under-voltages causes the starting torque of the motor to be reduced and increases the full load temperature due to drastic increase in current. In some instances, the motor will not accelerate at all, causing the motor to stall. Over-voltages on the other hand causes an increased starting torque, with increased starting currents, making the power factor to be relatively poor. This is not desirable since the increased currents causes additional voltage drop.

- Electronic equipment are less efficient in under-voltage conditions, the equipment will be more prone to voltage dip conditions which causes the equipment to stall or stop at times.
- Over voltages cause an increase in the magnetising currents of a transformer, in the presence of harmonics, the increase in voltage causes an increase in waveform distortion.

2.1.2. Voltage unbalance (asymmetry)

Three-phase voltages are not always perfectly equal in magnitude and symmetrically displaced in phase angle between the voltage phasors. It is the result of different loading per phase and/or asymmetrical phase impedances in the supply lines. The fundamental frequency 3-phase voltage phasors are transformed to the sequence domain in order to calculate the level of asymmetry.

In a three-wire network, a voltage asymmetry factor is expressed as the ratio of the negative sequence to positive sequence fundamental frequency phasor. In the case of a four-wire power system an additional zero-sequence asymmetry factor is expressed as the ratio of zero sequence to positive sequence fundamental frequency phasor. The voltage unbalance factor (VUF) is presented in Equation 2.1.

$$\%V_{unb} = \frac{V_{neg}}{V_{pos}} \times 100$$ **Equation 2.1**

Where:

V_{neg} is the rms value of the 50 Hz negative sequence voltage phasor

V_{pos} is the positive sequence voltage

- The voltage asymmetry factor is the PQ parameter of concern and is mostly referred to as voltage unbalance in PQ technical standards.

Figure 2.3 shows voltage unbalance in the time domain. It can be that both the amplitude and phase displacement between phasors are different.

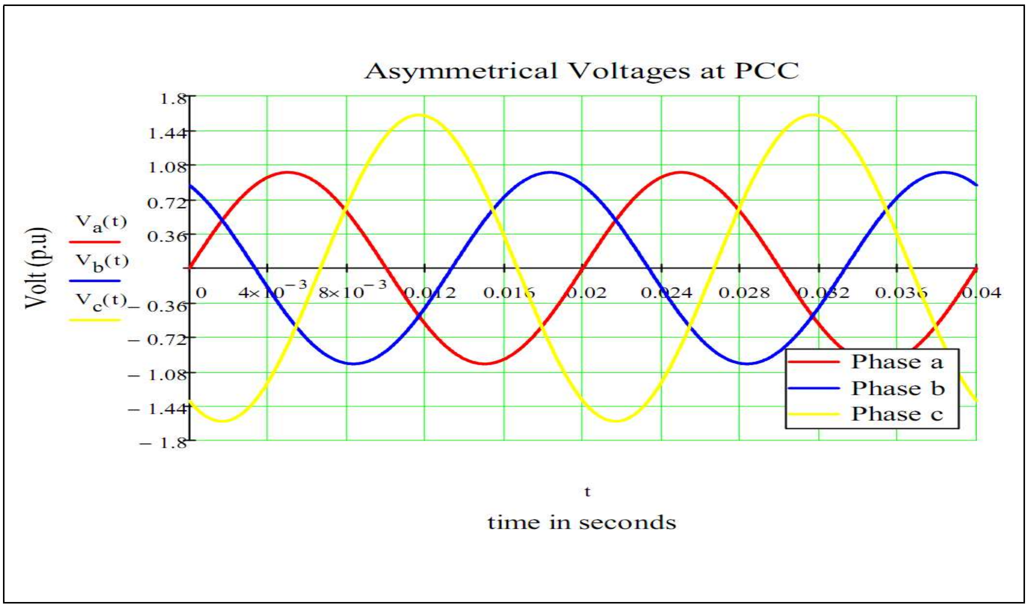

Figure 2.3: Voltage unbalance at the PCC [30]

In the case of 10 min values assessed on a 7 day sliding principle, voltage unbalance must be less than 1.5% for 95% of the time in networks with voltages greater than or equal to 132 kV and 2% for networks with voltages less than 132 kV [4].

Causes of voltage unbalance

Voltage unbalance in LV systems are mostly due to unequal single phase loading and in high voltage networks due to unbalanced loads such as arc furnaces and traction supplies to railways.

If the three-phase load is balanced, the current withdrawn is through unequal line impendences, then the voltage at the end of those impedances will be unequal.

Untransposed power lines can cause voltage unbalance due to uneven voltage drop in phase conductors.

Effect of voltage unbalance

A negative sequence voltage when applied to a rotating machine result in a reduction of torque. To compensate for the loss in torque, the slip frequency will increase withdrawing more line current which cause additional losses in the motor and why the winding temperature rise.

The increased operating temperature degrade the insulation strength of the motor. Apparent power loading of the supply system increase, increasing the line losses.

2.1.3. Voltage waveform distortion

Not all loads are linear. A non-linear load withdraws current from the supply system in a controlled manner, for example only during specific portions of the positive and negative cycles of the voltage waveform.

This non-linearity of current is mostly analysed in the frequency domain and is why harmonic analysis is used to describe the current waveform distortion. As harmonic currents also flow through the supply impedance, harmonic voltage drops then result in a distorted voltage waveform at the PoC, even if a perfectly sinusoidal voltage was applied to the upstream infeed of the power system.

If the supply impedance is low enough at harmonic frequencies, harmonic currents will not cause sufficient voltage harmonics to distort the voltage at the PoC up to the point that is becomes a concern. In a practical power system, supply impedance is a compromise between minimising voltage drops and the capital expenditure required.

For this reason, voltage waveform distortion can be a concern and why PQ parameters are used to assess the level of voltage distortion.

- Voltage waveform distortion is assessed by reflecting the Total Harmonic Distortion (THD) resulting from all the voltage harmonics as a single PQ parameter and by considering the individual voltage harmonic components as an additional PQ parameter.

Figure 2.4 shows distorted line neutral voltage waveforms for an LV power system. The distorted voltage waveforms are a result of the nature of the load drawing current downstream.

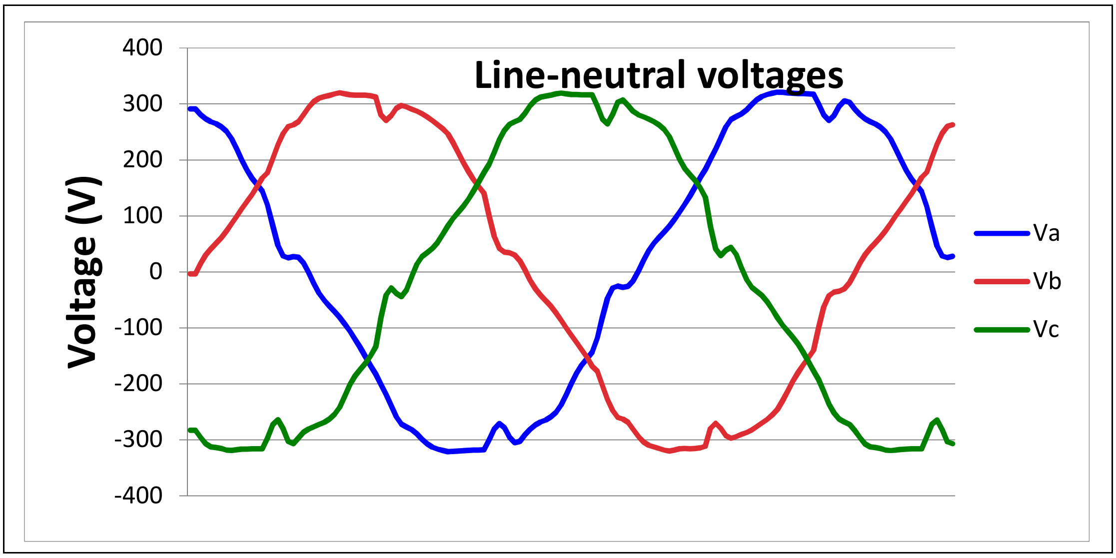

Figure 2.4: Distorted sine waveform [7]

Causes of voltage waveform distortion

Controlled thyristor rectifiers are well-known examples. Other causes include adjustable speed drives and solid-state heating controls [7].

Effects of voltage waveform distortion

Devices affected by distorted waveforms are [2][33]:

1. Transformers: Waveform distortion (current or voltage distortion) results in overheating of the transformer. Non-sinusoidal voltages used to excite the transformer cause an increase in iron (hysteresis and eddy) losses. Eddy currents (circulating currents in the conductors) concentration is higher at the windings of the transformer due to crowding effect of the magnetic field. The increase in losses is directly proportional to the square of the currents in the conductor and frequency, which ultimately cause an increase in the temperature of the transformer.

2. Cables: The normal flow of AC 50Hz current in a cable produces losses, presence of current distortion introduces more losses. The resistance of the cable is directly proportional to frequency due to the skin effect, whereby the unequal flux linkages across the cross section of the cable causes the current to flow on the edge of the conductor.

3. Neutral conductors: Three phase systems with equal loading in each phase will have zero current in the neutral conductor because each phase is out of phase with respect to the other, hence the currents in the neutral conductor cancels out. Unfortunately, non-linear loads such as computers produces these harmonics which add instead of cancelling out in the neutral conductor thus causing overheating of equipment.

4. Motors: These machines make use of variable speed drives (VSD). The voltages and currents from the VSDs to the motor are rich in harmonics. The voltage supplied to the motor is used to establish a magnetic field in the core, these results in iron (hysteresis and eddy) losses in the frame of the motor. Hysteresis losses are proportional to frequency. Therefore, an increase in frequency voltage components cause additional losses in the core of the motor due to an increase in the operating temperature of the core and the windings surrounding in the core. Non-sinusoidal voltages applied in a motor results in the circulation of harmonic currents in the motor windings.

5. Capacitors: Capacitor banks are designed to operate at a maximum of 110% of the rated voltage and at 135% of their kVAR rating. However, these limitations are exceeded if the power system is infested with current and voltage harmonics since they cause the voltage and current levels to be amplified (over voltage and high currents) due to resonance (series and parallel resonance). Since capacitive reactance is inversely proportional to frequency, the harmonic currents penetrate through the capacitor bank. The banks will act like a sink, it will attract harmonic currents, thus becoming overloaded.

2.1.4. Voltage flicker

Some types of loads, for example a crusher at a mine used to reduce the size of the mined product, withdraw current in a continuously changing fashion dictated by the torque requirements of the electrical motor driving the mill. A continuously changing voltage drop over the supply impedances then manifests at the PoC to that mine. This effect can penetrate to other PoC's in an interconnected network.

The change in voltage within an installation affects the lumen production of lighting equipment. When most of the lux level on a work surface is obtained from electrical lighting, a human can experience not only inconvenience such as irritation and headaches, but it can also trigger epilepsy.

This scenario is most relevant when the variation in voltage occurs at an interval of about 8.8 Hz. Practically, it manifests in the voltage signal as an amplitude modulation at 8.8 Hz.

- Voltage flicker is the PQ parameter of concern and assess the extent by which humans are at risk when exposed to lighting dominated by a varying electrical voltage source (minimal natural light).

Causes of flicker

The sources of flicker are electric welding machines, arc furnaces, motors at lifts and hoists, equipment with varying torque such as saw and rolling mills and large photocopy machines.

2.1.5. Voltage transients

Voltages transients, also known as Rapid Voltage Changes (RVC) are caused by normal network operations, for instance switching of network components and has a duration of a few milliseconds or less [4] than 20 ms otherwise it will be classified as an overvoltage. Voltage transient results in a steep rise in voltage and are relatively "short" compared to the 20 ms (50 Hz) of the fundamental frequency, refer to Figure 2.5. It can be that the voltage transient is not necessarily aligned with the peak of the voltage.

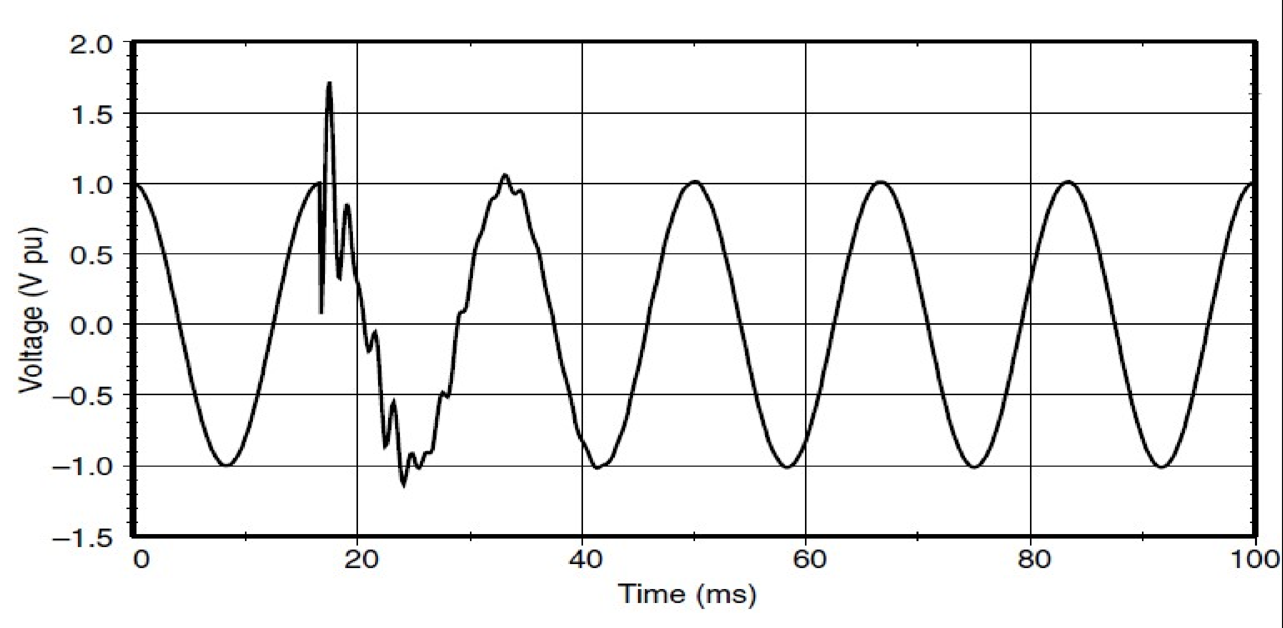

Figure 2.5: Voltage transient caused by the energising of a capacitor bank [2]

Voltage transients have a limited opportunity for accurate analysis is a challenge due to the limited bandwidth of voltage and current measurement transducers used in power systems. It is only possible to accurately record these parameters if special voltage and current transducers are used.

Causes of a voltage transient

A transient voltage is generated by any sudden change in the electrical circuit due to the stored energy contained in circuit capacitance (C) and inductance (L). They are mostly visible during the switching off large loads, energising of capacitor banks and load swinging (transferring load from one feeder to the other).

2.1.6. Voltage swells

Voltage swells are defined by the IEC 61000-4-30 standard as a deviation from the nominal voltage for a duration from 20 ms to 3 s. The deviation from the nominal voltage is set at +15% for networks with voltages less than 500V and +10% for networks with voltages greater than or equal to 500V [4]. There are no compliance criteria for voltage swells. Figure 2.6 shows a practical example of a voltage swell recorded in a three-phase system.

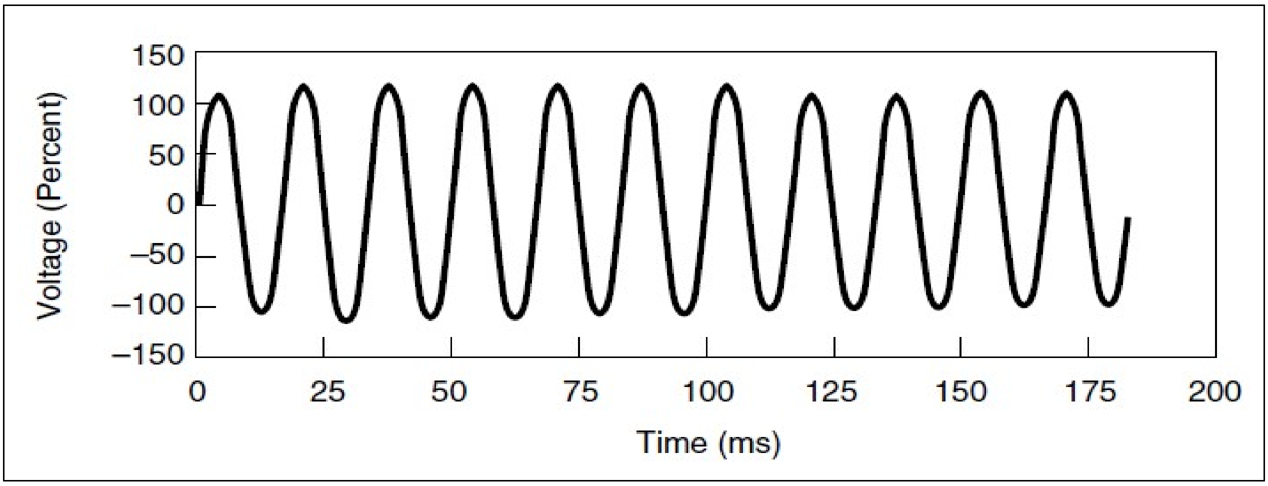

Figure 2.6: An instantaneous voltage swell [31]

Monitoring of voltage swells requires that all the phases of supply voltage be monitored for instances of voltages swells caused by three phase faults or loads. A capacitor bank can first emulate a short-circuit as capacitors are energised and thereafter be the cause for voltages to increase due to the injection of reactive power.

Causes of a voltage swell

The frequency of a voltage swell is less compared to voltage dips. A single-phase to ground fault causes a temporal voltage to increase in the un-faulted phases, this is common in ungrounded or floating ground delta. Disconnection of large loads in the system may also cause a voltage swell.

2.1.7. Voltage interruptions

Voltage interruption is caused by a loss of either one or more phases of supply to a customer for a duration of more than 3 s, it can either be momentarily (short duration with a range of > 3 s to 1 min) or sustained (for a duration exceeding 1 min) [4]. An interruption can often result in an under-voltage condition in other parts of the network. Figure 2.7 shows an example of a momentary interruption caused by the operation of a recloser to clear a fault.

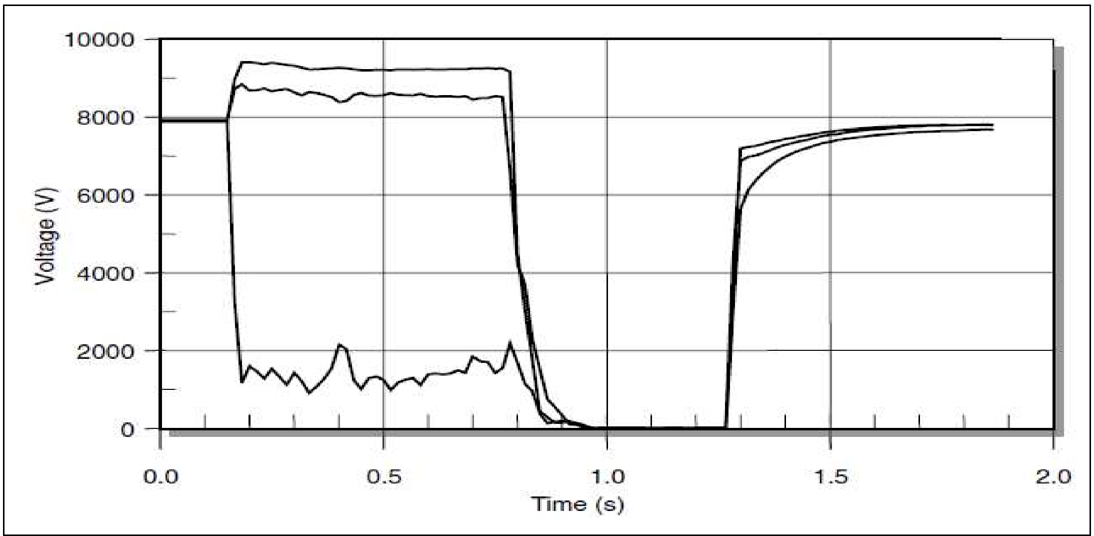

Figure 2.7: A momentary interruption in a three-phase power system [18]

Interruptions can either be planned (This is due to intentional disconnection of some parts of the network with the aim of performing maintenance and it results to a long interruption of the network) or unplanned (unintentional / malfunctioning operation of a protection device in the network / switching operations conducted to attend to an emergency condition). Voltage interruptions cause a complete shutdown of equipment.

2.1.8. Voltage dips

Fault conditions in a power system (short-circuits for example) are common occurrences and why protection equipment is designed to isolate the faulted circuit. Protection equipment would operate if the current towards the fault increase beyond a certain set point. This increase in current towards the fault increase the voltage drops in remote circuits.

The duration of the voltage drop at different points in the network (same dip event) is similar as it is dictated by the trip setting on the single protection device that clear (interrupt) the fault current. How much the voltage drops at a specific PoC, is set by the impedance between that PoC and the point where the fault is located. At the fault, the voltage can be zero if the fault condition is into zero impedance short-circuit. Ohm’s law dictates the voltage drop.

This reduction in voltage and the duration thereof represent a “loss of energy” served to electrical equipment and can shut down. Economic production is mostly affected as it takes time to commence normal operation of the affected plant.

For most users, voltage dips are the PQ parameter of highest importance as the impact is immediately noticed.

- The duration and depth of a voltage dip is used to classify a voltage dip event as the combination of how much voltage is lost for how long, represent a loss of energy. Specific combinations of duration and depth result in some voltage dips being more prone affect consumers.
- Voltage dips are classified in Southern Africa by the NRS 048-2:2007 in a unique way, designed to be a practical approach for utilities to manage the root-cause of the voltage dips and for users and to specify and operate electrical equipment such that the economic consequences of voltage dips can be minimised.

An in-depth discussion of voltage dips will be discussed later in the chapter.

2.2. Regulatory environment of Southern Africa

License holders are required by the regulator (e.g. SERA in the case of Swaziland) to comply with PQ standards as part of their licence conditions. NERSA (in SA) requires Eskom to serve SEC with a QoS beyond the minimum quality in electricity for SEC to deliver electricity of minimum quality to end-users.

Entities that sell electrical energy must manage networks and negotiate customer contracts as a means to manage PQ. Contractual relationships between utilities has to be set up when generation, transmission and distribution is handled by different utilities, to ensure compliance with the minimum standard of NRS 048 – 2:2007 [4]. A transmission company cannot comply with the minimum standards if the infeed from the generation utility does not comply.

Government tasks the electricity regulator with the responsibility of having a system in place that ensures that electricity is supplied to users within the compatibility requirements of NRS 048 – 2. The energy regulator also must address disputes between license holders and customers.

2.2.1 Power Quality standards

PQ standards were developed to provide equal starting points for PQ analysis and to enable analysers from different manufacturers to produce the same/similar results. Due to continuous measurement of raw electrical data at high sampling rate, shortfalls of the existing monitoring methods based on standards and regulations have been noted [2], [6].

Customers and utilities are restricted by PQ standards to ensure that customer equipment is compatible with the network. Customers are restricted in a sense that they should use products of good quality not likely to pollute the supply network and that can operate under non-ideal conditions as described for by the standards.

Utilities in Southern African should, but rarely do, ensure compliance to the minimum requirements of NRS 048-2. This harmonisation between different countries in Southern Africa aims at comparison of system technical performance and is a reference for equipment suppliers to design against [7], [8].

NRS 048-2 is used in the analysis of voltage dip data and the international measuring standards are used. The relationship between the different standards is shown in Figure 2.8.

NRS 048-2 was adopted from several of the IEC 61000-series and EN 50160 standards. SZNS 027-2:2012 is the official Swaziland standard adopted from NRS 048-2:2007. NRS 048-2:2007 is used for measurement and analysis.

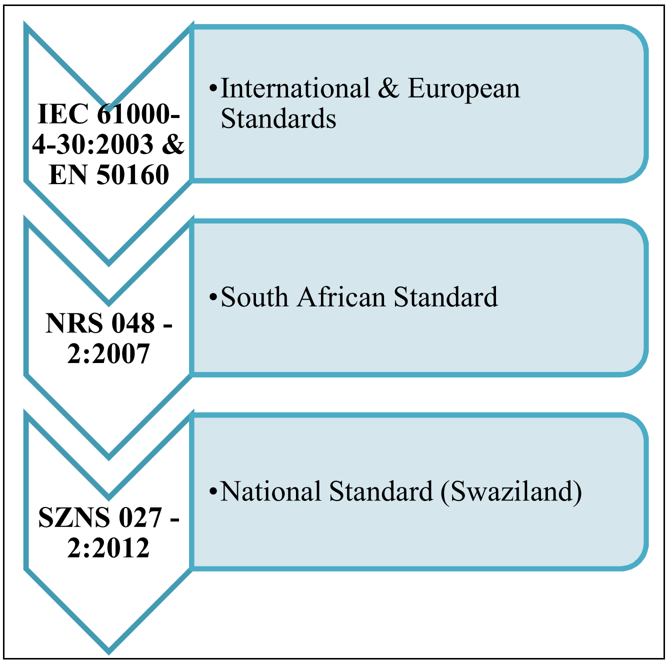

Figure 2.8: Relationship of applicable PQ standards

2.2.1.1. NRS 048–2:2007

NRS 048–2 specifies compatibility levels, limits, assessment methods and voltage characteristics for customers, electrical utilities and the national regulator as means of managing the level of PQ emissions supplied by licensees at the point of supply to individual customers. PQ parameters in use address voltage regulation, voltage unbalance, voltage dips, voltage transient, flicker, frequency, under voltages, over voltages and harmonics [4].

One of the goals the PQ standard is to provide a uniform approach in the characterisation of dip performance. It excludes phase angle jump, pre-dip and post-dip conditions during a dip.

NRS 048–2:2007 defines a voltage dip as a sudden reduction in the rms voltage below 90% of the nominal or declared voltage, for a period of between 20 ms and 3 s, in any or all the phase voltages of a single-phase or a polyphase supply. Dips are categorised according to classes S, T, X1, X2, Y, Z1 and Z2 as shown in Table 2.1

Table 2.1: NRS 048 voltage dip classes [4]

<table>
<tr><th rowspan="2">Range of dip depth
ΔU
(expressed as a % of U_d)</th><th rowspan="2">Range of residual voltage
U_r
(expressed as a % of U_d)</th><th colspan="3">Duration
T</th></tr>
<tr><th>20 < t ≤ 150 ms</th><th>150 < t ≤ 600 ms</th><th>0,6 < t ≤ 3 S</th></tr>
<tr><td>$10 < \Delta U \leq 15$</td><td>$90 > U_r \geq 85$</td><td rowspan="3"></td><td rowspan="2">Y</td><td></td></tr>
<tr><td>$15 < \Delta U \leq 20$</td><td>$85 > U_r \geq 80$</td><td rowspan="2">Z1</td></tr>
<tr><td>$20 < \Delta U \leq 30$</td><td>$80 > U_r \geq 70$</td><td rowspan="3">S</td></tr>
<tr><td>$30 < \Delta U \leq 40$</td><td>$70 > U_r \geq 60$</td><td>X1[a]</td><td rowspan="3">Z2</td></tr>
<tr><td>$40 < \Delta U \leq 60$</td><td>$60 > U_r \geq 40$</td><td>X2</td></tr>
<tr><td>$60 < \Delta U \leq 100$</td><td>$40 > U_r \geq 0$</td><td colspan="2">T</td></tr>
<tr><td colspan="5">NOTE: In the case of measurements on LV systems it is acceptable to set the dip threshold at 0,85 pu.</td></tr>
</table>

The standard differentiates the roles and responsibilities of the suppliers and customers with respect to voltage dip management, it states that:

a) ‘‘Licensees must manage protection performance times (for instance, the number of X-type dips allowed is more than the number of S-type dips),

b) Licensees must ensure proper management of faults occurring close to any particular customer, e.g. the acceptable sum of the number of T-type dips is less than the sum of the number of X-type or S-type dips,

c) There shall be a combined management between the utility and customers in terms of voltage dip performance of dip types S, X1, X2 and Z1,

d) The licensee must ensure that dip types T and Z2 are limited since they can lead to an interruption of customer processes,

e) The dip sensitivity of process equipment must be specified by customer to ensure appropriate mitigation measures are considered and implemented. The customer is encouraged to ensure that their plants can withstand short duration shallow dips,

f) Y-dips will be disregarded because all equipment is expected to ride through a Y-dip without being interrupted’’.

Voltage dips are based on the customer load compatibility and the protection characteristic of the network. Table 2.2 shows the basis of dip definitions and the relationship between the duration of a dip and the protection settings (zones of protection). A highlight of the cause and effect of each dip is also presented. The relationship of dip duration for the different types of dips vs the zones of protection is as follows:

- Zone 1 protection: Has a duration of 20 ms to 150 ms, resulting in dip types X1, X2 and T.
- Zone 2 protection: Has a duration of 150 ms to 600 ms resulting in dip types Y, S and T.
- Backup and thermal protection: Has a duration of 600 ms to 3 seconds results in dip types Z1 and Z2.

The factors determining the magnitude of a dip will be discussed at length later in the chapter.

Table 2.2: Basis for the definition of dip types [4]

Dip category	Values of duration & depth		Basis for definition
Y	Duration	>20 ms to 3s	Dip definition
	Depth	30%, 20%, 15%	Minimum plant compatibility requirement (this covers a significant number of short duration dips)
X1	Duration	>20 ms to 150 ms	Typical zone 1clearance (no pilot wire)
	Depth	30% - 40%	Desired plant immunity – as this spans many dips caused by remote faults on the licensee network
X2	Duration	>20 ms to 150 ms	Typical zone 1clearance (no pilot wire)
	Depth	40% - 60%	Dips potentially causing drives to trip, caused by remote faults on the licensee network
S	Duration	>150 ms to 600 ms	Typical zone 2 and accelerated clearance and some remote faults
	Depth	20% - 60%	Plant compatibility (drives trip > 20%) caused by remote faults on the licensee network
T	Duration	>20 ms to 600 ms	Zone 1 and zone 2 clearance times
	Depth	60% - 100%	Plant compatibility (drives trip > 60%) caused by remote faults on the licensee network
Z1	Duration	>600 ms to 3s	Backup and thermal protection clearance or long recovery times (transient voltage stability) or both
	Depth	15% - 30%	Remote faults and post dip motor recovery without stalling
Z2	Duration	>600 ms to 3s	Backup and thermal protection clearance
	Depth	30% - 100%	Closer faults and potential motor stalling

Dip characteristic values are well presented for the different types as the number of dip events recorded, which according to historical data have not been exceeded at 95% and 50% of monitored sites. Historical statistic data is provided for each voltage level. Table 2.3 and Table 2.4 indicate the number of dips recorded for each dip type in a year window for 95% and 50% of the site.

Table 2.3: Characteristic dip numbers per year for each category dip window for 95% of the sites [4]

Network voltage range (nominal voltages)	Number of voltage dips per year					
	Dip window category					
	X1	X2	T	S	Z1	Z2
6,6 kV to 44 kV extended overhead	85	210	115	400	450	450
6,6 kV to 44 kV	20	30	110	30	20	45
> 44 kV to 220 kV	35	35	25	40	40	10
220 kV to 765 kV	30	30	20	20	10	5

Table 2.4: Characteristic dip numbers per year for each category dip window for 50% of the sites [4]

Network voltage range (nominal voltages)	Number of voltage dips per year					
	Dip window category					
	X1	X2	T	S	Z1	Z2
6,6 kV to 44 kV extended overhead	13	12	10	13	11	10
6,6 kV to 44 kV	7	7	7	6	3	4
> 44 kV to 220 kV	13	10	5	7	4	2
220 kV to 765 kV	8	9	3	2	1	1

For comparison purposes, utilities are to measure network performance in terms of dips against Table 2.3 and 2.4. However, utilities must take note that the network voltage refers to the nominal voltage of the licensee network which supplies a measurement site.

2.2.1.2. SZNS 027-2:2012 PQ Standard

SZNS 027-2:2012 was adopted from NRS 048–2: 2007, as a result, the voltage characteristics, compatibility levels, limits and assessment methods are similar [9].

2.2.1.3. EN 50160 Standard

A voltage dip in this standard is defined as a temporary reduction of the rms voltage below 90% for a period of between 10 ms and 1 minute [10]. A voltage dip is considered a two-dimensional electromagnetic disturbance which is determined by both duration and the depth. The values of the residual voltage and duration is measured in percentages of the reference voltage.

There are different performance criteria used in the classification of voltage dips, i.e. the impact on equipment. These are [10]:

Criteria A: There shall be no disturbance in the function of the equipment. No decrease in performance / degradation below a performance level specified by the manufacturer.

Criteria B: This is similar to criteria A; the only difference is that degradation / a decrease in performance is allowed.

Criteria C: This is associated with a temporary loss of function of condition; the equipment can be restored by operating the controls (SCADA systems).

The electromagnetic environment and the different classification of voltage dips for statistical purposes are shown in Table 2.5. The values to be inserted in the CELLS are the number of equivalent events and polyphase aggregation is used in calculating the residual voltage.

Table 2.5: Classification of voltage dips according to residual voltage and duration [10]

Residual voltage	10 ≤ t ≤ 200	200 < t ≤ 500	500 < t ≤ 1000	1000 < t ≤ 5000	5000 < t ≤ 60000
90 > u ≥ 80	CELL A1	CELL A2	CELL A3	CELL A4	CELL A5
80 > u ≥ 70	CELL B1	CELL B2	CELL B3	CELL B4	CELL B5
70 > u ≥ 40	CELL C1	CELL C2	CELL C3	CELL C4	CELL C5
40 > u ≥ 5	CELL D1	CELL D2	CELL D3	CELL D4	CELL D5
5 > u	CELL C1	CELL C2	CELL C3	CELL C4	CELL C5

Since voltage dips are random in nature and the size of the network is increasing daily, it is not possible to obtain accurate statistical results. However, voltage dips can be classified according to the impact they have on the network in terms of their severity. The electromagnetic environment is characterised by the following classes [10], [10].

Class 1: This class refers to protected supply systems, the compatibility levels are lower than in the public supply network, e.g. measurement facilities.

Class 2: Refers to the PCC and IPCC in an industrial environment.

Class 3: Refers to IPCCs in an industrial environment.

The different recommended test level and duration of voltage dips is shown in Table 2.6, with the assistance of the classes defined above.

Table 2.6: Recommended test levels and duration of voltage dips [10]

Class	Test level and duration of the voltage dip				
Class 1	Dependent on the case, according to the requirement of the equipment				
Class 2	0% during ½ cycle	0% during 1 cycle	70% during 25/30 cycles		
Class 3	0% during ½ cycle	0% during 1 cycle	40% during 10/12 cycles	70% during 25/30 cycles	80% during 250/300 cycles

2.2.1.4. IEC 61000-4-30 Standard

The IEC 61000-4-30 edition 3 standard provides measurement methods and sets accuracy levels for recording PQ parameters. The standard is similar to NRS 048-2:2007, the only difference is that the NRS 048-2:2007 requires measurement of voltage parameters only whereas the IEC 61000-4-30 edition 3 set the Class A measurement requirement of both voltage and current parameters to improve analysis of PQ.

2.2.2. The concept of compatibility between supply and use conditions

The sustainability and improvement of an economic growth rate directly depends on both the reliability and QoS served to users. Southern Africa must participate in an international economy and to do this in a competitive manner, requires sophistication in the equipment used in the manufacturing and other industrial processes.

Modern equipment normally relies on advances in computerised monitoring and control of components/equipment. The concept of compatibility between supply and use conditions is widely used in PQ literature to visualise the operational risk at hand.

Voltage is supplied to customers and why the PQ standard is voltage based (Quality of Supply). Figure 2.9 visualise the compatibility principle adopted by NRS 048-2. It demonstrates that for all monitored sites in a power system, there is a range of probabilities of the measured level that should be less than the compatibility level at a minimum of 95% of sites.

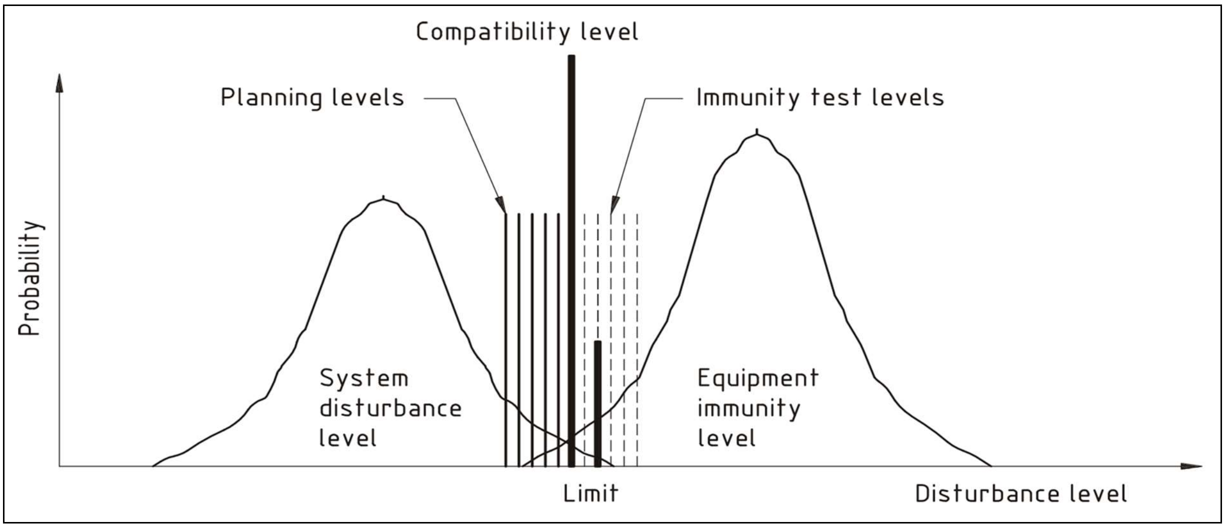

Figure 2.9: Compatibility levels of the principle adopted by NRS 048 – 2 [4]

Figure 2.9 demonstrates that for any PQ parameter, the planning levels (the internal quality objective of a utility) should be less than the compatibility level to ensure compliance to PQ standards [4]. Subsequently, the customer equipment must have immunity levels above the compatibility levels. The choice of the network planning level at any point of supply will depend on the parameter under investigation, the type of equipment used by customer and the confidence the utility has on the data available for planning.

Management of PQ involves installing PQ instruments, observation, checking and tracking of PQ emissions in the network over a period to ensure that they are within the minimum compatibility levels. During monitoring, trends of performance are noted.

The concept of immunity levels is important to equipment end users; equipment manufacturers must ensure that equipment meet PQ standards. Dip immunity tests are done in order to evaluate the dip tolerance of the equipment.

The most common voltage dip standards implemented include the following:

- International Electrotechnical Commission (IEC) 61000-4-11 & 61000-4-34,
- Semiconductor Equipment and Material's International (SEMI F42),
- Computer and Business Equipment Manufacturers Association (CBEMA) and
- Information Technology Industry Council (ITIC).

There are benefits of complying with the above-mentioned standards [11]:

a) Customer satisfaction will be increased due to a decrease in manufacturing and maintenance costs.
b) Elimination of error during manufacturing thus the efficiency of equipment will be increased. Competition amongst industries will be promoted due to the lowering of entry barriers.
c) The supplier will get profit due to reliability enhanced market penetration and remaining at the forefront in terms of technology.

A description of each standard is as follows:

2.2.1.5. SEMI F42 standard

SEMI F42 standard was formulated to test conformity of Photovoltaic (PV), LEDs, MEMS and flat panel display industries to SEMI F42 compatibility curve. The SEMI standards are documents in the form of guides, test methods, terminology, specifications etc [13], [14]. The industry association of semiconductors has developed 2 immunity voltage dip standards to improve the robustness of equipment, these are:

I. ***SEMI F47-0200 (Specification for semiconductor processing equipment voltage sag immunity)***: This standard deals with the specification for semiconductor processing equipment dip immunity. It specifies the requirements for voltage dips with a duration of 50 ms up to 100 s.

II. ***SEMI F4-09999 (Test method for semiconductor processing equipment voltage sag immunity):*** Outlines the test method for semiconductor processing equipment dip immunity, how the equipment is tested for compliance to the SEMI F47 standard. It specifies the test apparatus, test setup, test procedures, reporting and interpretation of the test results.

Semiconductor processing equipment are expected to tolerate voltage dips. The SEMI F42 standard requires the equipment to tolerate voltage sags up to 50% of the nominal voltage for a duration of up to 200 ms, up to 70% for up to 0.5 s and up to 80% for up to 1.0 s [14]. These requirements are defined in Table 2.7.

Table 2.7: Voltage dip duration and percentage deviation of equipment from nominal voltage [14]

Voltage Duration				Voltage sag
Second (s)	**Milliseconds (ms)**	**Cycles at 60 Hz**	**Cycles at 50 Hz**	**Percent (%) of Equipment Nominal Voltage**
<0.05	<50	<3	<2.5	Not specified
0.05 to 0.2	50 to 200	3 to 12	2.5 to 10	50%
0.2 to 0.5	200 to 500	12 to 30	10 to 25	70%
0.5 to 1.0	500 to 1000	30 to 60	25 to 50	80%
>1.0	>1000	>60	>50	Not specified

Figure 2.10 illustrates a voltage dip ride-through capability curve. Semiconductors and metrology must be designed in such a way that they conform to the voltage dip ride-through capability curve.

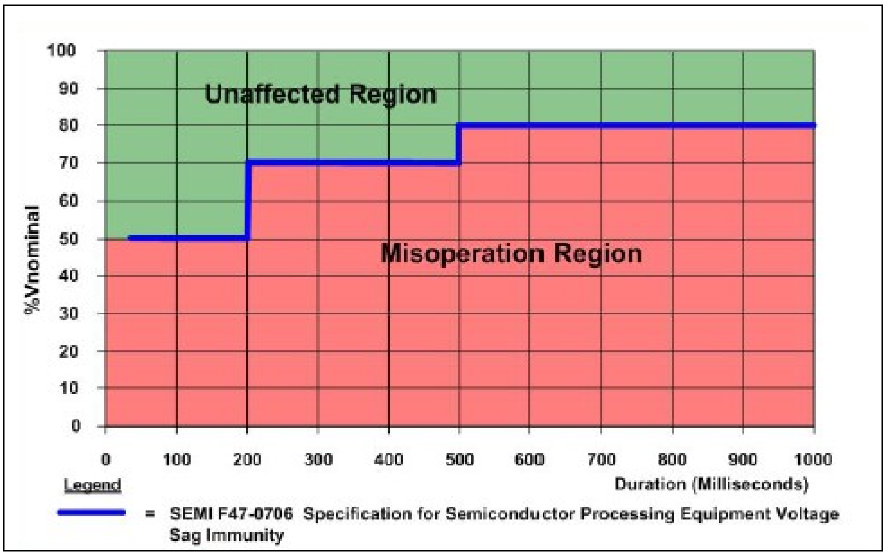

Figure 2.10: Semiconductor equipment voltage dip capability curve [26]

Equipment is expected to function optimally (without any disturbance) when exposed to voltage dips with the following characteristics:

- Nominal voltage of more than 50 V, duration less than 200 ms
- Nominal voltage of more than 70 V, duration between 200 ms < t < 500 ms
- Nominal voltage of more than 80 V, duration between 500 ms < t < 1000 ms

The equipment will malfunction if:

- Nominal voltage is less than 50 V, duration less than 200 ms
- Nominal voltage is less than 70 V, duration between 200 ms < t < 500 ms
- Nominal voltage is less than 80 V, duration between 500 ms < t < 1000 ms

2.2.1.6. IEC 61000-4 standards

The IEC 61000-4 standards define the immunity test methods with preferred ranges of test levels for electrical and electronic equipment. The equipment is connected to a low voltage power supply network which is exposed to voltage dips, voltage variations and momentary interruptions. There are two recognised standards under IEC and both standards specify similar duration and magnitude of dips and how the dips can be implemented on single phase and three phase equipment [3]. These standards are:

I. **IEC 61000-4-11 standard**: The standard is applicable for equipment rated up to 16 amps/phase.

II. **IEC 61000-4-34 standard**: Applicable for equipment rated above 16 amps/phase.

The above standards are similar to the SEMI F47 except for the dip magnitudes. The Generic Immunity Standards and Product Standards requires that dip immunity tests are performed in accordance with the basic EMC standards such as IEC 61000-4-34 and EN 61000-4-34 standards [3], [13]. The main objective of the IEC standards is to define generic voltage dip test levels for different types of equipment, it is not specific.

2.2.1.7. (ITIC) CBEMA standard

The ITIC standard was known as the CBEMA standard, originally developed in the late 1970s solely for describing the tolerance of mainframe computer equipment to voltage dips and transients. The non-existence of other standards during this time, obligated industries to adopt this standard [15]. However, the standard was revised in collaboration with EPRI and was named after a new council, the ITIC (Information Technology Industry Council) but the concept of the standard remained the same.

The intent to revise the standard was to obtain a curve which can better reflect the performance of single-phase computers. Even though the standard was primarily developed for 120 V computers, it can be used as reference in testing the ride-through capability strength of other equipment types and equipment designed for other voltage levels with respect to all PQ problems. [15], [16].

Figure 2.11 illustrates the ITIC curve and how it can be used as reference in equipment testing. Equipment tested for compliance with reference to the ITIC curve comply with the standard if the performance of the tested equipment is not in the prohibited region.

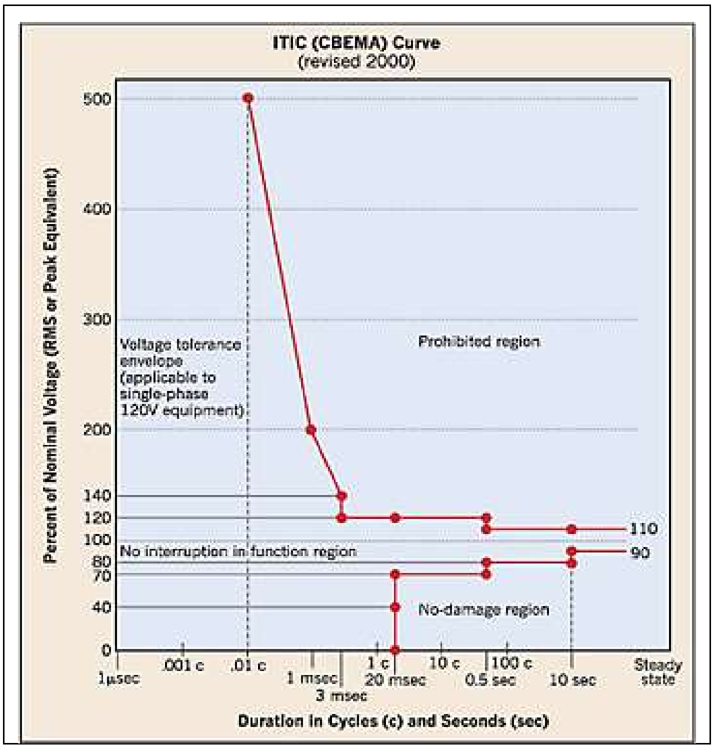

Figure 2.11: The ITIC power acceptability curve [16]

The difference between the CBEMA and ITIC curve is that the ITIC curve has expanded the acceptable operation area of tested equipment and the instrument used in checking compliance is much simpler to design due to the expansion of the acceptable region.

2.2.1.8. Limitations of the compatibility standards

All the above standards, except for the ITIC tolerance curve specify the dip tolerance with respect to dip duration and dip magnitude for a three-phase symmetrical dip. Therefore, the standards disregard the specification of dip tolerance with respect to phase shifts which are associated with voltage dips, whereas these factors are crucial in efficient analysis of dips (especially for power electronic devices such as dc drives).

2.3. Theoretical principle of voltage dips

Voltage dips are the most well-known example of QoS concerns as the customers are directly affected when a plant, for example, shut down. Interruptions normally requires attention to a local feeder whilst the mitigation of dips can require attention to several feeders, even far away and not under the control of the local utility where the concern exists.

Also, the number of dips per annum can be expected to be much higher than the number of interruptions, meaning the number of times that the client is affected will be dictated by the dip performance of the network to which connected and not the interruption performance.

Even though dips are random in nature, there are measures which can be implemented to decrease their impact. The next section analyses cause, effects and mitigation of voltage dips.

2.3.1. The IEC 61000-4-30 definition of a voltage dip

A voltage dip is defined as a sudden reduction in the rms voltage for a duration of between 20 ms and 3 s of either any or all the phase voltages of a poly phase or single phase supply [3]. If duration of dip lasts longer than 3 s, it is regarded as an interruption. The behaviour of current and voltage waveforms before (pre-event), during and after (voltage recovery) a voltage dip is important for analysis of the dip. Figure 2.12 presents the IEC 610000-4-30 measurement of a voltage dip.

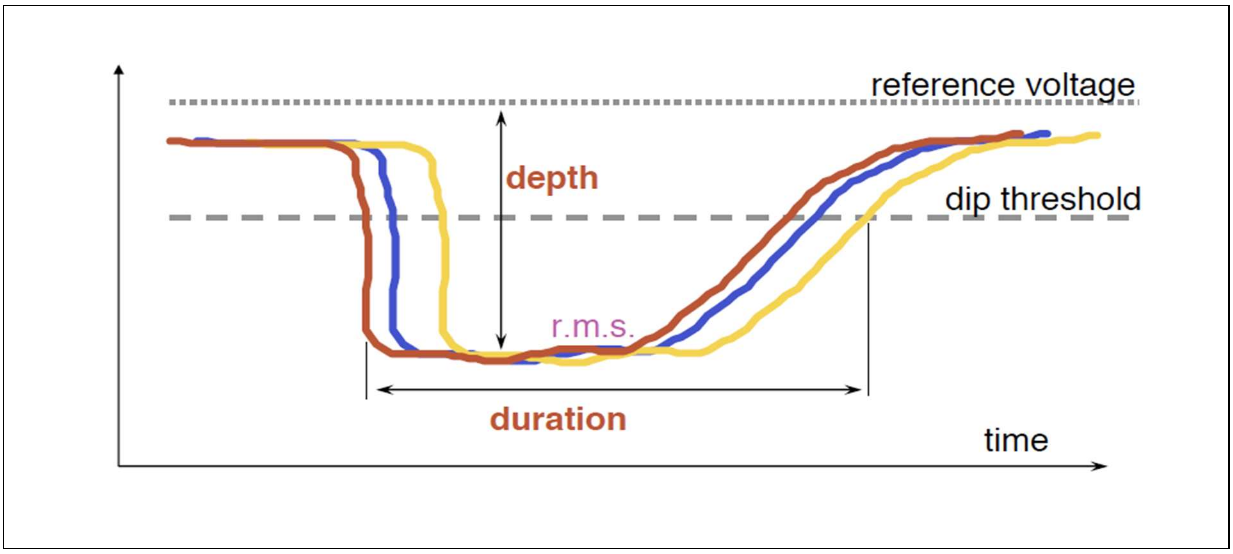

Figure 2.12: IEC 61000-4-30 definition of a voltage dip [34]

A voltage dip is mostly due to a fault current. At the fault, the voltage can be zero, but as impedance between the fault and the point where the measurement of the dip is done, increase, the reduction in voltage will be less (higher residual voltage).

Equipment can malfunction during a voltage dip condition is the reduction of voltage is high enough and the duration long enough. This concept of compatibility was discussed in section 2.2.2.

2.3.2. What determines the duration and depth of a voltage dip?

There are several factors affecting the duration and depth of a voltage dip. Even though a voltage dip is mainly defined by its magnitude and duration, a need arouses to include the phase angle jump and the point on wave because the behaviour of the load during a voltage dip cannot be fully explained by magnitude and duration only. Additional information is also provided on the power system event that led to the occurrence. These factors are [2]:

2.3.2.1. Magnitude of the dip

The magnitude is defined as the biggest difference between the declared voltage and residual voltage, refer to Figure 2.13. Most systems, especially the transmission system operate at a voltage slightly above the nominal voltage in order to compensate for voltage drops. To better understand the causes of the difference in voltage magnitude, a simulation was done in DigSILENT, results are shown in Figure 2.13.

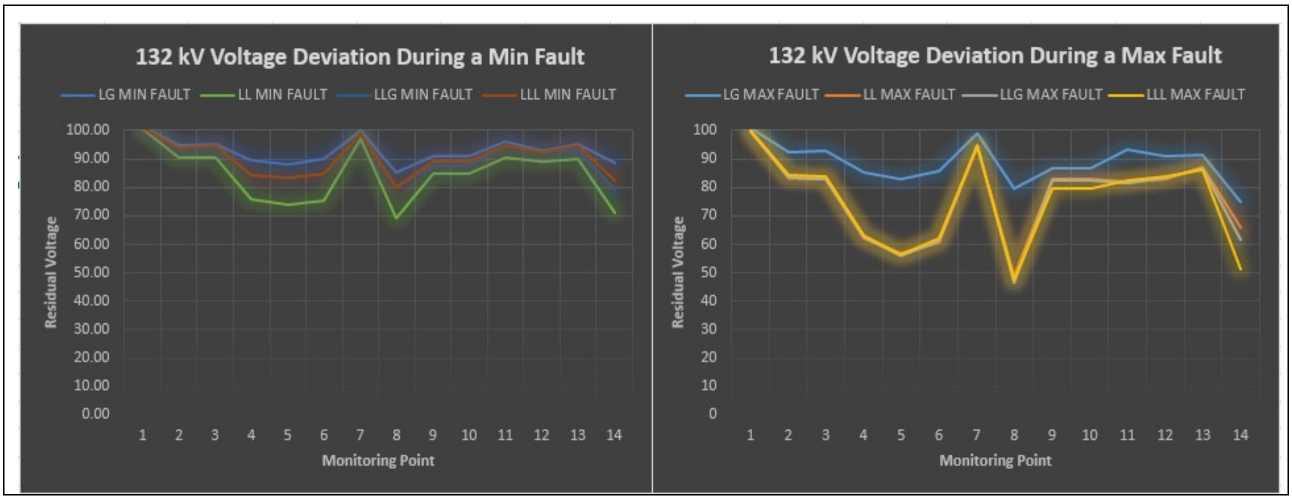

Figure 2.13: Simulation results illustrating the factors determining the magnitude of a voltage dip

Where:

Min fault - indicate minimum fault current

Max fault - indicate maximum fault current

Short circuit faults (Phase to ground, phase to phase, two phases to ground and three phase) were simulated at 132 kV, along Mnkinkomo – Stonehenge feeder. Only faults which results to maximum (has negligible fault impedance) and minimum (significant fault impedance) fault currents were simulated.

Minimum fault current: To record a minimum fault current, a significant fault impedance was simulated far from the monitoring point (closer to the source).

Maximum fault current: To record a maximum fault current, a negligible fault impedance (close to zero) was simulated close to the substation, where the monitoring instrument is located.

The maximum fault current causes the voltage to drop more when compared to a minimum fault current. The shape of the waveforms shows the characteristic (impedance) of the power system, it is because of this reason that the graphs on the left is similar to those on the right despite the type of fault. Figure 2.13 illustrates the effect of the type of fault, the location of the fault and the impedance of the fault.

The residual voltage during a dip is determined mainly by the following factors [2]:

- **Type of fault**: The type of fault is the main factor determining the magnitude and phase shift of a dip. Faults can either cause balanced (symmetrical) or unbalanced (asymmetrical) voltage dips. A balanced dip will be mostly the result of three-phase load switching (transformer energisation, motor start-up) whilst network faults will cause mostly unbalanced dips.
- **Fault impedance:** This is the impedance into which the fault current flow. Ohms law dictate the residual voltage as the product of fault impedance and fault current sets the voltage drop. At the fault, the voltage can be zero and as the distance increase (with an increase in impedance), the residual voltage of the dip will increase.
- **Pre-sag voltage level**: A pre-sag voltage is the level of voltage before the occurrence of the dip, whether the voltage was above or below the declared voltage. If voltage was above declared voltage before the occurrence of a dip, the dip magnitude will be less significant and if below, dip magnitude will be significant. If declared voltage is above nominal voltage, it will assist in compensating for voltage dips.
- **Configuration of the network:** If the network has double circuits feeding one busbar, the magnitude of a dip will be less because a dip occurring in one circuit will result in voltage compensation by the other circuit. Whereas the magnitude of a dip will be low for a single circuit configuration.

2.3.2.2. Duration of voltage dip

It is the time it takes from the point the voltage of the first phase drops below 0.9 pu up to the point the voltage of the last phase rises above 0.9 pu, refer to Figure 2.17. The duration mainly depends on the trip setting of protection equipment and recovery time of the connected load. Faults in transmission systems are cleared by circuit breakers and protection devices with a fault clearing time of between 100 and 500 ms [2]. Distribution systems could use fuses with a fast fault clearing time. The fault clearing time in transmission networks is less than that of distribution network because faults levels are higher in transmission networks than at distribution levels, it is mostly overcurrent protection only.

2.3.3. Phase angle jumps during voltage dips

A short circuit in the network does not only cause a drop in the magnitude of the voltage but also cause a change in the phase angle, known as a phase angle jump or phase shift and is illustrated in Figure 2.14.

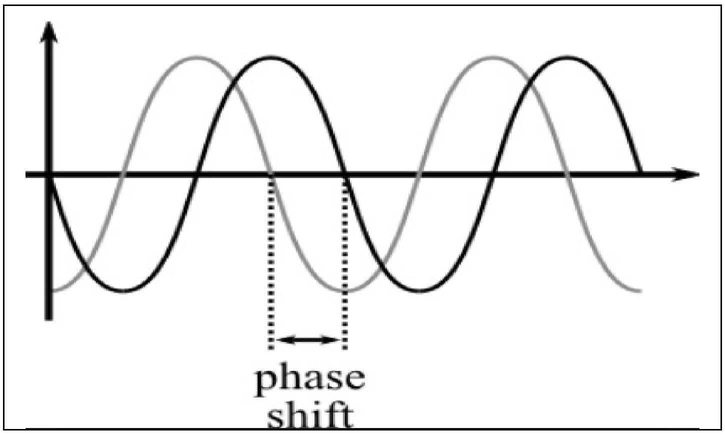

Figure 2.14: A voltage dip with a phase angle jump [38]

Phase shift are not a concern for most equipment but can be problem for power electronics using zero cross detection. The phase angle jump during a three-phase fault is due to the change in the impedance angle (R/X ratio) of the source and the feeder.

In the case of a three phase fault, the derivation of the voltage at the PCC for a given feeder is presented in Equation 2.2 [2]:

$$V_{PCC} = V_{predip} \frac{Z_f}{Z_{f+} Z_s}$$ **Equation 2.2**

Where:

V_{PCC}: The calculated voltage at the PCC

V_{predip}: The pre-dip voltage

Z_s: The source impedance

Z_f: The impedance between the fault and the PCC

To calculate the voltage phase angle shift for the fault in case the source and feeder impedances are different is presented in Equation 2.3:

$$arg(V_{pcc}) = tan\left(\frac{Xf}{Rf}\right) - tan^{-1}(\frac{Xf + Xs}{Rf + Rs})$$ **Equation 2.3**

Where:

arg: the angle between the positive real axis to the line joining the point of origin

Rf: The real component of the impedance between the fault and PCC

Xf: The reactive component of the impedance between the fault and PCC

Xs: The reactive component of the source

Rs: The real component of the source

The phase shift is small when the impedance angles of Z_s and Z_f are similar. However, a larger phase shift is obtained when the impedance angles of Z_s and Z_f are totally different, this can be expected in distribution networks where the R/X ratio of distribution transformers is high.

There is no phase shift between corresponding phases of a Y/Y connected transformers. However, there is always a phase shift in a Y/Δ and Δ/Y configuration between the windings of a transformer.

A fault in one phase causes a voltage drop in the faulted phase. The 2 unaffected phases may, however, display a drop in voltage, a rise in voltage or no change at all. This is determined by the ratio between the negative and positive sequence source impedances.

2.3.4. Root-cause of voltage Dips

Faults are the main cause of voltage dips [7], [8]. They can be categorised as short circuits faults or earth faults. Voltage dips due to faults are of concern to a customer because of the damage they cause to the operation of an equipment. Short circuits are defined as a deliberate or an accidental decrease of impedance in a circuit. These can either be symmetrical (balanced, occurs in all three phases) or unsymmetrical (unbalanced, occurs in one / two of the phases).

There are different types of short circuits which occur in a three-phase system:

a) **Line to Line (L-L) Short Circuit** – Phase to phase short circuits constitutes 15% of all system faults [18]. They are a result of two conductors touching maybe due to a tree falling on top of the conductors.

b) **Line to Line to Ground (L-L-G) Short Circuit** – Occurs when two conductors come in contact with the ground. They constitute 3% of the system faults and can be due to a tree touching both conductors.

c) **Single Line to Ground (L-G) Short Circuit** – This is the most common fault occurring in the network. They constitute 80% of system faults occurring in the network [18]. They occur when trees grown into or come in contact with one of the conductors. It can also be a result of one phase touching the ground or a neutral wire.

d) **Three Phase (L-L-L) Short Circuit** – This is when all three conductors' touches. This is a very rare fault with a constitution of 2% with respect to system faults [18]. They are a result of conductors touching due to incorrect tensioning (sagging of conductor).

Voltage dips due to short circuits are associated with high fault levels. A fault level is defined as the maximum current that would flow at a particular point in case of a short circuit condition in the network. There are two factors determining the amount of fault current flowing during a short circuit, the total impedance connected from the source up to the faulted area and also the system voltage [16]. The impedance of the system includes the resistance, reactance, feeder conductors, transformers and any other equipment connected in the flow of current.

Short circuit currents are made up of the DC and AC components, with the AC component decaying at a very slow rate compared to the DC component. The ratio of the resistance to reactance is presented in Equation 2.4.

$$\text{Short circuit ratio} = \frac{X}{R}$$ **Equation 2.4**

There are quite several assumptions made during the calculation of fault levels in order to simplify the calculations. These assumptions are:

- Saturation effects are neglected
- Resistances are neglected, when the numbers are negligible when compared to the reactance.
- Short transmission line impedances are neglected.

- Capacitance neglected; the reactance of the machines is assumed to be constants.
- The impedances of switchgears, current transformers and bus bars are neglected
- The waveform of the current during a short circuit condition is assumed to be pure sinusoidal.

Calculation of short circuits requires representation of the system impedances from the source of the short circuit current up to the point of the short circuit. Short circuit currents are calculated from the system fault level (KVA). The most common methods used in the calculating short circuit currents with a brief description are [16], [16]:

I. The composition method – The method is used when the characteristics of the power system are not known. The upstream impedance is an estimate of the short circuit current at the origin. The power factor at the origin of the circuit and at the faulted area are assumed to be the same. Formula used in calculating the short circuit current is shown in Equation 2.5.

$$Ik = \frac{Sk}{\sqrt{3} * U}$$ **Equation 2.5**

With:

I_k = Short circuit current when fault has occurred

U = Nominal line voltage before dip occurrence

S_k = Short circuit power during a fault

II. The impedance Method - This method is used extensively in low voltage networks to calculate short circuit currents at any point in an installation with a high degree of accuracy. Knowledge of the power system characteristics are known and available, e.g. transformer ratings. Steps followed in calculating fault currents using this method are shown in Equation 2.6 and Equation 2.7.

- Calculate the MVA during the fault

$$MVA_{Fault\ level} = \frac{Rated\ MVA\ x100}{Percentage\ Impedance}$$ **Equation 2.6**

- Thereafter, the maximum current during the fault is:

$$I_{Fault} = \frac{MVA_{Fault\ level}}{\sqrt{3} * V}$$ **Equation 2.7**

Identifying the root-cause of dips is important in the management of dips. It will ensure that the correct mitigation measures are implemented. The main causes of short circuit faults and earth faults which results in voltage dips are discussed below.

2.3.4.1. Fire

Uncontrolled fires can affect reliability of supply. Transmission and distribution lines close to a sugar cane field, grass, bush or a forest are susceptible to fire.

Fire common during the dry season. Sugar cane is burnt to reduce the amount of manual labour required for harvesting. Burning of sugar cane is mostly intentional. Sometimes the fire gets out of control and damage the wooden structures. Short circuits resulting causes voltage dips.

Air around the conductor when polluted by smoke can cause arcing between the lines. The insulators on pole structures can become contaminated causing a flash over between line and earth. Bush related fire are usually unintentional hence they are not easy to control. Figure 2.15 shows an electrical network made of wooden structures which is up in flames due to a burning forest.

Figure 2.15: Wooden structures in flame due to a burning forest [30]

Voltage dips caused by fire are prone in the distribution network where the structure are wooden. Damage caused by fire is paid for by the utility.

2.3.4.2. Storms

Network structures may cause the network to collapse when exposed to a heavy rains and strong winds. Phase to ground faults and earth faults when conductors touch result in voltage dips. Research indicate that 75% of storms are associated with lightning affecting reliability of supply and why lightning in Swaziland is prominent analysed in detail [43].

Lightning can be an indirect strike is due to electromagnetic coupling from a strike in the surrounding of an overhead line. An electromagnetic wave is generated when lightning terminates in a grounded structure which results to voltage being induced on adjacent structures.

Direct lightning strike on a conductor causes significantly high voltage pulses at the point where it struck and propagate as travelling waves to either direction from the point of lightning origin [43]. Areas with high lightning activity negatively influence the dip performance of a utility.

A direct and indirect lightning strike cause a significantly high voltage in conductors. The high voltage will at times result in a short circuit due to a flashover between the line conductor and earth.

Figure 2.16 shows an example of lightning striking a tower in the distribution network. During the lightning strike, a significantly high instantaneous voltage is generated which causes a short circuit between the overhead line and the tower results in the flow of fault current causing a voltage dip. The breaker detects the flow of fault current and clears the fault.

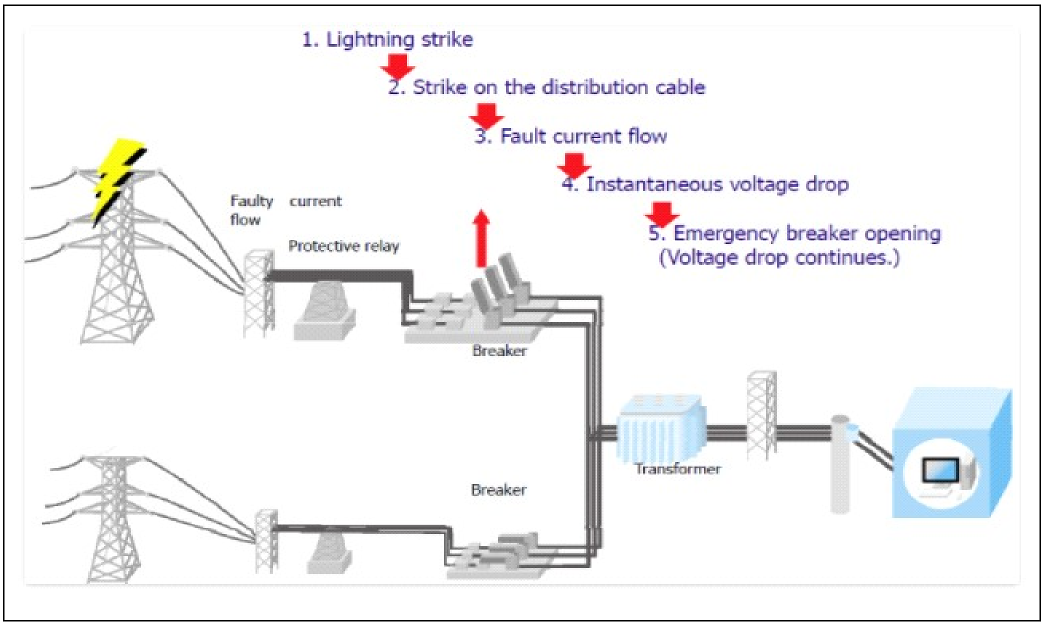

Figure 2.16: Lightning striking a distribution network cable [43]

Every year, in Swaziland, deaths caused by lightning strikes are reported. The alarming increase of deaths, damage on the electrical network and telecommunications reported each year, prompted the need to quantify and map lightning events throughout the world. The recent technology of remote sensing enable accurate detect, locate and measure lightning strikes in real time throughout the world. This technology makes it possible to obtain good results which can be used to predict lightning [43].

Swaziland is characterised with four eco-climatic conditions of a highveld region (above 4000 ft ASL), the semi-arid Lowveld and the Lubombo lowveld. The climatic conditions result in four seasons of the year and is largely dependent on the distance from the ocean, prevailing winds and the topology. Definition of the four seasons is as follows:

- Summer: 1st November to 30th January
- Autumn: 1st February to 31st April
- Winter: 1st May to 31st July
- Spring: 1st August to 30th October

Figure 2.17 shows the average annual lighting activity.

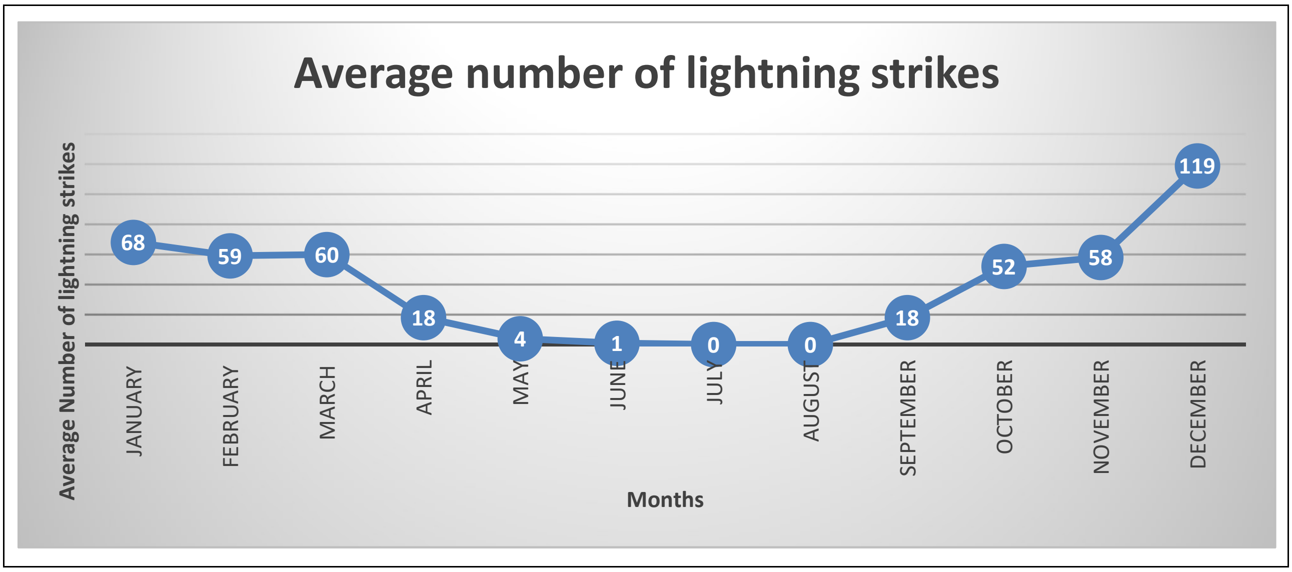

Figure 2.17: Monthly variation of lightning activity in Swaziland [43]

The daily variation of lightning activity is shown in Figure 2.18.

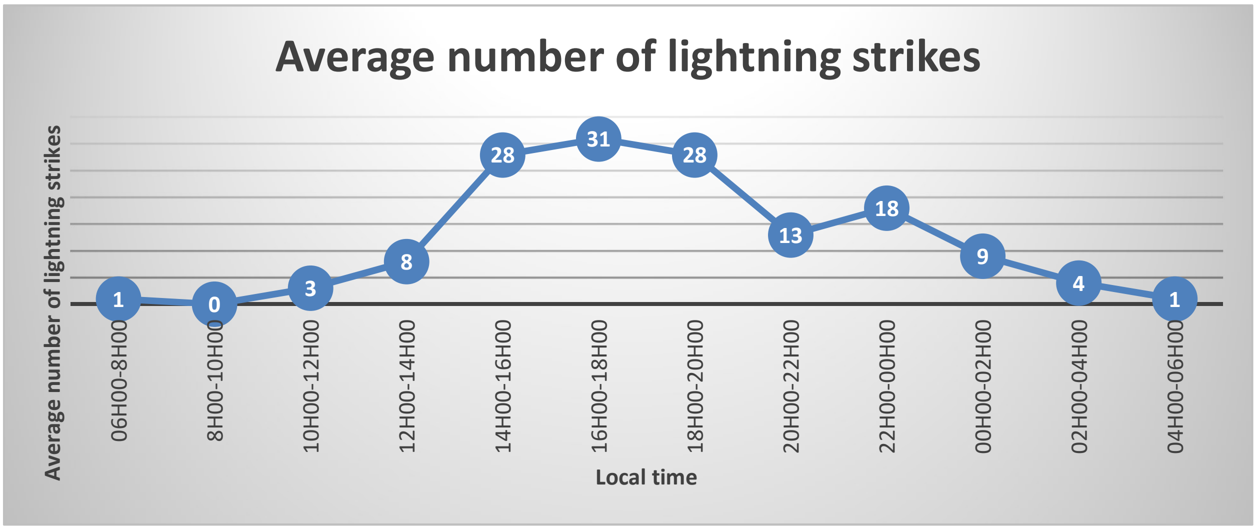

Figure 2.18: Daily variation of lightning activity in Swaziland [43]

A high lightning activity is experienced between 14h00 to 20h00 followed by a second small peak in the late evening between 22h00 to 00h00.

A significantly high number of voltage dips is recorded in the summer season due to the harsh weather conditions associated with it. This information will assist immensely in studying the pattern of voltage dips occurrence in section 3.4. It is expected in section 3.4 that a high number of dips will be recorded during the summer season and less during the winter season.

2.3.4.3. Birds

This is prone to overhead lines where bird species see an opportunity for nesting and perching on the lines. Electrical faults caused by birds are:

- Bird electrocution: Birds with large wings attempt to perch on the lines and conductors [2], [30]. They bridge the airgap between the live wires or live and neutral wires thus resulting to a short circuit, often results to an outage.
- Bird streamers: Large birds emits long watery conductive excretion which reduces the strength of the air gap thus resulting to a flashover between live conductors or between live and neutral conductors causing outages, known as streamer outages.
- Bird collision: These faults occurs when birds collide with power lines causing a short circuit and are seldom [2].
- Bird nesting: Lack of bird nesting sites results in birds opting to nest on power structures because they offer a safe and sturdy environment. Large birds use large sticks and old electrical wires to make a nest and often protrude below the nest to bridge the gap between the conductor and the earthed structure resulting in flashovers during wet conditions [30].

Figure 2.19 shows an example of birds with a potential of causing short shorts in power lines.

Figure 2.19: Examples of birds with a potential of causing short circuits [2]

The first picture shows a large bird where the wings bridge the clearance between conductors resulting in a short circuit and the second picture shows how birds emitting watery excretion can cause flashover across the line insulator.

2.3.4.4. Human and animal interface

Technicians may cause unintentional tripping of the network during maintenance. Cable and copper theft regularly cause short-circuits. Animals can cause a fault in unprotected cable trenches.

2.3.4.5. Equipment failure

Equipment such as circuit breakers, transformers, auto-reclosers and voltage regulators can fail due to:

- Lack of maintenance,
- Weather,
- Incorrect settings of equipment.

2.3.4.6. Conductors

Conductor faults occurs when conductors come into contact. The clearance can be compromised by:

- Conductors not correctly tensioned.
- Falling of trees on conductors.
- Sagging of conductors caused by perching birds.
- Overloading of conductors increase line temperature and the increase in sag can be enough to cause a flash-over to vegetation shown in Figure 2.20. Strong wind can blow loose-hanging conductors into touch.

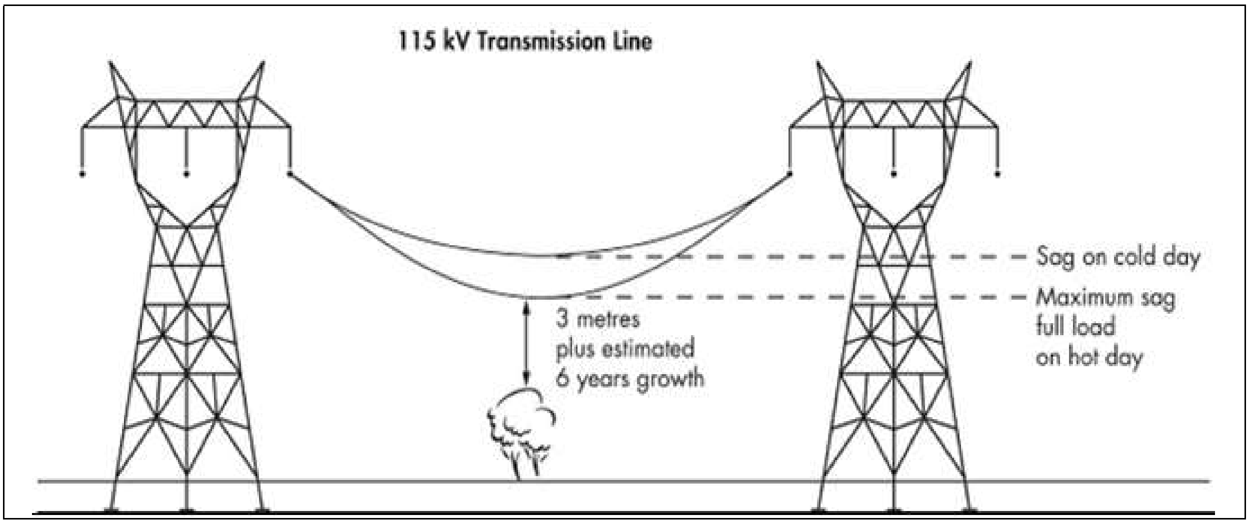

Figure 2.20: Sagging of conductors [33]

The probability of conductors clashing in the transmission network is less compared to distribution networks since transmission networks have more clearance than the distribution networks.

2.3.4.7. Jumpers

A jumper connects the ends of a line conductor across the insulators at a pole as shown Figure 2.21. A jumper can break as shown in Figure 2.21 causing a local interruption and voltage dips in other parts of the network.

Figure 2.21: Broken jumper [43]

Jumpers break due to:

- Not properly fastened on phase conductors resulting in a hot spot that with time, break.
- High fault current during a fault.
- The material of the jumper does not match the material of the conductor, resulting in an electrochemical reaction degrading the contact area.

2.3.4.8. Switching

Switching interrupts/diverts current from one circuit to another:

- To prevent overloading conditions by transferring load from one feeder to the other.
- Isolating a line for maintenance purposes or when an abnormal truck has to pass under a line.

In order to reduce the impact or probability of a voltage dip during switching, the power supply is usually run in parallel with different load angles. This will result in fast transient voltage change followed by a dynamic condition before the settlement of a new steady state load angle. Parallel power supplies are common in the transmission networks but are costly to implement. Parallel lines reduce the dip depth as the fault levels are higher.

2.3.4.9. Vegetation

Poor maintenance of the line servitude can result in overgrown vegetation in close proximity with live conductors. When wind blows, overgrown trees can touch conductors, resulting in an earth fault as shown in Figure 2.22.

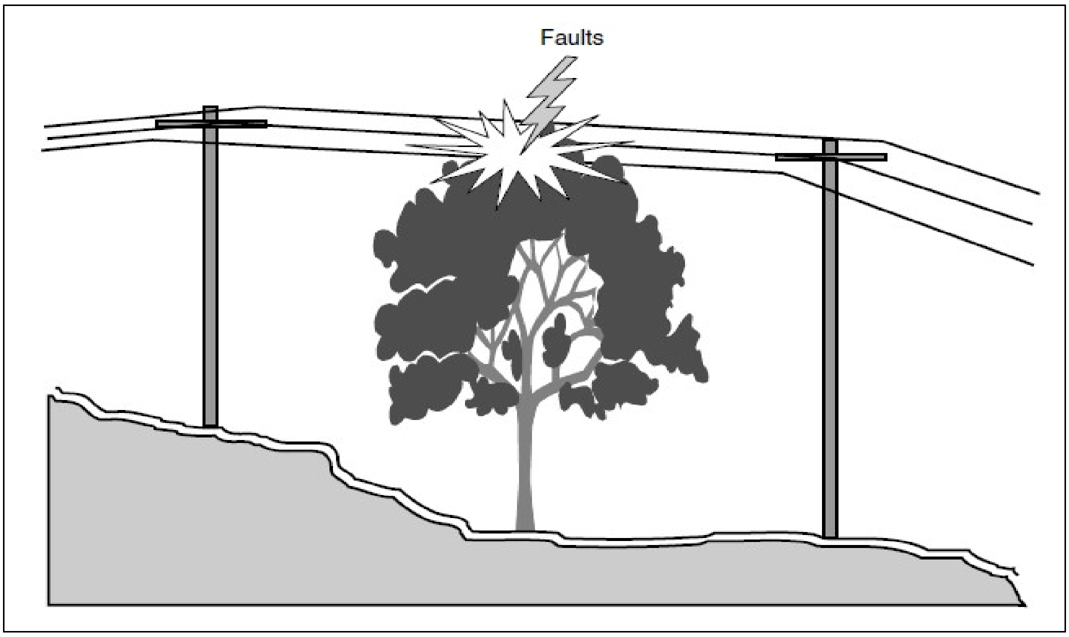

Figure 2.22: Single- line to ground fault caused by a tree [1]

Voltage dips due to trees touching live wires are common in the SEC distribution network and will be discussed in section 3.9.12.

2.3.4.10. Customers

Faults can be emanating from the customer plant or the energisation of large loads. Direct on-line starting of motors withdraw large currents resulting in balanced voltage dips if the system impedance causes a large enough voltage drop over the supply line impedance. All customers connected to the same PCC will then be exposed to the dip condition, an example is shown in Figure 2.23

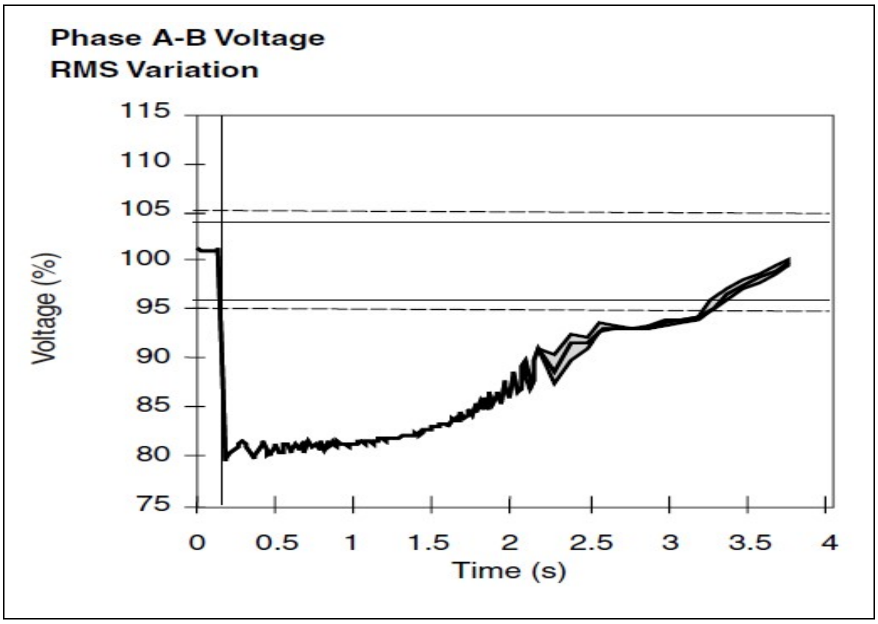

Figure 2.23: A balanced voltage dip due to motor starting [39]

2.3.4.11. Cable faults

Underground cables cause faults (and dips) when cable insulation fail.

2.4. PQ monitoring

Power Quality Monitoring (PQM) is the process of recording, analysing and interpreting measured data. The recording of data is mostly done by continuous measurement of voltage and current parameters at different sites over a period, chosen to be representative of a power system or section thereof (such as voltage level). PQ monitoring consist of a combination of technologies from conditioning the analogue voltage and current measurements to post processing and calculations of the characteristics of the measured waveforms [16], [18].

Data analysis and interpretation is normally done manually, but due to recent advances in signal processing and artificial intelligence, it is also nowadays possible to automate the analysis and interpretation of recorded data to obtain the PQ performance information with minimum human interference [2]. Before engaging in any PQ monitoring processing, one needs to identify the objective of monitoring.

The objectives of PQM are:

- To measure compliance to the regulatory requirement of the license agreement in the case of being a supplier of electrical energy.
- To, in general, attain visibility on network performance.
- To contain the business risk to the utility and to the users by using the PQ data to prioritise mitigation of concerns, for network planning purposes (upgrades and maintenance).
- To derive the baseline for network performance.
- To collect statistical information over time and then to identify trends.
- To identify the root-cause of PQ concerns, for instance voltage dips.
- To match trip and dip events and collect the metadata needed for root-cause analysis of voltage waveform events.
- To assess PQ at individual sites for compliance to the minimum technical standards.
- To benchmark the annual performance of the whole network against the regional and historical norm.
- To derive characteristic voltage dip and interruption performance.
- To identify and mitigate specific PQ problems.
- To, by understanding the root-cause of PQ concerns, manage the network for improved performance.
- To provide data to customers for better equipment specification and system design.

2.4.1. Network visibility

To install PQ instrument at all points of the network is impractical. Sites to be permanently monitored have to be selected based on the objective of monitoring.

The goal is to achieve sufficient visibility of PQ performance in order to globally manage PQ such that end-users are served with QoS compatible to the minimum requirements. Strategic considerations pertaining to a specific network will dictate the location of PQ monitors [2], [20], [21]. For example, the infeed to the network (at generators or from other utilities supplying) ideally must be monitored.

Measurements at points of delivery to customers can be considered when the customer is of strategic importance (water, sanitation, hospital) or being a key customer (motor manufacturer for example). The final decision will be to support the level of observability needed for the utility to manage PQ in that specific network so that customers will be served with QoS well within the minimum requirements of the technical standard pertaining.

2.4.2. Instrumentation requirements

The standard distinguishes 2 classes of measurement performances, class A and S [3]:

Class A

Class A instruments are used where precise measurements are needed to assess compliance to a PQ standard, contractual applications, resolving disputes between utilities and customers. It will produce comparable and repetitive results. Class A compliant instruments meet the highest performance and accuracy [3].

Class S

Class S instruments are used for statistical surveys, trouble-shooting purposes and applications where the uncertainty of the outcome is not important. It cannot be used for the assessment of compliance to a PQ standard [3] [19]

2.4.3. Configuration of PQ instruments

Configuration of PQ instruments is required for a fair comparison of results for different PQ instrument being connected to different voltage levels. The secondary voltage of an instrumentation Voltage Transformer (VT) is standardised as 110 V in SEC substations. Both 5 A and 1 A secondary current circuits are used for Current Transformers (CT).

Connection of the instruments to the network (voltage and current measurements) will depend of the voltage level, Low Voltage (LV), Medium Voltage (MV) or High Voltage (HV) [26], [27]. These connections are briefly discussed below:

Connections to LV circuits

LV voltage connections

Voltage connections to an LV are relatively easy since most PQ instruments are designed to be compatible with direct connection to inputs directly from 230 V to 690 V.

LV current connections

Clamp-on transducers and Rogowski coils are used for current measurement. Frequency response requires consideration of higher order harmonics needs to be measured with precision [26].

Clamp-on CT accuracy can easily be affected by the physical position of the instruments. Changes in relative position of the current carrying conductor, distance to bends of the current carrying conductor and rotation will all give different results [27] . This limitation is more prone to flexible coils. Care must be taken during installation to ensure that the current measuring devices are installed the same way in order to yield similar results, (for instance, the polarity of the CTs can cause the devices to have different results).

Connections to MV circuits

MV voltage connections

In the case of an MV connection, a transformer capable of reducing voltage down to 110 V is required. Instrumentation transformers are preferred compared to protection transformers because they have a higher accuracy which is a priority for reliable results.

MV current connections

Direct connection of the PQ instrument to the 5 A/1 A circuit is possible and requires special safety considerations. Clamp on current transformers or Rogowski coils can also be used to avoid interruption of the CT circuit. Interruption of the CT circuit can cause an open circuit resulting in incorrect measured results.

Connections to HV circuits

HV voltage connections

Magnetic VTs should have a better frequency response than capacitive VTs, but as the focus of the research is the development of a voltage dip management program, the accurate measurement of higher order harmonics, are not that important.

HV current connections

The same considerations apply, namely that either direct connection to 5 A/1 A circuit can be done of an additional clamp-on transducer can be used.

2.4.4. Data availability

NRS 048:2 specifies the valid dataset for an assessment of compliance to compatibility of a site. In the case of a long-term statistical measurement, the assessed value must be based on data remaining after flagged[3] and missing data has been excluded, provided that not more than 10% of the 10 min values has been excluded.

Whereas in the case of a specific customer complaint investigation, assessed values must be based on remaining data after missing and flagged data has been excluded provided that not more than 2% of the 10 min values have been excluded.

Table 2.8 shows the PQ data availability for the period in the SEC network.

[3] This is a concept used to avoid counting a single event more than once for different parameters, for example, counting single dip as both a dip and a flicker variation.

Table 2.8: Data availability for PQ instruments installed at SEC

Location	Data Availability (%)
Nhlangano II Substation	97.9
Edwaleni II Substation	98.6
Edwaleni II Substation	98.5
Big Bend Substation	97.5
Big Bend Substation	97.6
Hhelehhele Substation	98.2
Ka-Langa Substation	98.3
Matsapha Substation	99.1
Nginamadvolo Substation	98.2
Simunye Substation	97.5
Sithobela Substation	97.6
Stonehenge Substation	98.8
Stonehenge Substation	98.5
Nhlangano II Substation	98.8
Sidvokodvo Substation	99.2

The PQ data is considered useful for statistical analyses.

2.4.5. Time stamping of data

The certainty by which events are time-stamped is important for synchronisation of events recorded at different points of a network. GPS time-stamping is preferred in the SEC network to enable efficient dip-trip matching.

2.4.6. How PQ data can be managed

PQ management requires mitigation to ensure existing PQ emissions are maintained, controlled or reduced to minimum compatibility levels. PQ emissions in the networks must be assessed to support PQ management towards a reliable transmission and distribution networks.

Monitoring and management of PQ is important due to an increasing demand of reliable power supply to consumers.

PQ management requires PQ monitoring [13], [23], [24]. Dip data for example must include different seasons of the year. The size of stored data can be large.

2.4.7. Analysis of recorded data

Recording data at several points over a long period result in a lot of data. Every day, 24 x 6 10 min values for 4 PQ parameters are retained. After a year, the 10 min data and dip event data per PQ instrument could be 32 MB.

It is not possible to analyse a vast amount of data with normal spreadsheet programs. For this reason, the PQ data at SEC was hosted in an Oracle database and query tools used to extract information by means of user-configurable query tools.

Compliance to compatibility assessment reports for a single site can be made based on the NRS 048-2:2007 standard or several sites can be analysed simultaneously for comparative analysis of dip performance.

The concept of brushing and linking was available to enhance result interpretation. It identifies correlation between parameters or variables.

It simultaneously shows bar charts and histograms as shown in Figure 2.24. A single bar becomes highlighted when clicked (brushing), at the same time, all bars related (corresponds) to that bar will also be highlighted to visualise the correlation.

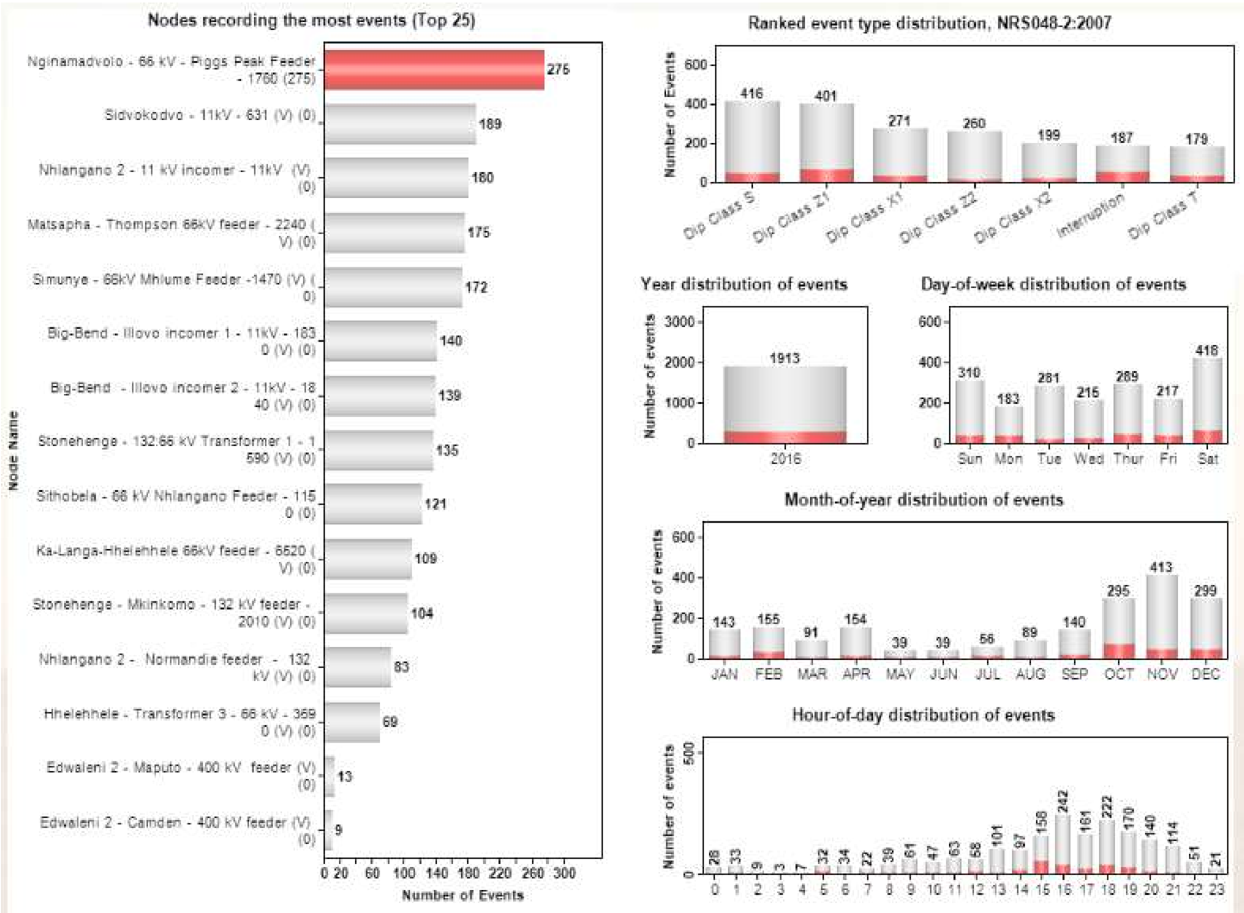

Figure 2.24: Concept of brushing and linking [31]

The explanation of the different graphs marked in alphabets is as follows:

Graph A: shows the event distribution of the different sites, with the worst performing site at the top.

Graph B: Ranking of the events with the respective or resulting voltage dip types to identify the dominant dip type and to show the correlation between events and voltage dips.

Graph C: Shows the events recorded in a specific year. Figure 2.24 only shows the number of events recorded in the year 2016.

Graph D: Distribution of events according to the different days in a week to identify worst performing days.

Graph E: Distribution of events according to the different months in a year to identify the seasonal impact of weather on event distribution.

Graph F: Distribution of events according to the different hours of a day to correlate the distribution of events according to specific times.

The brushing and linking concept in Figure 2.24 revealed the following as demonstration of how brushing and linking has helped the analysis of dip performance:

- Nginamadvolo- Piggs Peak feeder is the worst performing site.
- Dip S dominates.
- A high number of events were recorded on a Saturday.
- Most events occurred October, November and December (rainy season).
- A high number of events were recorded in the afternoon (afternoon thunder showers).

2.4.7.1. Time aggregation of voltage dips

Time aggregation is used to identify a network incident that has been the cause to a number of voltage dips occurring at the same time. A single lightning strike can result in the recording of a number of dips at the same time and some at locations remote from the point where the incident occurred.

Accurate time-stamping is needed to reliably group events together. If GPS is used, a time uncertainty of better than 1 µs is possible. Simply by assuming that several dips that occurred at the exact same time can hardly be due to unrelated root-causes, aggregating those dips to a single network incident shift the focus of multiple dip event analysis to the analysis of a single network incident.

Figure 2.25 visualise this concept of time aggregation.

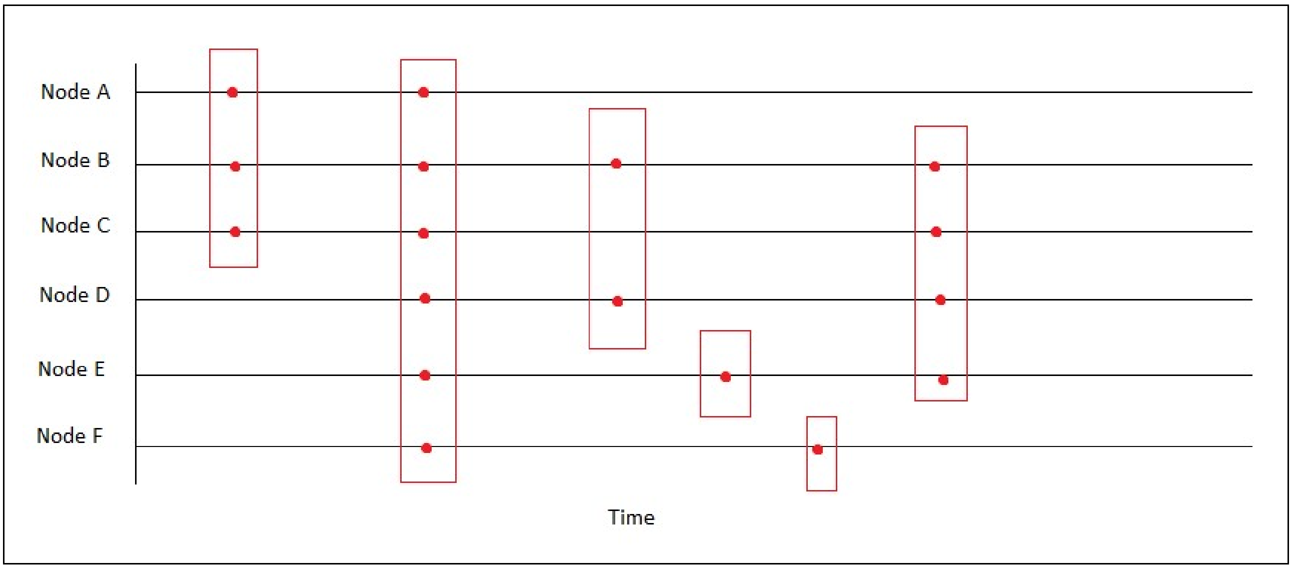

Figure 2.25: Grouping of events into incidents

The figure demonstrates how 17 voltage dips which are a result of 17 events were reduced to 6 network incidents. The nodes indicate the different locations where the PQ instruments are installed. The more the PQ instruments installed in a network the more prominent the data reduction will be.

2.4.7.2. Voltage dip root-cause analysis

Proper analysis of dip root-causes is vital in dip management. Requirements of dip root-cause analysis are:

- A person responsible to do the investigation. This person must have the skills to analyse the recorded data, typically that will be rms profile and waveform data before, during and after the event to determine direction (downstream/upstream) and a plausible cause such as short-circuit, 3-phase load action and others.
- This person must have knowledge of the power system processes involved in the occurrence of the event.

- This additional information on the root-cause can require metadata to be sourced from technicians who know why what protection has tripped. It has then to be added to the PQ database and tagged as the information relating to the specific dip event.
- All the contributing factors to the event must be identified. These are the conditions / situations which increase the likelihood of the event. Contributory causes are indirectly related to the occurrence of the event which resulted in a voltage dip. For instance, stormy weather resulted in the breaking of a rotten wooden structure, the root-cause in this case is the stormy weather even though the wooden pole was rotten.
- Knowledge of the physical location is crucial in network analysis as it enable faults to be geographically plotted.

Thereafter, based on the analysis of the root-cause information over a period time, priorities can be set for mitigation.

2.4.7.3. Normalisation of voltage dip data

It is of utmost importance that the data is normalised before it can be reported on and used in various streams. Normalisation refers to an approach implemented on data to ensure a fair comparison. Normalisation simplifies data because quantities expressed in a per unit form are similar despite the voltage levels. There are two methods which are widely implemented in data normalisation, normalisation by using a single power quality index or normalising using the Global utility average [54].

Normalising using a single power quality index is conducted using the same PQ standards. It required that the normalised indices must be interpreted using the standard normalised to [55]. Figure 2.26 shows Meyer's normalised PQ index.

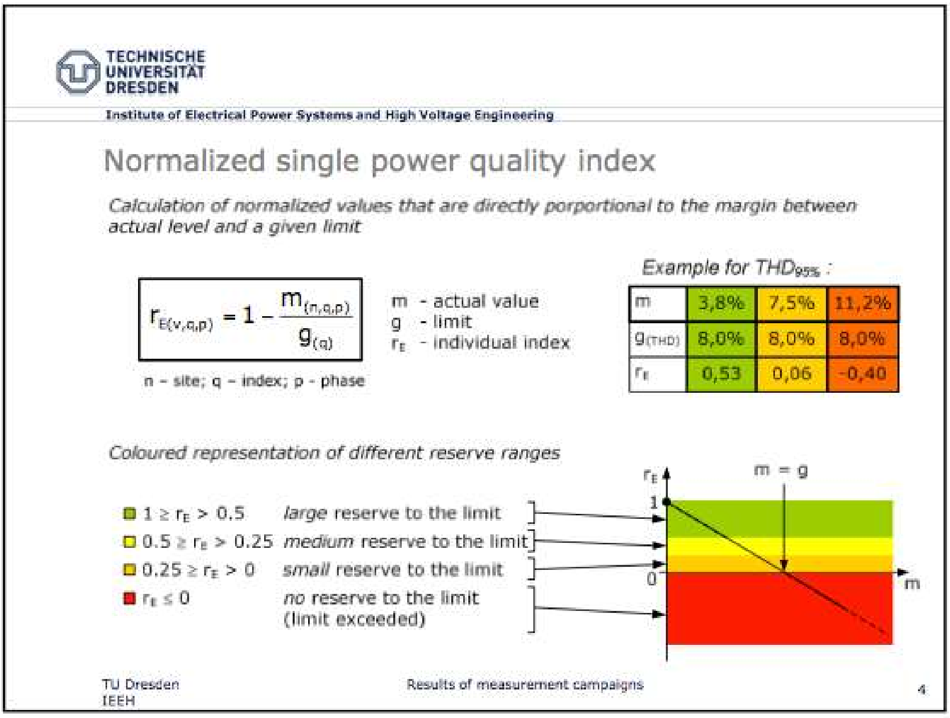

Figure 2.26: Normalised PQ index [55]

A study done in Australia suggested that a Global utility average (average over all the measurement points, for all sites and all utilities involved in the measurement campaign) can be used as a measure to normalise to [54]. This method is of an advantage when comparing sites against each other. Table 2.9 shows the normalisation of different PQ parameters for a utility against the global utility average to enable fair comparison of sites.

Table 2.9: Normalisation by the global utility average

Indices	Utility Average		Global Utility Average		Normalised Utility Average	
	LV	MV	LV	MV	LV	MV
Voltage Deviation	5.30%	2.12%	5.10%	2.50%	1.04	0.85
Unbalance	1.40%	6.30%	1.29%	1.02%	1.09	6.18
Harmonics	5.80%	3.98%	5.90%	2.70%	0.98	1.47
Sags	342	98.7	394.5	165.2	0.87	0.60

Either one of the methods above will be used in normalising practical data before it can be analysed and reported because the number of instruments in the different voltage levels is not the same. This will result in a fair performance comparison between sites.

2.4.8. Reporting of QoS

Monitoring of PQ parameters is not sufficient, a report must be formulated in order to identify and mitigate any issues before major damage is done. The longer the damage is left un-attended, the higher the costs of mitigating. SAPP has stipulated requirements on how to report on QoS issues in order to harmonise the reports between different utilities. ESKOM has also advanced significantly in as far as QoS is concerned, PQ reports are distributed to different stakeholders daily. The way SAPP and ESKOM report on QoS issues will be discussed.

2.4.8.1. Southern African Power Pool (SAPP)

SAPP aim to co-ordinate interconnected electrical utilities in Southern Africa and created a common market for electricity in the SADC region. A Quality of Supply Work Group (QoSWG) was created by SAPP members in order to address PQ issues between countries.

Electrical utilities under SAPP (e.g. SEC, EDM, and ESKOM) are required to install PQ instruments (capable of monitoring both voltage and current parameters) on interconnected power systems in order to report on PQ performance on a monthly basis using an information sharing procedure.

The reporting procedure was formulated by the QoSWG members. The report is distributed to all SAPP members to devise strategies on how to mitigate concerns.

SEC monitor voltage dips at all interconnectors (Edwaleni II, Stonehenge and Nhlangano II).

Requirements of the SAPP QoS standard, specification of the QoS instruments and QoS information sharing procedure are discussed below.

2.4.8.1.1. SAPP QoS standard

SAPP adapted the NRS 048–2:2007 QoS assessment and reporting standard in 2010. Electrical utilities within SAPP are expected to maintain a high level of PQ compliance in interconnecting power lines.

2.4.8.1.2. Specification of QoS instruments in SAPP

SAPP has set standards and requirements for the QoS instruments to be installed in all interconnecting countries.

Instruments must record both current and voltage parameters in accordance to IEC 61000-4-30 edition 3 to ensure reliable, repeatable and comparable results. Class A or class S instruments may be used.

2.4.8.1.3. QoS information sharing procedure

Analysis of recorded data and reporting on performance is needed. A QoS information sharing procedure was compiled by SAPP to be used for reporting. It indicate the performance of the interconnector in terms of voltage regulation, voltage unbalance, voltage dips, harmonics, planned and unplanned interruptions as described in Appendix A.

Each utility is expected to compile a QoS report every month using the procedure in Appendix A and send to SAPP by the 10th of the next month.

Table 2.10 shows, as an example, the status of the different utilities with respect to this requirement. Most utilities are not participating.

Table 2.10: Status of QoS reporting on interconnected networks between utilities

Utility	PQ instruments	Central database	Monthly reports
BPC	Yes, Phokoje Sub still pending	Yes	Reports received but not consistent
CEC	Yes	No	Reports not received
EDM	Yes	Yes	Reports received but not consistent
Eskom	Yes	Yes	Reports received but not consistent
HCB	Yes	Yes	Reports received but not consistent
LEC	Yes	Yes	Reports not received
LHPC	No	No	Reports not received
NAMPOWER	Yes	Yes	Reports are received on a monthly basis
SEC	Yes	Yes	Reports are received on a monthly basis
SNEL	Yes	No	Reports not received
ZESA	Yes	Yes	Reports received but not consistent
ZESCO	Yes	Yes	Reports received but not consistent

- SAPP shall consolidate all reports sent by utilities into one report.
- The report shall be distributed to all SAPP members if need be to assist with detailed investigations of the performance of the interconnectors. Click the link below to access a report compiled for the months of February and March 2017.

  https://www.dropbox.com/l/scl/AABLRFKYpTO7Uog_rSYcrR4N4X5NM8tXO5M

- Each utility shall provide SAPP with contacts and names of 2 personnel responsible for generating monthly QoS reports for each utility. However, the list has not yet been forwarded to SAPP, the reporting is currently done by the QoS representatives per utility.

The inconsistency in the submission of monthly reports by other utilities was noted by SAPP and utilities were urged to conform to the requirements since non-conformance in the future will result in penalties.

SAPP plans to have a central database by the year 2025 for QoS instruments installed in all interconnectors and to have access to the QoS data. All QoS information shared between utilities shall be protected by the confidentiality clause in Article 23 of the Memorandum of Understanding (MOU) [53]. An MOU is not a legally binding document but is viewed as a serious document by the law.

2.4.8.2. ESKOM

A comprehensive PQ management system has been implemented by ESKOM in an effort to comply with licence requirements. Five hundred and twenty sites are being monitored on a daily basis and the measured data is pushed to a central database for storage. The central database interfaces with the oracle database (a master database containing asset location and equipment attribute data). There are tools in place used for reporting on QoS performance. Amongst these QoS parameters is the reporting of voltage dips. Figure 2.26 shows the different types of dips recorded in the ESKOM network.

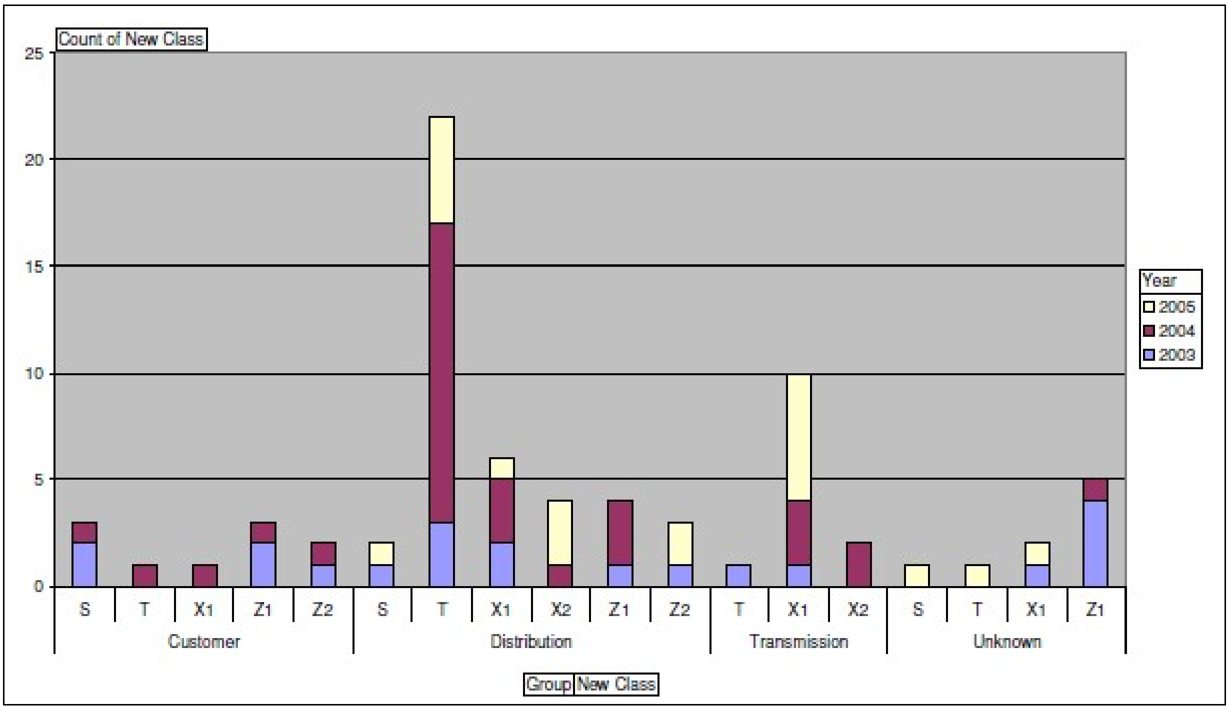

Figure 2.26: Distribution of voltage dip events in the ESKOM network [1]

The following is observed in Figure 2.26:

- The number of voltage dips recorded in the 2003 up to 2005
- The different types of dips recorded
- The responsible parties
- Dip type T, Z1 and Z2 are less in the transmission network because the tripping time at transmission network is less than 150 ms.
- A significant number of T dips in the distribution network was recorded, this can be attributed to faults and varsity of the network.

It is of utmost importance to categorise dips in terms of responsible parties for proper dip management and to ensure that the responsible party takes ownership.

Other than the types of dips recorded at different voltage levels, knowledge of the cause of dips is vital. Figure 2.27 shows the different root-causes of dips from 2003 up to 2005.

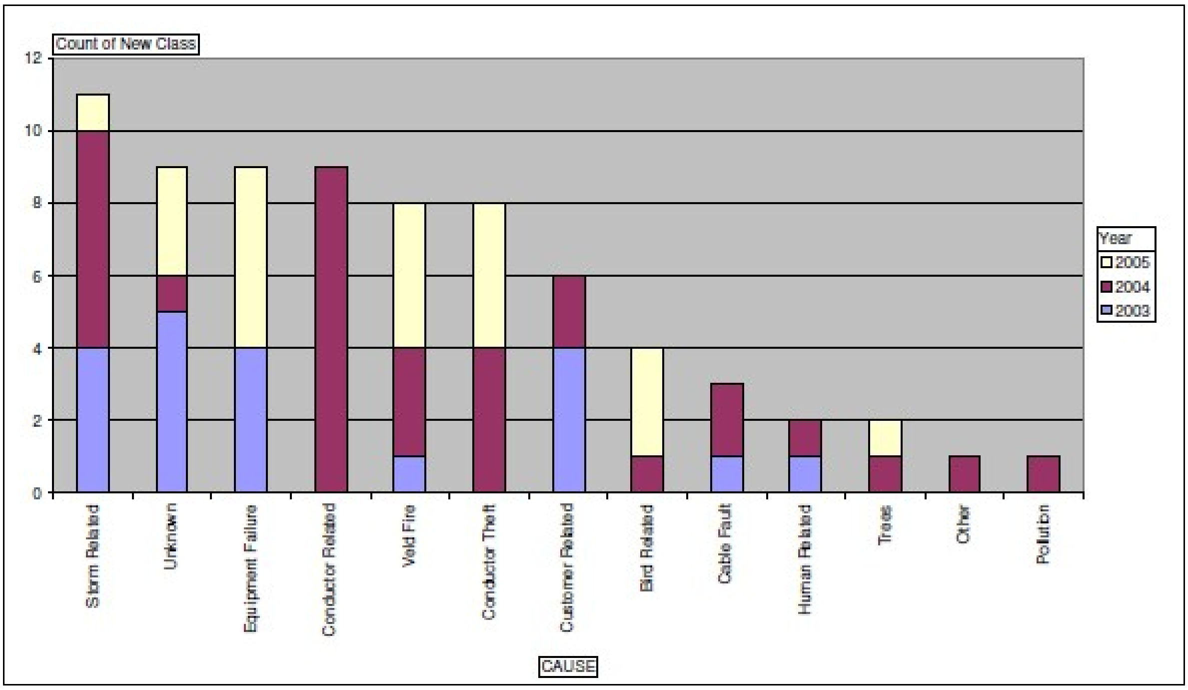

Figure 2.27: Root-causes of voltage dips for a steel plant [1]

The following is observed in Figure 2.27:

- The first six root-causes contributed 73% of dips events from 2003 up to 2005.
- A significantly high number of dips were storm related, less were recorded in the year 2005.
- The failing rate of the equipment is high, it needs to be investigated.
- The number of dips with unknown root-causes makes it difficult to mitigate since an unknown root-cause cannot be mitigated.

The way the voltage dips are recorded will enable management to prioritise in terms of implementing corrective actions and to acknowledge those that are within their control. Dips that are not within the control of the utility will be forwarded to responsible parties.

2.5. Impact of voltage dips on loads

Voltage dips can cause the tripping of customer equipment resulting in a loss of production (leading to financial losses). The impact of dips on industrial processes can be more than due to interruptions [30] as the number of dips during a specific period is normally higher. Equipment sensitive to voltage dips include variable speed drives (VSD), induction motors and contactors [2], [27].

2.5.1. Induction motor

The response of induction motors to voltage dips differ depending on the type and duration of the voltage dip. In an event a three-phase balanced voltage dip occurs, a decrease in supply voltage to an induction motor causes the magnetic flux in air gap to be no longer related to stator voltages on the terminals. The flux decay with a time constant of several cycles. During this time, the induction motor becomes a source of reactive power lowering the power factor. The torque of the motor is also reduced and can be to the extent that the motor to stall.

Complex analysis in the sequence (Fortesque) domain is needed to analyse unbalanced voltage dips at induction motors due to the change in sequence impedances. During the first few cycles, the contribution of the fault current is equal to the increase in positive sequence voltage whilst the zero and negative sequences remain unchanged. When the decrease in the speed of the motor equals the decrease in the positive sequence impedance, the positive current will increase and the positive sequence voltage will drop causing the motor to stall or stop depending on the severity of the dip [30].

The recovery process of a motor after a voltage dip is similar to the starting process, inrush currents six to ten times the normal steady state current of the motor (due to magnetisation) can be expected during acceleration.

2.5.2. Contactors

Sub-station contactors are normally energised at 110 V DC. The hold-in coil of a contactor can lose enough energy during a voltage dip to disconnect a load. Figure 2.28 show the 3 main parts of a typical industrial contactor:

- Magnetic circuit
- Control coil
- The spring-loaded mechanical link (controls the contacts)

The magnetic circuit consist of the armature and yoke. The yoke is mechanically linked to a contact arrangement with multiple normally open and normally closed contacts. Current in the control coil induces a magnetic field which flows through the armature. The field reduces airgap by producing a strong attraction force, if force is stronger than the pressured spring which pushes the yoke away from the armature, the yoke will move in order to close the gap. The mechanical link will ultimately operate the contact arrangement [14].

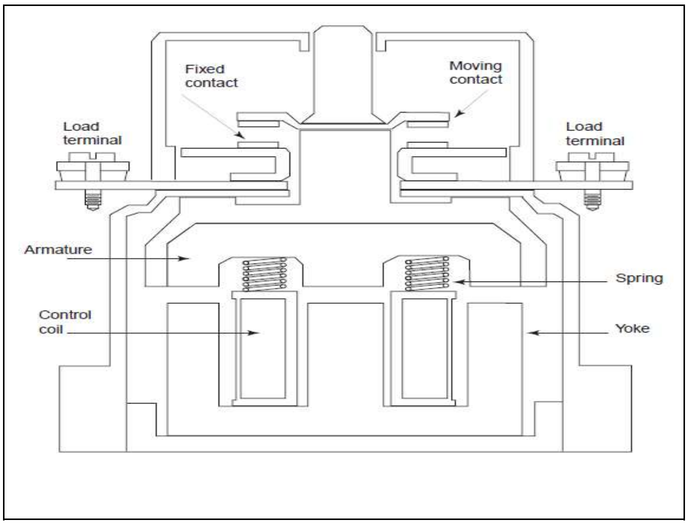

Figure 2.28 Typical diagram of a contactor [14]

The occurrence of a voltage dip causes contactors to drop out when the nominal voltage drops to below the dropout voltage of the coil. Contactors also prevent uncontrolled starting of motors until the supply voltage has stabilised [14].

2.5.3. AC Variable Speed Drives (VSD)

A VSD regulates torque and speed of an electric motor by varying the voltage and frequency supplied to a motor [2] and shown in Figure 2.29. It consists of a rectifier that supplies DC to a PWM inverter that controls the voltage and frequency to the induction machine.

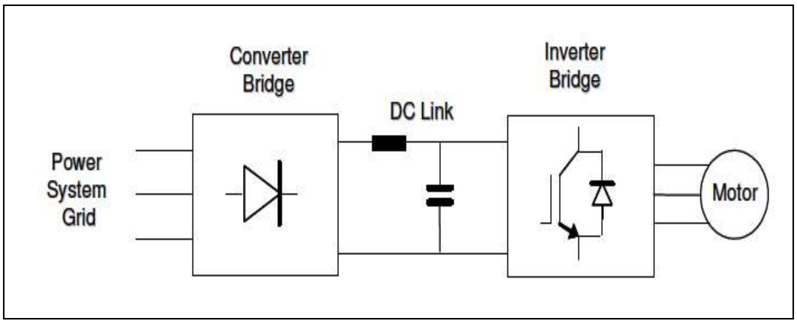

Figure 2.29: An example of the configuration of an AC variable speed drive [17]

2.5.3.1. Impact of balanced voltage dips on AC VSDs

When a VSD is subjected to balanced voltage dips, the DC bus voltage is reduced and below a voltage threshold, the VSD can no longer maintain the torque of the motor and will shut down [2].

2.5.3.2. Impact of unbalanced voltage dips on AC VSDs

In the case of unbalanced voltage dips, the diode conducts in a non-symmetrical pattern. The capacitors charges to the peak of the line-line voltage which results in one or more of the peaks being less than the nominal of the capacitor voltage. It results in the capacitor discharging for a long duration until the next peak voltage is adequate to forward bias the diodes.

If the voltage dips are not too deep, the operation of the VSD is largely unaffected as the PWM inverter will generate a balanced three-phase output voltage, but the maximum amplitude is limited by the magnitude of the DC voltage.

2.5.4. DC Variable Speed Drives

The dc drives consist of a three-phase controlled rectifier which powers the armature winding and a single-phase controlled rectifier for the field winding [2], [16]. Figure 2.30 shows a configuration of a dc drive which has a separately excited armature and field winding. A voltage dip leads to a voltage drop on the AC supply which results to a drop in armature voltage, this in turn cause a decay in armature current [16].

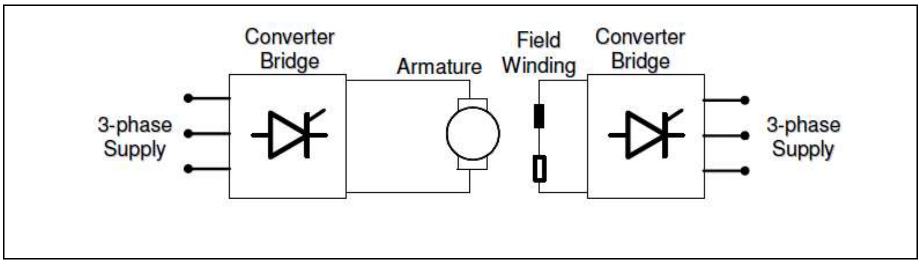

Figure 2.30: An example of a DC drive configuration [16]

An asymmetrical voltage dip can result in commutation failure of the thyristors. Symmetrical voltage dips can also cause commutation failure due to a phase angle jump.

2.6. Mitigation of voltage dips

Root-causes such as lightning are not under the control of the utility and the dips resulting cannot be easily avoided. The rest of the root-causes can be mitigated either on the system or customer loads. However, the high costs associated with mitigation pose a challenge.

Important factors to be considered during mitigation of voltage dips are [16]:

I. The cause and origin of voltage dips.
II. Type of network: Overhead lines are prone to voltage dips when compared to underground cable, since overhead lines are exposed to the environment (harsh weather conditions, trees and birds).

Solutions include network configuration changes, reduction of fault clearing times (trip settings) and active voltage conditioning.

2.6.1. Modification of the system configuration

Modification of the system can include [2], [50]:

- Installation of a generator near sensitive customer loads for voltage support during a voltage dip.
- Supplying sensitive customer from more than one substation and/or circuit to reduce the depth of the voltage dip.
- Increase the fault level to a customer to reduce the depth of dips.
- A higher tap setting at supply transformers for a higher supply voltage than the declared voltage to reduce the loss of voltage during the dip.

- Constant voltage transformers that make use of the characteristics of the magnetic saturation of the transformer core to support the output voltage during a disturbance on the input circuit.
- Change system configuration from ring to radial in order to reduce the increase of fault current during a dip occurrence.
- Increase the electrical distance to the faulted point by current-limiting reactors at strategic points of the network.

2.6.2. Reduce the number of faults

Since short circuits are the main cause of voltage dips, mitigation thereof can reduce the number of voltage dips. Options To

- To improve the impact of lightning on overhead lines by lightning arrestors and improved footing resistance of towers.
- Installing devices on towers to contain birds perching.
- Install and replace insulators with hydrophobic insulation in areas with known pollution problems.
- Improving system maintenance by cleaning of insulators, clearing of vegetation below power lines etc.
- Replace overhead lines with underground cables.
- Protect against animals entering mini substations.

2.6.3. Reduce fault clearing time

The duration of the dip is determined by the settings of protection devices clearing the fault. Fast clearing of faults in the network does not imply a reduction in the number of voltage dips but rather a decrease in the duration of dip [50]:

- Proper discrimination of faults between breakers in order that the breaker closest to the fault clears the fault fast.
- Fast current-limiting fuses.
- Single-phase auto recloser to only disconnect the faulted phase.
- Impedance/distance protection schemes to improve selectivity of protection insulating the faulted section.

2.6.4. Voltage stabilizers

Voltage stabilisers can mitigate voltage dips. Equipment are connected between the sensitive load and the supply to contain the propagation of the disturbance [50].

2.6.4.1. Rotating Uninterruptible Power Supply (UPS)

Motor-generator sets as in Figure 2.31 illustrates how a motor, flywheel and generator in feeds power to the load. The ride-through time is set by the flywheel storing of kinetic energy to be released into the generator if the input to the motor changes, for example during a dip.

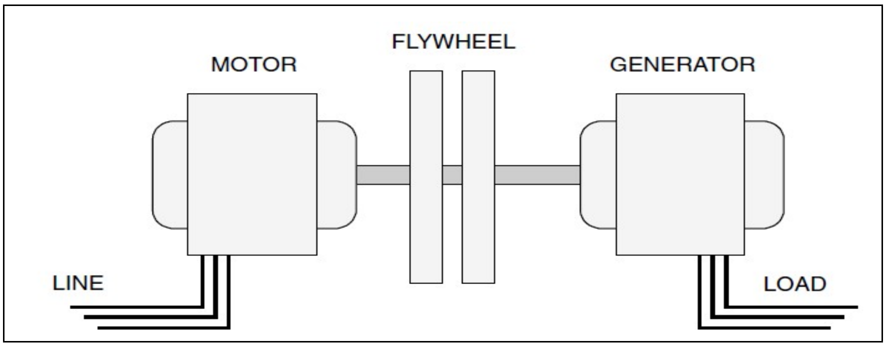

Figure 2.31: A motor generator set with a flywheel [7]

Disadvantages of motor-generator sets [2]:

- Maintenance.
- Standby losses.

Flywheel technology is capable of voltage dip and interruption ride through from 10 s to 2 min due to high speed flywheels and advanced power electronics [7].

These flywheel energy storage systems can operate in a vacuum and use magnetic bearings to reduce standby losses [14].

2.6.4.2. Static transfer switches and fast transfer switches

Fast transfer can be by convectional breakers switching from a primary to a backup supply in seconds whereas vacuum breakers can transfer in less than 2 cycles. Static power electronic switches can transfer within a quarter of a cycle.

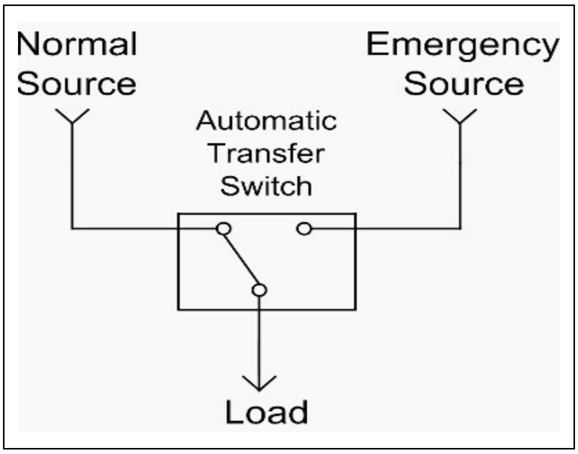

Figure 2.32: Static transfer switch between main and alternative source [14]

The benefits of a transfer switch are realised when there are two independent supplies to a customer, e.g. two feeders from different substations with different dip behaviour.

2.6.4.3. Static Uninterruptible Power Supply (UPS)

A UPS use battery storage to supply loads when the utility falls away. It can be done by an online, standby or hybrid configuration [7].

On-line UPS

The load is fed directly from the UPS as shown in Figure 2.33 isolating the input disturbances from the output.

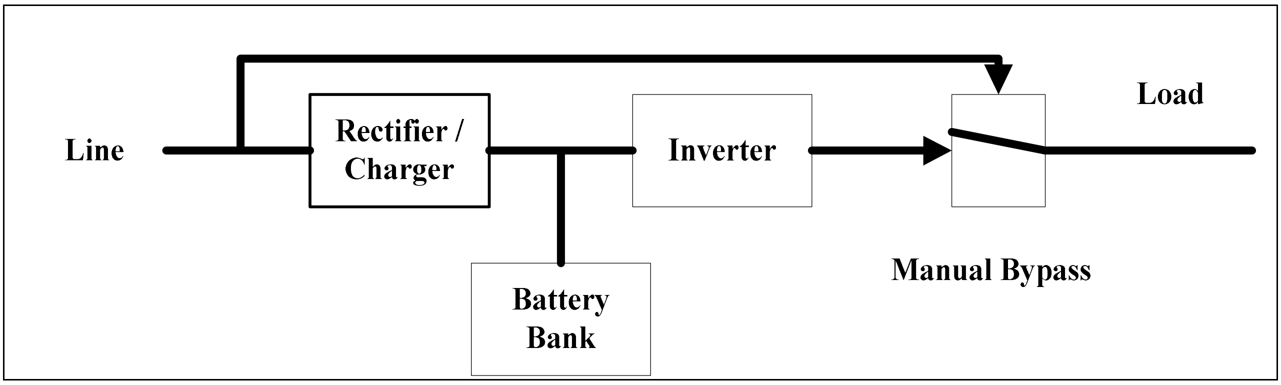

Figure 2.33: A typical configuration of an on-line UPS [7]

Energy losses have to be sustained continuously but voltage is continuously regulated.

Standby UPS

The standby UPS transfers the load from the utility to the Ups when needed. The transfer time is critical in protecting the load from a voltage dip. It does not provide transient and voltage regulation, refer to Figure 2.34.

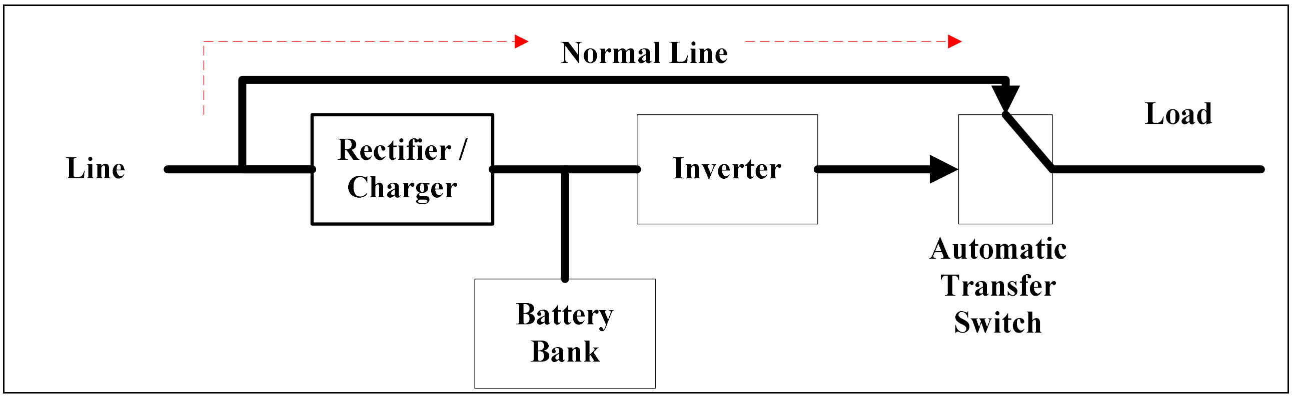

Figure 2.34: A typical configuration of a standby UPS [7]

2.6.4.4. Ferro-resonant transformers

Ferro-resonant transformers are constant voltage transformers (CVTs) and more efficient in constant loads than in variable loads such as motors. Inrush currents in motors are a problem because of the tuned circuit on the output. These devices are highly excited on their saturation curves to provide a constant voltage output during an input voltage variation. A typical CVT is shown in Figure 2.35.

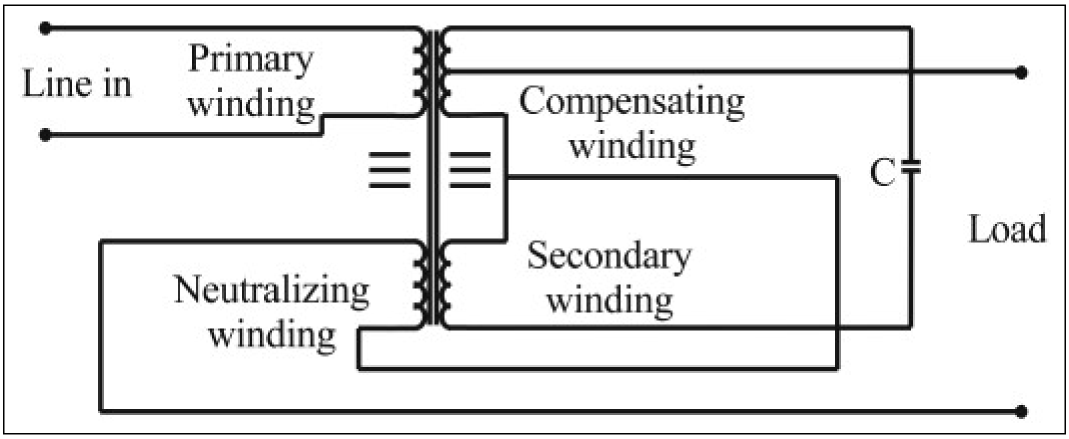

Figure 2.35: A typical CVT [7]

It has a good response time of 25 ms and requires minimal maintenance. The transformers has a disadvantage of collapsing under heavy loading and does not have the ability to supress transients emanating from the plant.

2.6.4.5. Magnetic synthesisers

Magnetic synthesiser's operating principle is similar to the CVTs except they are three-phase devices. They utilise resonant circuits made of non-linear capacitors and inductors to store energy which can be used to provide a constant supply voltage to critical three-phase loads in case a voltage dip occurs.

The devices are available from 15 to 200 kVA and are used to provide a continuity of supply in process loads with large computer systems where a slight variable in supply voltage is not tolerated [50]. Magnetic synthesisers can compensate for all types of dips. Figure 2.36 illustrates the process of a magnetic synthesiser, from the input up to the output of power.

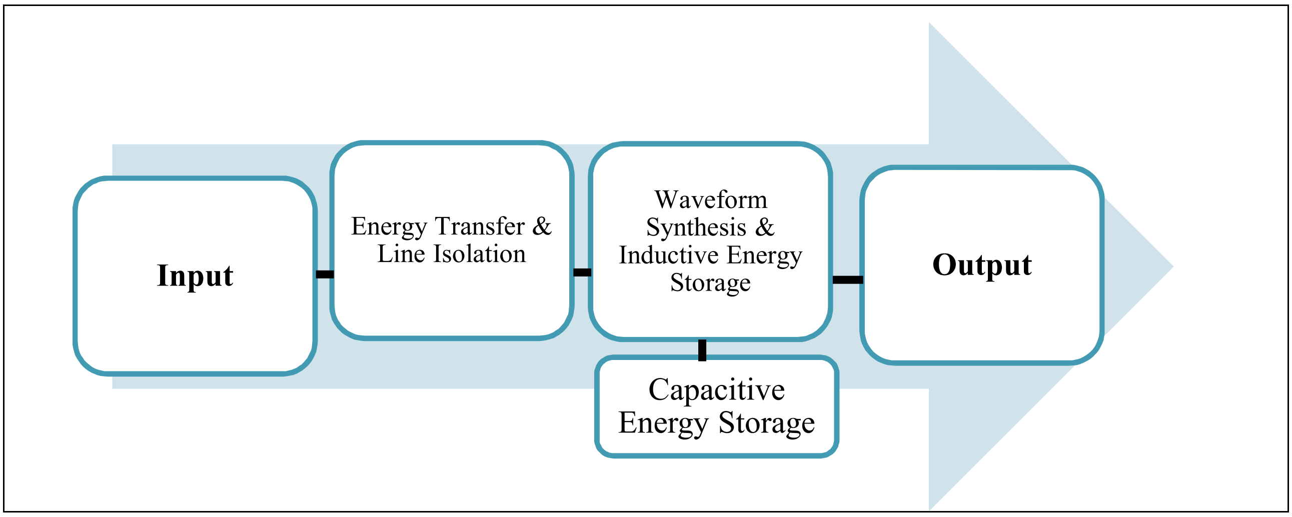

Figure 2.36: A process of a magnetic synthesiser [2]

Figure 2.37 shows a comparison of the voltage dip ride-through capabilities for a magnetic synthesiser against the CBEMA curve which was discussed in section 2.2.1.7.

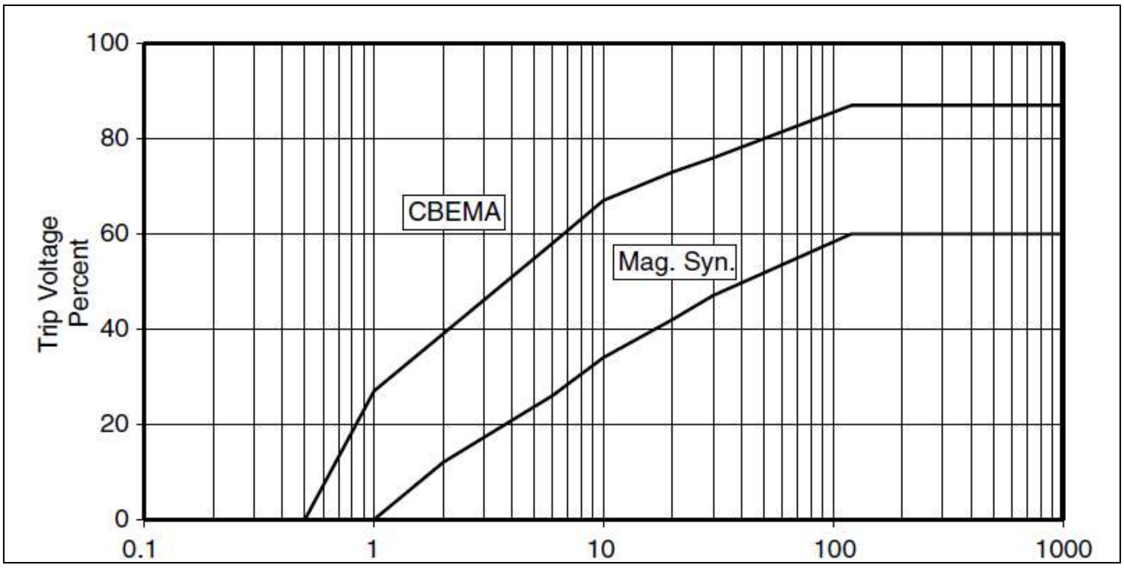

Figure 2.37: Voltage dip capability ride-through for a magnetic synthesiser

The transfer of energy and isolation of the main line is achieved using non-linear chokes in order to eradicate noise. Distinct voltage pulses are combined to form AC output waveforms and temporarily stored in the saturated transformers and capacitors as current and voltage. The energy storage result in a pure sinusoidal voltage and current waveforms being supplied through a zig zag transformer.

2.6.4.6. Active voltage conditioning (AVC)

The advance of power electronics has resulted in new opportunities of providing voltage dips ride through. One of the recent opportunities is to boost the supply voltage by injecting voltage in series with the remaining nominal voltage. They are known as AVC and are available in a variety of sizes with a range of 1-5 kVA which can be installed in single phase and medium voltage systems [50]. They are the most effective dip mitigation available. Figure 2.38 shows a three-phase active voltage conditioner with a permanent winding in series and by means of a secondary winding, injects the missing component.

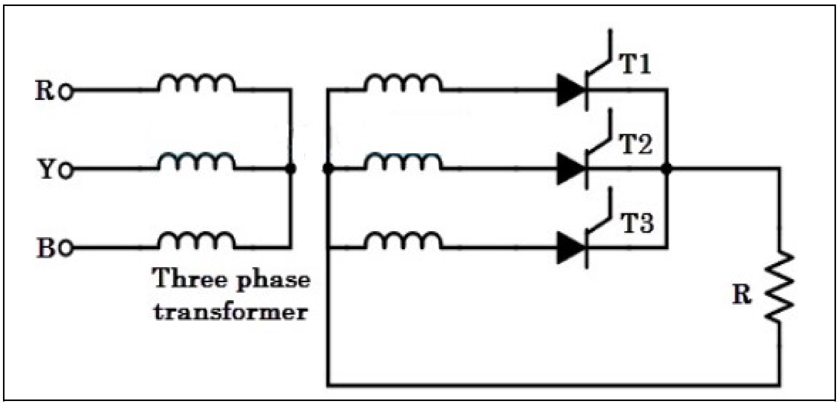

Figure 2.38: Three phase AVC [2]

There are different manufacturers of the AVC, but the two main manufacturers are ABB and Schenieder. No matter the manufacturer the principle operation of the AVC is similar, the only difference is in the time taken to correct the dip and the types of loads compatible with. The features of the AVC are:

- Complies with SEMI F47 standard
- Compensate for dips within 2 ms, the duration is not dependent on the load or power factor.
- Sag correction for a minimum of 100 seconds
- The device draws voltage from the utility supply hence there is no need for batteries, thus the maintenance costs are reduced.
- It provides continuous dip compensation for industrial loads such as motors without the need to bypass operation.
- It offers continuous protection without the need to reset of recharge.
- Designed to operate in indoor and outdoor operations.
- Reliability is increased with 99% efficiency during normal operations.

2.6.4.7. Shunt controllers

Shunt controllers are devices used in the mitigation of shallow dips. They are connected in parallel with to the load [7]. Their operation is the opposite of series compensators, they constitute a current as a source. The current required is mainly reactive by assuming that the impedance of the source is also reactive. The two devices which are widely available in the market are Static Synchronous Compensator (STATCOM) and Static Synchronous Generator (SSG) [2]. Figure 2.39 shows an example of a shunt controller injecting current on the line.

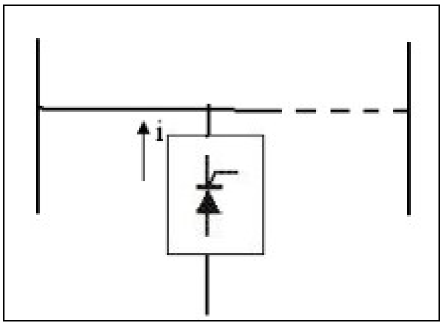

Figure 2.39: A typical topology of a shunt controller

Shunt controllers are most effective in controlling voltage, especially in the substation bus since the current is injected on the line. Their disadvantage is that they cannot control the power flow in the network

2.7. Cost evaluation of voltage dip mitigation measures

Discussing the different methods currently available to reduce or eliminate the impact of a voltage dip is not sufficient for one to make a sound decision on which method / device to purchase. Understanding of the costs of the devices and whether they will be effective after implementation is very critical to avoid unguided and poor decisions making. The following are steps which serves as guide line with regards to the choice of which device to purchase [2], [50].

- The performance of the system with respect to PQ must be characterised such that each PQ parameter is quantified into measurable values.
- Estimate the costs associated with the deviation of each PQ parameter from set standards.
- Describe the costs and effectiveness of the different alternatives of the mitigation of voltage dips.

Characterisation of voltage dip performance and the available devices available for voltage dip mitigation have been discussed. The focus now will be on evaluation of the costs associated with the mitigation measures discussed in section 2.6.

The costs associated with the impact of voltage dip events differ for utilities and industries. The costs are significantly high if the final product is in short supply and there are inadequate capabilities of to make up for lost production. It is a difficult task to quantify the costs of the consequences resulting from voltage dips. The costs of a voltage dip event can be categorised into three major sections:

- Losses relating to the product, for instance, loss of product and materials.
- Losses relating to labour, for instance, overtime and repair costs.
- Ancillary costs, for instance, shipping delays.

The costs are directly proportional to the severity (magnitude and duration) of the voltage dip event. It is easier to explain the relationship of the costs and voltage dip severity using a matrix. In most cases, momentary interruptions will cause a disturbance in a load not protected with energy storage and voltage dips will always have a negative impact in the load as well. For instance, a voltage dip with 40% nominal voltage causes 80% of the economic impact that a momentary interruption causes, hence the weighting of the impact will be 0.8 [46].

Thereafter, the weighting values are applied to an event, event costs are expressed in per unit of the momentary interruption costs. Weighted events are then added, and the sum is the total cost of all the events expressed in the number of equivalent momentary interruptions. Table 2.11 illustrate a weighting factor an investigation.

Table 2.11: Total costs of PQ variations [52]

Category of event	Weighting for economics analysis	Number of events per year	Total equivalent interruptions
Interruption	1	5	5
Dip with nominal voltage below 50%	0.8	3	2.4
Dip with nominal voltage between 50% and 70%	0.4	15	6
Dip with nominal voltage between 70% and 90%	0.1	35	0.2

Knowledge of the costs associated with the voltage dip mitigation technologies is critical in making sound decisions. The costs include the procurement, installation, operating and maintenance of the device, it can be relatively cheap to purchase a device only to discover that the maintenance costs associated with it are unbearable. Table 2.12 shows the costs of the devices with the operating and maintenance costs.

Table 2.12: Costs of the voltage dip improvement technologies [52]

Alternative category	Typical costs (Rand)	Operating and maintenance costs (% of initial costs per year)
Control protection (< 5 kVA)		
CVTs	13 000/ kVA	10
UPS	6 500/ kVA	25
Dynamic dip corrector	3 250/ kVA	5
Machine protection (10-300 kVA)		
UPS	6 500/ kVA	15
Flywheel	6 500/ kVA	7
Dynamic dip corrector	2 600/ kVA	5
Facility protection (2 - 10 MVA)		
UPS	6 500/ kVA	15
Flywheel	6 500/ kVA	5

DRV (50% voltage boost	3 900/ kVA	5
Static switch (10 MVA)	7 800/ kVA	5
Fast transfer switch (10 MVA)	1 950/ kVA	5

Voltage dip costs estimation is not enough the effectiveness of the mitigation measures /methods require quantification. Effectiveness quantification is only possible after the implementation of voltage dips measures to reduce / eliminate them. Table 2.13 shows an example whereby the different technologies discussed in section 9 are already implemented and their performance is evaluated.

Table 2.13: Effectiveness of voltage dip mitigation technologies [52]

Voltage dip compensating device	Interruption (%)	Nominal voltage below 50%	Nominal voltage between 50% and 70%	Nominal voltage between 70% and 90%
CVT (controls)	0	20	70	100
Dynamic dip corrector	0	20	90	100
Flywheel ride-through technologies	70	100	100	100
UPS	100	100	100	100
Static switch	100	80	70	50
Fast transfer switch	80	70	60	40

The effectiveness of the devices is measured against the number of voltage dip events recorded for different nominal voltage ranges.

2.8. Conclusion

The theoretical principles of electrical PQ have been discussed in detail in this chapter in order to appreciate, acknowledge and acquire knowledge from previously published work of the context at hand. Various PQ standards formulated aid as a guidance against which all PQ measurements, data analyses and equipment manufacturing will be done to ensure consistency of results.

The various ways of installing PQ instruments at different voltage levels were investigated in order to obtain efficient (reliable and repeatable) results. PQ parameters were discussed with the main focus on voltage dips. The assessment methods of both international and national standards were implemented on PQ instruments and recorded data.

The different ways of reporting at ESKOM and SAPP were discussed. Results in ESKOM indicated that dips were dominant in the distribution network when compared to the transmission network. The different dip root-causes presented enabled prioritisation with respect to dip mitigation measures. Dips due to storm related root-cases recorded the highest number. These poses as a challenge in terms of mitigation because they are difficult to mitigate. Dips due to unknown causes recorded the second highest. This is a problem because dips with unknown root-causes cannot be mitigated. Reporting on QoS issues on interconnected power systems was discussed to have an idea of how reporting is conducted at SAPP.

There are several mitigation measures implemented in electrical utilities, but the best option is to ensure that the network is well maintained (preventative measures). A cost benefit analysis must be firstly conducted to ensure that the benefits outweighs the downsides. Implementation of the mitigation measure is not sufficient, there must be tools in place to measure its effectiveness.

The theory above was investigated to have an in-depth insight and a holistic approach on how best the voltage dip management program for SEC can be formulated.

3. Analysis of voltage dip performance at SEC

Dip performance of the SEC network is first analysed as means to develop a network model in DigSILENT that can be used to validate root-cause analysis.

Field data used in the development of the model reflects a full year to include the impact of changing climatic conditions on dip performance.

3.1. Dip-trip matching of voltage dips

The concept of voltage dip-trip matching is used by ESKOM to relate a voltage dip event to a specific cause, as some protection equipment would have cleared ("trip" condition) a fault somewhere in the network. A reason of why the "trip" occurred is the information needed to evaluate options to mitigate the root-cause.

SEC has adopted the same approach by adding meta-data (the "reason") to the electrical parameters recorded during a dip event. It requires an operator to analyse the dip event and manually enter the meta-data into the PQ dip database as shown in Figure 3.1.

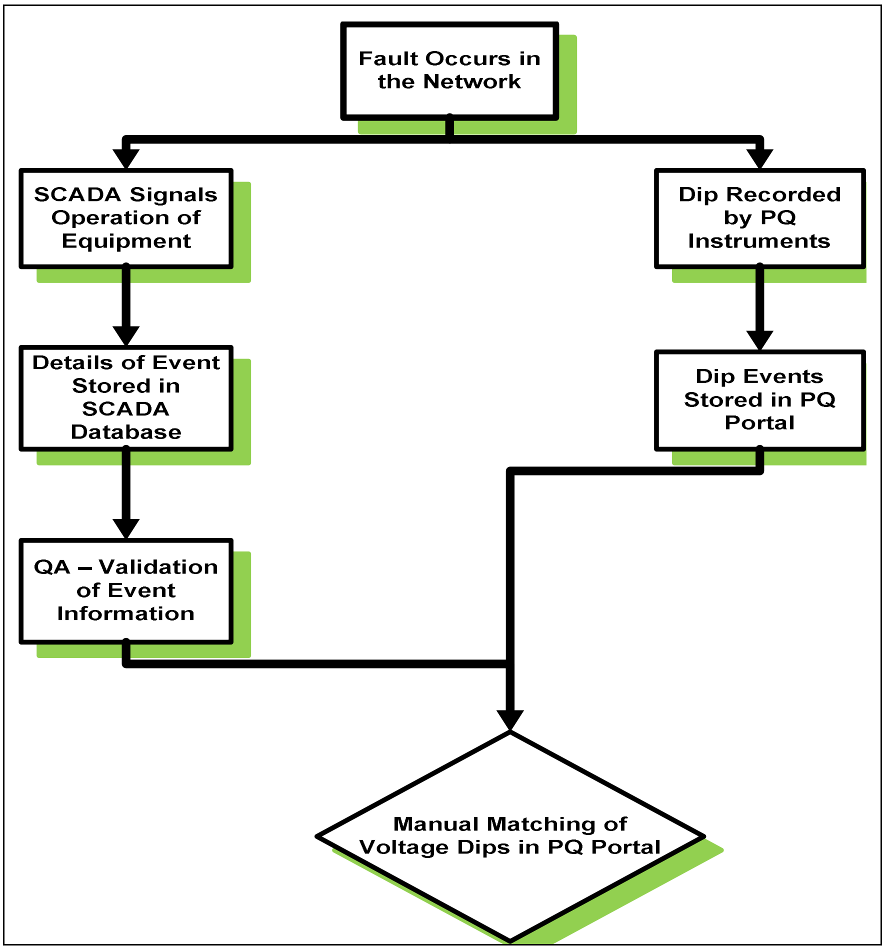

Figure 3.1: Method of dip-trip matching

The SEC SCADA system monitors the operation of protection equipment which can be used to correlate a trip condition to a voltage dip event based on comparison of the time-stamping of the SCADA event with the PQ event. It is important that the time-stamping of the fault event in the SCADA database and that in the PQ database allows the matching. Fortunately, the voltage waveform events in the PQ database and SCADA database are GPS time-stamped and referenced to UTC.

Details of the network event (an event can only have one root-cause) are stored in the SCADA database and the National Control Centre (NCC) operators will validate the information by for example, contacting the technician that attended to the fault condition. These NCC operators will then manually forward the event information (as metadata) to the PQ database. This PQ database is the main repository where over time, all the additional information of voltage waveform events is recorded.

Steps taken to ensure that each event on the network is valid (QA) are:

- **Analysis of dip events per site:** During the case of multiple events recorded at a single location during the same period due to a single root-cause resulting in a number of breaker operations (reclosers for example), then the PQ database should have automatically retained only the deepest dip to reflect the worst impact on end-users.
- **Aggregating dip events to a dip incident:** Between different sites where a dip event was recorded at the same time, by automatic time-matching, the PQ database will group that single dip event from each site into a single network incident and for the incident, retain the deepest dip event.
- **Dip root-cause:** The root-cause must reflect, showing in detail on what happened and where the faults are analysed in terms of the geographical layout of the network.
- **Dip ownership:** Direction (upstream/downstream) from where the PQ instrument is located is derived to assign ownership of the root-cause. For example, the dip could be from the Eskom network, then it will require Eskom to consider options to prevent it in future and to provide SEC with the root-cause information. If internal, then SEC "owns" the dip event.

The above QA is the responsibility of NCC personnel tasked and trained for this purpose.

An important benefit of the SEC approach to voltage dip management is to be able to evaluate the network impact of specific dip incident and if the root-cause information presents an opportunity to operationally intervene to prevent future occurrence, then the dip performance of the network can immediately benefit. This is an important aspect of Quality of Supply and Service to users.

Over the longer term, the accumulation of statistical information on dip performance and root-cause information, will support the planning and operation of the network as both the financial and technical teams of SEC can now base decisions on validated system technical performance information.

3.2. Using the web portal to access the PQ database

The SEC dip data was continuously pushed via the Internet to an Oracle database customised for PQ management. It was acquired commercially and the research in this dissertation used this as a tool to develop a voltage dip management program for SEC.

An example of the results obtained by using an automated query tool, is shown in Table 3.1. Metadata is manually added after root-cause analysis. Data regarded as metadata is in columns 4, 10, 11, 12, 13 and 14.

Information in colour blue indicate that it is system generated, it cannot be changed by system users but can be changed by system administrators, whereas information in black can be changed anytime by system users.

Table 3.1: The on-line PQ database, dip incident reporting tool [44]

No:	Data Source	ID	**Incident Name**	Date	Worst Duration (s)	Worst Residual Voltage (%)	Number of affected Sites	Number of classified Events	**Cause**	**Circuit**	**Voltage Level (kV)**	**Responsible Party**	**Status**
1	Ours	602387	Phase Overcurrent	2016-04-28 10:04:22	371163.264927	0	1	1	Switching	Balegane – Nginamadvolo 66 kV	66	SEC	Published
2	Ours	601237	Phase Overcurrent	2016-04-27 23:53:51	0.884020	82.27	2	5	Broken Jumper	Balegane – Nginamadvolo 66 kV	66	SEC	Published
3	Ours	601186	Phase Overcurrent	2016-04-27 17:43:51	0.880400	81.62	4	6	Broken Jumper	Stonehenge – Ngwenya II	66	SEC	Published

The definition of the columns is as follows:

- **ID**: The PQ management system generates a unique number for a dip incident by time-aggregating a number of dip events occurring at the same time.
- **Incident name**: Shows the type of fault relating to the dip, obtained from the SCADA system. When the SCADA system is down (which rarely occurs), not able to provide details of an incident, technicians manually collect the root-cause information.
- **Date:** Date and time of dip event.
- **Worst duration:** The longest duration if more than one dip event was recorded at the same time. An aggregation interval of 1 minute is in use since not all the instruments are time-stamped by GPS, this allows for clock-drift on those instruments being time-synchronised by the PQ data server.
- **Worst residual voltage:** A network incident can result in multiple voltage dip events and the dip with the worst residual voltage has to be the closest to where the fault occurred.
- **Number of affected sites:** The number of sites where a dip was recorded during the same time.
- **Number of classified events:** One PQ instrument can record a number of waveform events (dips and swells) within time-aggregation interval used for a single network incident (one ID number), for example in row 3, observe that 6 waveform events were recorded during one network incident (ID 601186) but that occurred at only 4 different sites, meaning an instrument (or 2 instruments) have recorded more than one waveform event.
- **Cause:** The root-cause of a dip event added to the database by system operators (mostly from the SCADA database).
- **Circuit:** Indicate the circuit where the fault causing the dip event originated (added by the operators who know which circuit was tripped).

- **Voltage level:** The declared network voltage at the faulted circuit.
- **Responsible party:** It assigns ownership of the root-cause, for instance SEC, IPPs or ESKOM.
- **Status:** Dip events being analysed, and the results added to the database indicating completion time.

The information in Table 3.1 was analysed and consolidated to extract useful information which can be used in formulating the annual dip performance of the SEC network.

3.3. Time aggregation of voltage dip events into dip incidents

The concept of time aggregation of voltage dips was presented in section 2.4.7.1. This exercise aims at removing the unnecessary dips which may mask the actual dip performance. A time aggregation interval of up to 10 seconds is selected but to present a more vivid picture of the effect of equipment, then the aggregation time of 1 minute up to an hour is selected [2].

Two protection philosophies are implemented at SEC:

- If a fault is detected, the breaker opens for 3 sec and close, if the fault was not cleared, the breaker opens again and attain lock-out status.
- If a fault is detected, the breaker opens for 3 sec and close, if the fault is not cleared, it opens for 5 sec and closes, if fault condition now still exists, the breaker will open and attain lock-out status.

The above philosophies imply that a breaker can operate for a maximum duration of 8 sec to clear a single fault / event. The settings of the above equipment indicate that multiple events with a duration of 8 sec can be aggregated to one incident. Hence an aggregation time of 8 seconds was selected.

Figure 3.2 shows the impact of time aggregation of dips per site, before and after the aggregation of multiple events with a duration of 8 sec to one incident.

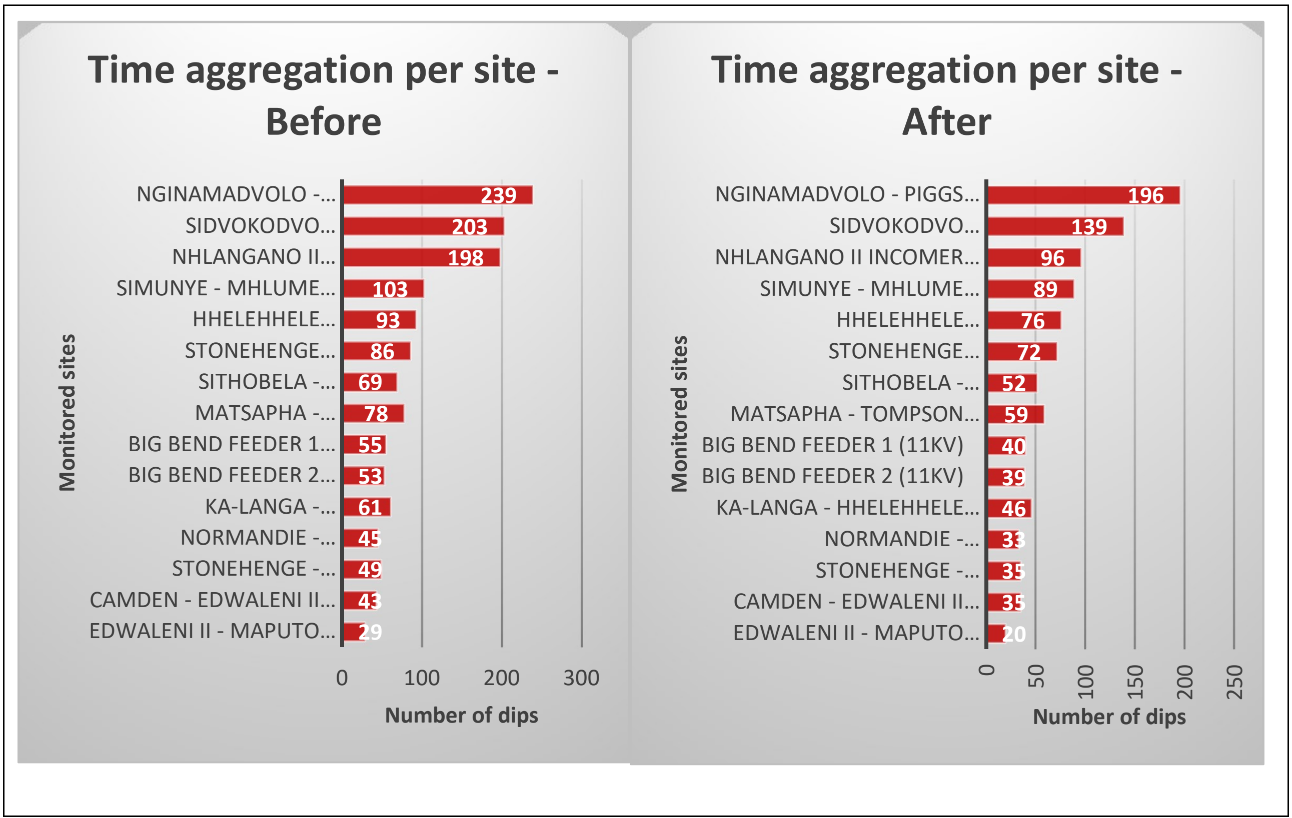

Figure 3.2: Impact of time aggregation per site

The impact of time aggregation is significant, especially on the monitored 11 kV feeders where most of the equipment using the auto reclose function is located.

Time aggregation of dips between the different sites was also done as depicted in Figure 3.3.

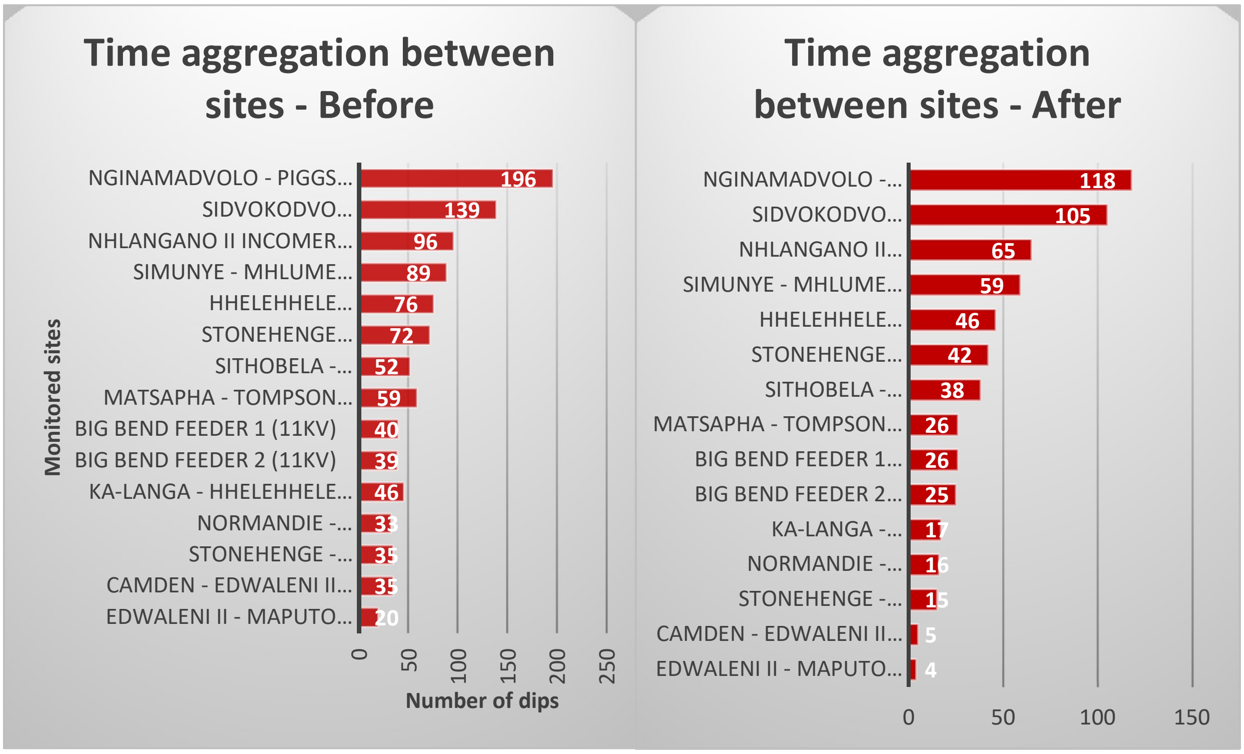

Figure 3.3: Impact of time aggregation between different sites

The impact of aggregation between sites results in significant reduction in dips as compared to aggregation of dips per site. This can be attributed to the fact that a dip occurrence in the network may be recorded by more than 1 instrument.

3.4. Ranking of site in terms of dip performance

During the exercise of removing unnecessary dips, the site with the lowest voltage was retained since it was regarded as being close to the faulted area. Figure 3.4 shows the actual dip performance of the network.

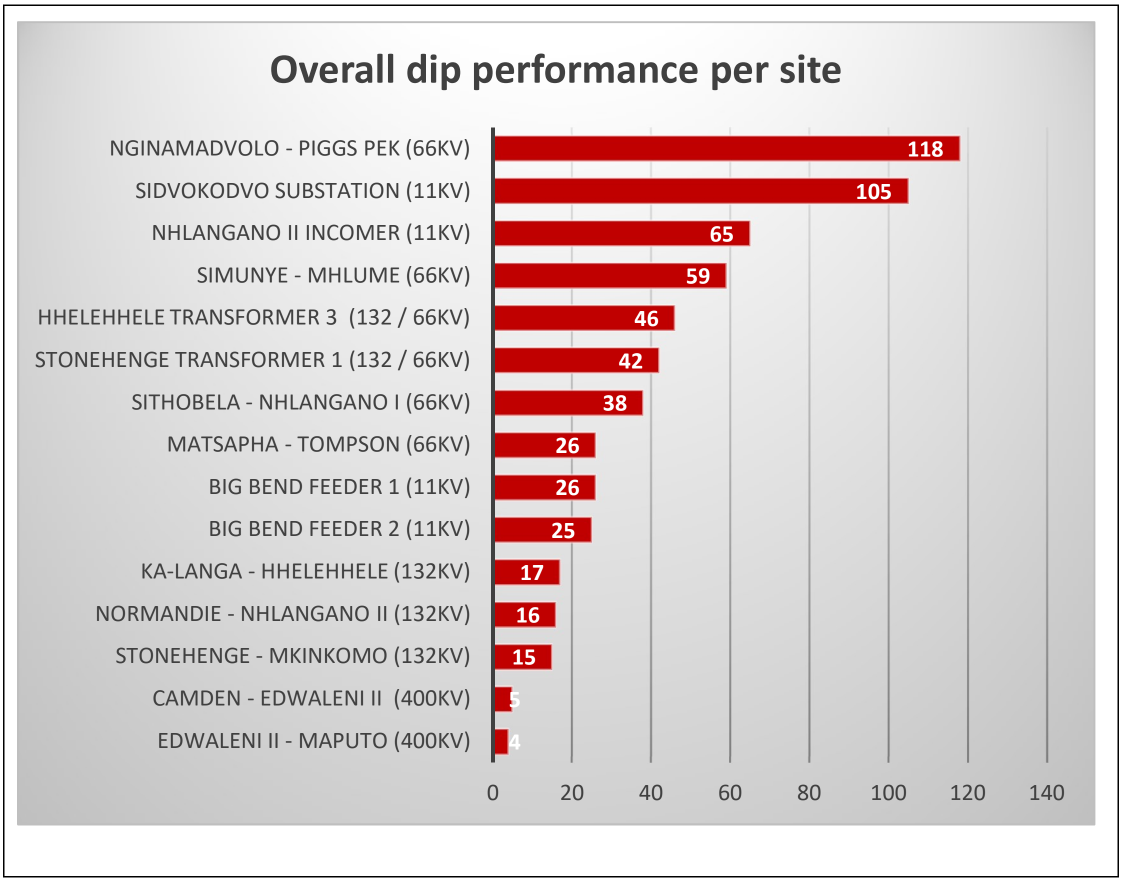

Figure 3.4: Actual dip performance of the network

The following is noted in Figure 3.4:

- Dips recorded at Nginamadvolo –Piggs Peak feeder is a concern. If, and how it can be mitigated, requires understanding of the driving factors (root-cause).
    - The information in the database (for Nginamadvolo –Piggs Peak feeder) was improved by the installation of an additional PQ instrument at Maguga power station since data from Nginamadvolo –Piggs Peak feeder indicated that the direction of the dips was due to downstream events (where Maguga power station is located). No additional root-cause information was available during the writing of the dissertation.
- Dips at Normandie – Nhlangano II feeder is also a concern since they can penetrate deep into the network as it is an infeed into SEC.

Drilling further, the different types of dips recorded by the different sites in Figure 3.4 are shown in Figure 3.5

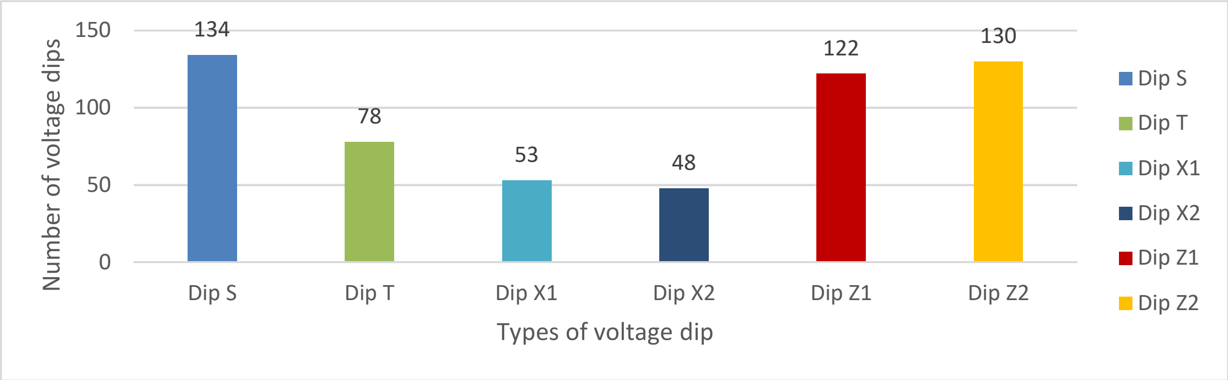

Figure 3.5: Different types of dips recorded

Observe that S, Z1 and Z2 dips dominated the annual dip performance as shown in Figure 3.5. Different standards, i.e. the Semi F42, IEC 61000-4 and ITIC/CBEMA have a compatibility requirement (area) that is the same than the dip Y area of the NRS 048.

3.5. The impact of climatic conditions on voltage dip performance of the network

Weather affect the annual distribution of dips as discussed in section 2.3.4.2. During summer, lightning and winds can cause over-voltages and electrical structures to break. Line conductors, jumpers and porcelain insulators can be damaged resulting in short circuit conditions. Trees at proximity to power lines can be blown into lines causing earth faults.

The distribution of recorded dips for the different seasons is shown in Figure 3.6.

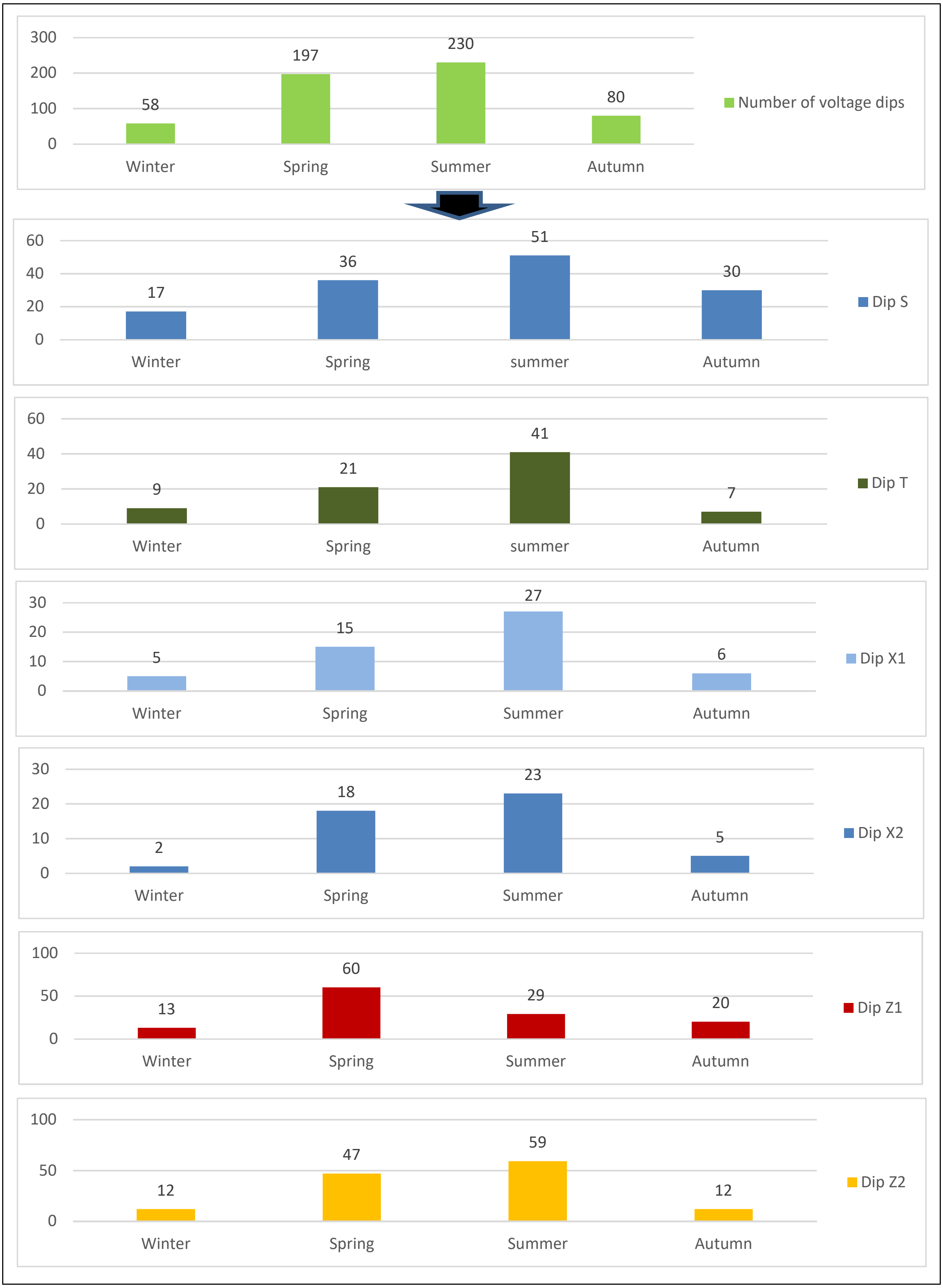

Figure 3.6: Distribution of voltage dips according to seasons of the year

Most dips were recorded during the summer and spring months, correlating well with the lighting activity discussed.

About 95% of the SEC network make use of overhead transmission and distribution power lines, exposed to weather conditions such as lightning. The remaining 5% is underground cables, being shielded from weather.

3.6. Assigning ownership to voltage dips

Root-cause analysis of voltage dip events aims amongst others to identify the network in which the fault that caused the voltage dip event, is located. It assigns ownership (responsibility) of the dip for the purpose of devising some type of intervention to reduce the overall number of dips in that network.

Eskom owns the network surrounding the SEC network. Internal could mean an IPP feeding into the SEC network. But it is also possible to distinguish between the different internal networks, as different networks are under the responsibility of different people.

In the latter case, a network where for example a high number of dips are the result of maintenance being neglected, then the person responsible for that network must be assigned ownership (responsibility) for those dip events. Intervention can then improve the dip performance of that network.

Visibility of this ownership in the PQ database should contribute in motivating the person responsible to intervene as the performance of that person will be visible to all users with access to PQ-portal. Figure 3.7 shows the distribution of dips and parties responsible.

Figure 3.7: Voltage dips assigned to responsible parties

All parties contribute towards the T and Z2 dips, this is a concern because the standard emphasises the limitation of these dips since they are bound to result in an interruption of customer processes.

Figure 3.8 shows a percentage of the responsible parties for clear identification of their contribution.

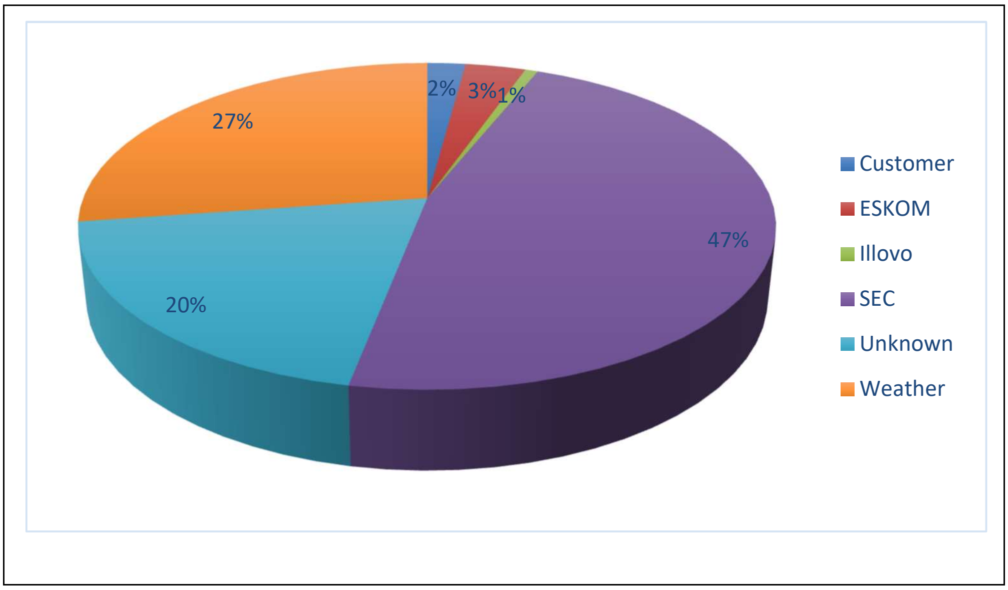

Figure 3.8: Voltage dips assigned to responsible parties

- 47% of the recorded dips belong to SEC.
- 27% of the dips were caused by weather hence they are not under the control of SEC as weather related voltage dips could mostly not be avoided. Those protection mechanisms which can assist, such as proper earthing and clean insulators are addressed separately and assumed to be within the organisational norm.
- 0.7% were caused by Illovo (an IPP selling electricity to SEC), Eskom and customers.
- Normandie - Nhlangano II feeder (132 kV) is responsible for 2% of the dips caused by Eskom, only 1% originate from the Camden – Edwaleni feeder (400 kV).
- Due to unavailability of details for some of the dips even after a formal investigation, they were categorised as unknown.
    - 20% of the dips were unknown, this is a problem since SEC cannot manage dips if the root-cause is unknown.

Mitigation measures of dips presented in Figure 3.8 are discussed in detail in chapter 5 with a priority on dips recorded in the transmission network.

3.7. Comparison of dips in terms of voltage levels

The number of instruments in the different voltage levels are different, hence comparison of the sites against each other can only be done after the data is normalised, the concept was discussed in section 2.4.7.3. The colour coding as explained in that section indicate:

r_E = Individual index

$1 \geq r_E > 0.5$: Large reserve to the limit (green)

$0.5 \geq r_E > 0.25$: Medium reserve to the limit (yellow)

$0.25 \geq r_E > 0$: Small reserve to the limit (Brown)

$r_E \leq 0$: No reserve to the limit (red)

Anything less than 1 was normal, above that, it indicates a poor performance.

Table 3.2 shows normalised dips for the different voltage levels, with a value of 1 regarded as the limit (per unit principle).

Table 3.2: Normalised dips per voltage level

Voltage Levels (kV)	Dip Performance
400	0.12
132	0.64
66	1.09
11	1.47

The following is noted in Table 3.2:

- 56% of dips were recorded in the transmission network and 44% in the distribution network.
- The number of dips recorded in the 11 kV network is high compared to those recorded in the 66 kV network despite the fact that the number of instruments are more in the 66 kV network. This is where the concept of normalisation is visible.
- As it can be expected, the number of dips recorded in 400 kV and 132 kV networks are less since:
  - The networks are made of steel structures and
  - The clearances are larger.

3.8. Root-cause analysis

Before the normalisation of data, results indicate that most dips were due to unknown root-causes and storms. However, after the normalisation of data the results reveal otherwise. The root-cause data was normalised and presented in Table 3.3 and Figure 3.9.

Table 3.3: Normalised dips per root-cause

Root-cause	400 kV	132 kV	66 kV	11 kV
Human & animals	0.00	0.00	0.94	1.61
Fire	0.00	0.00	1.22	1.61
Cables	0.00	0.00	0.31	0.39
Switching	0.30	0.00	1.76	0.44
Customers	0.00	0.00	0.71	2.50
Birds	0.00	0.00	0.68	2.56
Jumpers	0.00	0.37	0.84	2.10
Equipment	0.00	0.85	1.12	1.36
Conductors	0.15	0.30	0.56	2.55
Vegetation	0.00	0.59	0.46	2.65
Unknown	0.14	0.85	1.35	0.88
Storms	0.19	0.85	1.29	0.97

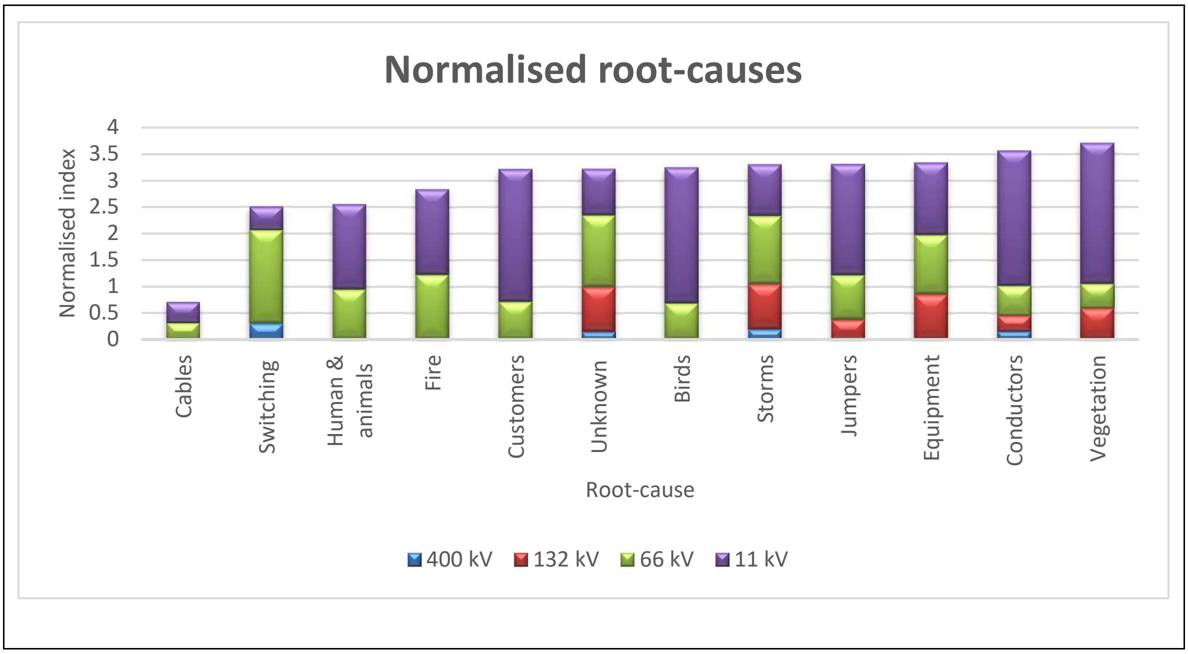

Figure 3.9: Normalised dip root-cause at different voltage levels

Each root-cause is analysed below:

3.8.1. Human and animals

Human and animal related dips are due to faults caused by humans and animals coming in contact with the power system causing either phase-phase faults or earth faults.

- 63 of dips were recorded in the 11 kV network and 37% in the 66 kV network.
- Out of the 63% recorded in the 11 kV, 35% were caused by cars hitting the wooden structures. This is because most of the 11 kV lines are run in parallel with the roads. The remaining 28% was caused by animals coming in contact with live conductors. This is common in power lines cutting through the forests where most of the animals reside, monkeys are the culprits at Usuthu feeders. There are substations, for instance Kentrock substation which has space inside the tunnels used to run cables into the control room, mice and snake's craw into the live chambers and cause short circuits. To mitigate such, foam was put inside the tunnels to ensure that they are tightly sealed.

3.8.2. Fire

Fire is a problem mostly in the Lubombo region as most of the sugar cane fields and veld are in this area.

- 57% of fire related faults emanated from the distribution Network[4] and 43% on the 66 kV networks since they are made of wooden structures.
- 19% of fire related faults in the transmission network were caused by pollution which resulted in phase-phase faults and phase-ground faults. These faults cause arching between the lines or between the line and the ground.
- Most of the 11 kV and 66 kV structures are highly exposed to fire because they cut through sugar cane fields and forests.
- In an event the cane is ripe, they are set on fire in preparation for harvest, at times the fire gets out of hand and burn overgrown grass and vegetation below and next to power lines causing electrical structures to burn and collapse. Upon collapse, the conductors may clash and result in a voltage dip. The pole insulators also get burnt and the conductor comes in contact with the pole causing phase to

[4] Distribution voltage is between 230V – 11 kV

ground faults. It is also for this reason that a high number of voltage dips is recorded in summer because that is when the sugar is ready for harvesting.

- In cases whereby the servitudes of the power lines are well maintained, with less grass below and next to them, the smoke from the fire can cause pollution.

3.8.3. Cables

Insulated underground cables at SEC are used in some suburbs and where insufficient space exist for pole structures.

- 56% of dips were recorded in the 11 kV network and 44% in the 66 kV network.
- Dips which were a result of faulty cables occurred in the feeders leaving the substation and the power cables within the substation.
  - These faults occurred at Sidvokodvo (cables under-rated after refurbishment), Piggs Peak (cable overloaded most of the time, it failed during a phase fault), Big-bend and Nhlangano II (cables failed during phase faults) substations.

3.8.4. Switching

Network switching operations result in transient overvoltage which propagate through the network. The severity of the transients caused by switching depend on the type of switching. Parallel power supplies (firm supply configurations) are common in the transmission networks to assist with voltage stability. For example, switching occurring in one feeder will not have any impact on the supply voltage to the customer, provided they have a single bus-bar (the voltage in the bus-bar will remain constant). SEC only has a few of these configurations due to the associated high costs.

- 70% of switching operations occurred in the 66 kV network, 12% on 400 kV and 18% on the 11 kV network.
- 55% of the switching operations on the 66 kV and 11 kV networks were due to maintenance purposes, to isolate only the components that require maintenance. The maintenance was necessitated by the frequent need to maintain wooden pole structures which are widely used in the 11 kV and 66 kV networks. It was also necessitated by the frequent need to maintain the protection equipment installed in these networks since the more the equipment is operated, the more maintenance required.
- Overloading conditions are prone at the 11 kV Stonehenge substation, thus resulting in switching in order to transfer the load (load swinging). Switching in the 11 kV network is also due to capacitor switching, as they connect and disconnect from the system. These capacitors assist immensely in compensating for reactive power to improve voltage stability.

3.8.5. Customers

Voltage dips can be due to faults emanating from within the customer plant.

- 78% of voltage dips were recorded at the 11 kV network and 22% at 66 kV network.
- 45% of the 11 kV dips were recorded at Big-bend and Nhlangano II substations. These substations have industrial customers which are directly fed from the 11 kV network. Customer loads include electric motors which can draw several times their normal full load current during start-up, thus causing a voltage dip. 8% were recorded at Sidvokodvo substation where there are two long outgoing feeders experiencing a voltage drop during high loading periods.
- 60% of the substations which recorded dips caused by customer loads are in the Lubombo region, where some of the industrial customers are located.
- Substations in the Lubombo region experience under-voltage between December and March when the IPP, Illovo Sugar is not generating. The IPP will be conducting their maintenance during this period since it is an off-crop season, thus they will be importing power from SEC. Customer loads fed directly from the 11 kV network will definatly result in voltage dips during this period in the 11 kV and 66 kV networks because of the under voltage.

- The Northern SEC grid receives power from Eskom III and the Southern grid from Eskom IV. During the unavailability of the IPP, normally open points between the two grids are closed to stabilise the network. It is compromised by long feeders in-between causing voltage drops. Nhlangano II – Ka-Langa 132 kV feeder is the major contributor to the voltage drop (length). During this period, the sending voltage at Nhlangano II substation is at 130 kV then it will be 121.9 kV at Ka-Langa substation. This is a significant technical loss. The 132/66 kV transformers at Ka-Langa substation will tap up to the last level, to maintain the output of 66 kV.

This under-voltage is a concern as 60% of key customers are in the Lubombo region and the load is growing.

3.8.6. Birds

Electrocution of birds and bird streamers (watery conductive excretions causing a flashover between line and earth) contributed significantly to voltage dips. It is mostly at lines through forests.

- The voltage dips were recorded in the 11 kV and 66 kV networks, with 79% on the 11 kV network.
- 43% of voltage dips were caused by the electrocution of birds and 57% were due to bird streamers.
- 18% of dips recorded at the 11 kV network emanated from power lines cutting across forest areas such as Mhlambanyatsi, Bhunya and Mpisi.

3.8.7. Equipment

Electrical infrastructure equipment can malfunction and cause faults. SEC conduct preventive, corrective and condition-based maintenance to support availability of equipment. Some older equipment remains in service even after it has passed its expected life. It will continue to be maintained as part of the run-to-failure strategy.

- The 66 kV network recorded 33% voltage dips, 41% on the 11 kV network and 26% on the 132 kV.
- The voltage dips recorded in the 66 kV and 132 kV networks were due to the malfunctioning of the equipment-run-to-failure, these include the following:
  - Oil circuit breakers which cause unnecessary power interruptions due to worn out parts. For example, when the oil becomes older, the quality of the oil is degraded compromising insulation and cooling of the breaker. It can result in a failed breaker mechanism to be replaced with a SF6 breaker.
  - Insulation strength in substation transformers can be compromised when oil is not well maintained and may cause flashover between windings.
  - Lack of maintenance at line isolators can cause arcing during operation leading to failure.
  - Poor voltage regulation at points in the network where tap changers are under maintenance.
- Voltage dips recorded in the 11 kV network were due to:
  - Malfunctioning of oil reclosers as a result of oil degradation. SEC aims to replace all with a vacuum type which should be more reliable.
  - Poorly maintained 16 kVA transformers.

3.8.8. Jumpers

A jumper refers to the conductor across a pole between adjacent lines.

- 64% of broken jumpers were in the 11 kV network, 25% in the 66 kV network and 11% in the 132 kV network.

Reasons for faulty jumpers are:

- Loose connection of jumpers causing hot spots such as in Figure 2.21.
- Excessively high fault currents when a short-circuit between phase conductors occur.
- Overload conditions damage older jumpers.

3.8.9. Conductors

Different conductors used at SEC for overhead lines are:

- 11 kV: Gopher, 10 MVA
- 66 kV: Hare 32 MVA
- 132 kV and 400 kV: Wolf or Lynx, 92 MVA

Short-circuit between conductors can damage conductors during high faults currents. For example, Figure 2.20 shows a transmission line where conductors may come in contact due to wind as the line has sagged too much.

- 72% of the faults were recorded on the 11 kV, 16% on the 66 kV, 8% on the 132 kV and 4% on the 400 kV networks.
- As clearance between the conductors increase, the chances of conductor clashing, decrease.

3.8.10. Vegetation

SEC requires that transmission and distribution lines must have a clearance distance of between 10 – 25 meters, depending on the type of structure. The decision was made, taking into consideration the falling distance of the structure, the bigger the structure, the greater the clearance distance required. In transmission power lines, wooden poles must have a clearance of 16 metres on either side (on the left- and right-hand sides) of the poles and steel structures a clearance of 20 metres on either side. Distribution power lines only have wooden structures and must have a clearance of 10 – 15 metres from either side.

The above implies that there shall be no buildings, vegetation and forests within the stipulated clearances. A major challenge for SEC is that 15% of the power lines cut through privately owned forests, making it difficult to enforce this requirement. During the summer season, vegetation and trees grows rapidly and can cause line-earth faults.

Table 3.3 shows that:

- 72% of the voltage dips caused by trees touching the lines were recorded on the 11 kV network.
- Only 28% were recorded in the 66 kV and 132 kV networks.
- Transmission lines are higher than lines in distribution networks and should be less prone to earth faults caused by vegetation.

3.8.11. Unknown

Unknown as a root-cause indicate that a dip could not be matched with any SCADA event and the additional investigation was not successful.

- Table 3.3 shows that 77% of voltage dips with an unknown root-cause are in the transmission network (66 kV, 132 kV and 400 kV) and 23% in the distribution network.

Research at several utilities, including Eskom indicated that bird streamers are responsible for most of dips with unknown root-causes. Mitigation of bird-related faults were partly successful at Eskom. Details of mitigation measures at SEC will be discussed in chapter 5.

3.8.12. Storms

Storm related include voltage dips whose origin can be related to adverse weather conditions such as heavy rains, strong winds and lightning. Research indicate that lightning is responsible for 75% of voltage dips in overhead power lines as discussed in section 2.3.4.2.

- Table 3.3 shows that storm related dips were recorded in all voltage levels, with 29% on 11 kV, 39% on 66 kV, 26% on 132 kV and 6% on 400 kV networks.
- 65% of storm related dips were recorded in the Lubombo and Shiselweni regions. These regions experience the highest lightning activity in the country, and they have long feeders exposed to

lightning. As discussed earlier on, under-voltage exists in these regions, contributing to a higher number of voltage dips.

3.9. Propagation of voltage dips

Voltage dips measured at a site will include dips with a local and remote root-cause due to the interconnected nature of the electrical network. A single dip event can result in numerous dips being recorded throughout the network. The extent to which the dip propagate depends on:

- **The impedance of the electrical network**: A good system impedance (low impedance) leads to less voltage dip propagation. A fault in one phase causes a voltage drop in the faulted phase, however, the two unaffected phases may either show a drop-in voltage, a rise in voltage or no change in voltage. An increase in impedance between the monitoring point and the faulted area results in an increase in residual voltage.
- **The vector configuration of the interposing transformers**: There are different types of transformer configurations, Y/Y, Y/Δ and Δ/Y and each result in a different phase shift and residual voltage.

The SEC network consist of the Northern Central region (Combination of Northern and Central grids) and the South Eastern region (combination of the Southern and Eastern grids) as shown in Figure 3.10.

- The Northern Central region is fed from Edwaleni II 400 kV infeed (main source) and four hydro power stations (Edwaleni, Ezulwini, Maguduza and Maguga) with a combined capacity of 60.6MW. The hydro power stations do not contribute to base load due to the variation in water availability.
- The South Eastern region is fed from Nhlangano II 132 kV (main source) and two IPPs, Illovo (available throughout the year except for December –March) and Buckswood solar plant (Its availability depends on weather conditions, sunny weather is favourable).

The two regions operate independently unless a need arise to connect the entire network together, open points separating the two are marked in green in Figure 3.10.

The separation of the network into two regions affect the propagation of dips. Dips occurring within a certain region will be recorded only by the PQ instruments installed in that region, unless the networks are connected.

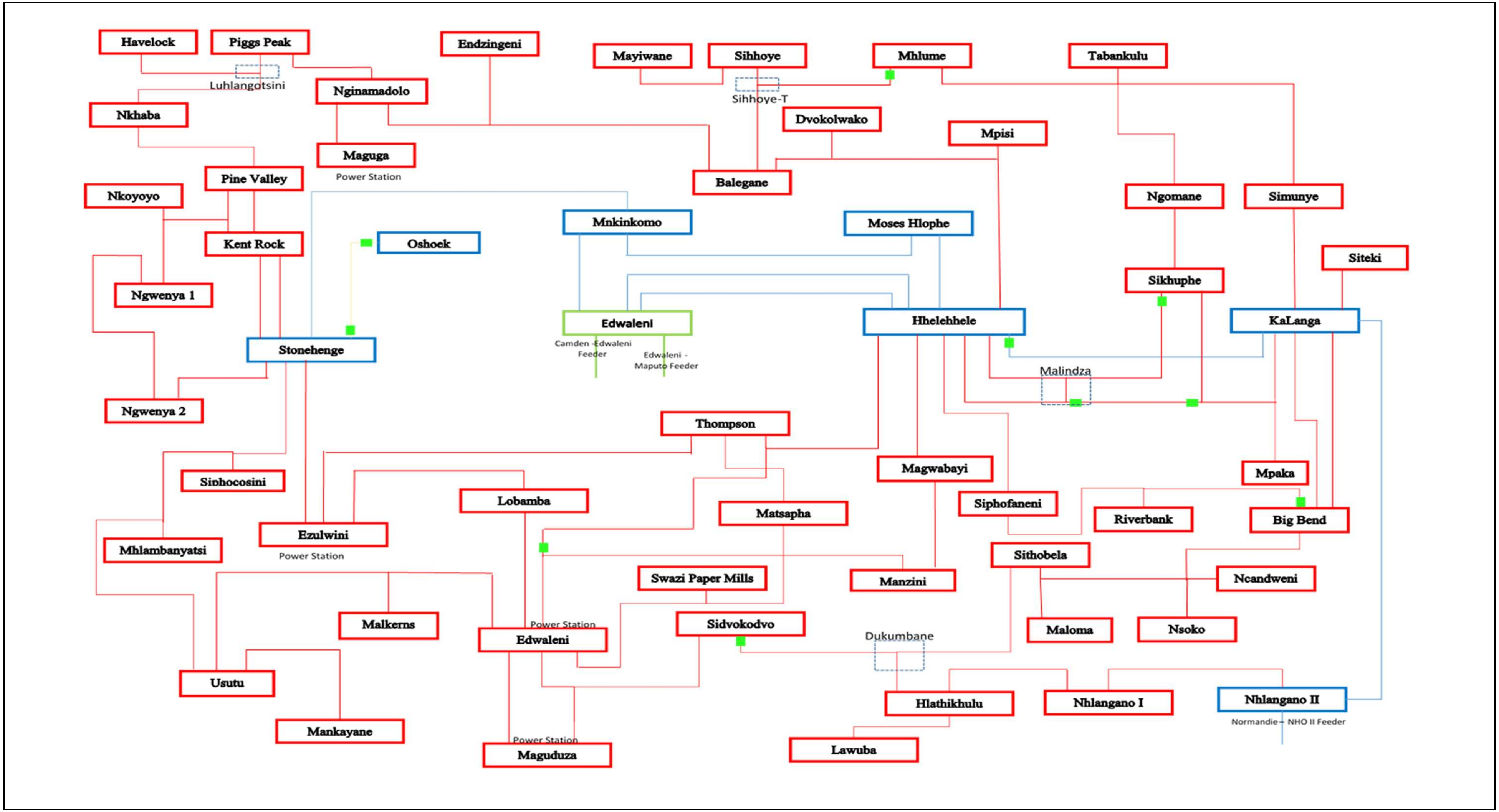

Figure 3.10: Single line diagram of the SEC network

Figure 3.11 shows an example of a fault which occurred in the network. The fault resulted in several dips recorded by more than 1 instrument. The voltage and current RMS profiles indicate that it was a phase - phase fault which resulted in significant reduction of voltage in the blue and red phases.

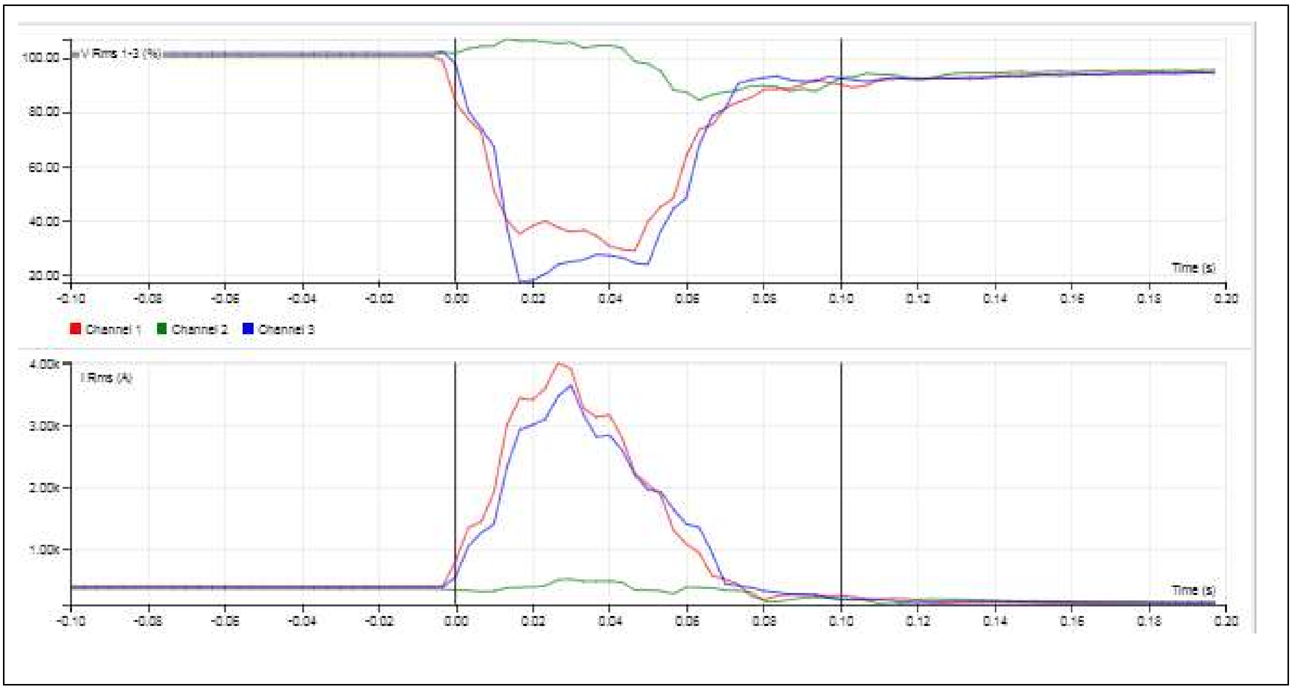

Figure 3.11: RMS voltage and current waveforms

Voltage dip propagation is demonstrated by Figure 3.12 where a phase – phase fault occurrence caused by a broken jumper resulted in several dips being recorded.

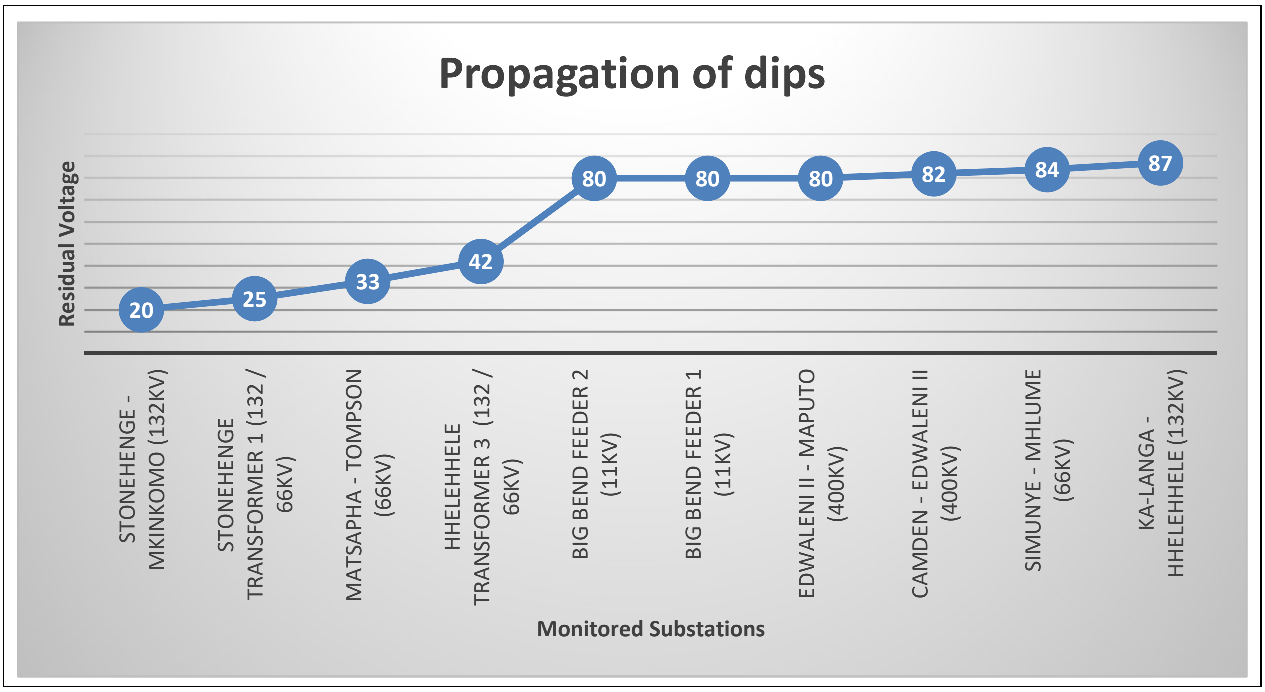

Figure 3.12: Propagation of dips caused by a phase – phase fault

Details of this dip incident is as follows:

- The fault occurred along the Stonehenge – Mnkinkomo feeder.
- The voltage was reduced to almost 20% of declared voltage.
- Dip events were recorded in both the transmission and distribution networks.

- The residual voltage increased further away from the faulted area as dictated by Ohms law.

The fault occurred when the Northern-Central section and the South-Eastern sections were connected by closing all the normally open points on the Normandie – Nhlangano II feeder. Only infeed into this network was from Edwaleni II 400 kV infeed. As a result, the dip was also recorded by PQ instruments installed in the South-Eastern region such as at Big-bend, Simunye and ka-Langa substations.

The variance in voltage magnitude recorded at different monitoring points resulted in different types of dips, since an increase in distance between the point of measurement and the fault will result in a decrease in the depth of the dip. The impedance between the point of measurement and the fault increases with distance, the concept is discussed in section 2.3.2.1.

3.10. Conclusion

This electricity supply company aims to improve the dip performance of the electrical network by monitoring, and then managing voltage dips from the root-cause of each voltage dip. For this reason, strategic monitoring of PQ is done, data collected and analysed with a focus on root-cause analysis and benchmarking dip performance over time, against other similar networks. Other PQ parameters are also analysed, but in the research reported in this dissertation, the focus is on voltage dips.

40% of dips were recorded in the summer season, 35% in spring, 14% in autumn and 10% in winter. A high number of dips were recorded in summer due to associated harsh weather conditions. Ownership (internal/external to SEC) of each dip was derived.

A breakdown of the ownership of dips was done to ascertain the contribution of each stakeholder. 20% of dips had unknown root-causes, making it impossible to mitigate. From the results of the root-cause analysis, SEC devised mitigation measures, presented in chapter 5.

4. Verification and validation of voltage dip root-cause information

Field data hosted in the PQ database has been manually analysed for root-cause and the result requires verification. It was done by simulating the root-causes in a network model developed for the entire SEC network. Validation by field data is then done to confirm that the simulation results can be used to verify the root-cause information (entered as meta data in the PQ database). How verification and validation was done, is addressed below.

4.1. Simulation tool

DigSILENT™ was used for network modelling in this research. Voltage dips can be studied by means of three approaches in DigSILENT™:

- A basic steady state approach that uses a steady state network model under balanced network conditions, taking into consideration only the fundamental components of voltages and currents.
- A three-phase steady state function uses a steady-state network model under balanced and unbalanced network conditions. This function can simulate individual phase values which are very important for accurate analysis because less than 5% of all system faults are caused by balanced faults.
- An electro-magnetic transient model that uses a dynamic network model for short and mid-term transients under balanced and unbalanced network conditions. It is mainly used in the analyses of power system faults or transient overvoltage, over currents and harmonics and waveform distortion. They normally use three phase instantaneous values for calculations. It is for his reason that the simulation speed is low, and the tool also requires more detailed models.

The three-phase steady state function was used because it can conduct simulations for balanced and unbalanced conditions.

4.2. Development of the SEC network model

The DigSILENT™ model of the SEC network was done by the planning engineers. I also had an opportunity to be part of this exercise whilst under the Engineer in training program. It was done for 11 kV, 66 kV, 132 kV and 400 kV. Circuits less than 11 kV were not included because the network is vast. Loading in networks below 11 kV were lumped to obtain useful simulation results.

The simulation of the model was executed as follows:

1. An Auto-CAD™ single line diagram of the SEC network was used as reference.
2. Arc-GIS™, showing the geographical location of distribution and transmission power lines was another reference such as distances between the different points in the network and i.e. position of a transformer in the power line.
3. Firstly, a class library was created for:
    - Substation / Transmission transformers, from 2.5 MVA up to 250 MVA and distribution transformers, from 16 kVA up to 2 MVA, refer to Table C.1.
    - Line conductors used at different voltage levels, refer to Table C.2.
    - Type of towers implemented at different voltage levels, refer to Table C.3.
    - Type of generators used for hydro generation, refer to Table C.4.
4. The full network was modelled in DigSILENT™ first simulated for small sections of the total network to verify the model.
5. A successful simulation of the full SEC network was achieved, and the simulated load flow results correlated against field data as validation. This model is now used extensively by SEC for network planning to conduct:

- Network demand forecasting for short term, mid-term and long-term load growth, System studies to identify network congestion resulting from network capacity constraints and network refurbishment requirements,
- Reducing overall system technical losses,
- Optimisation of network components.

Individual substations were simulated with all details pertaining. Figure 4.1 shows one of the substations simulated.

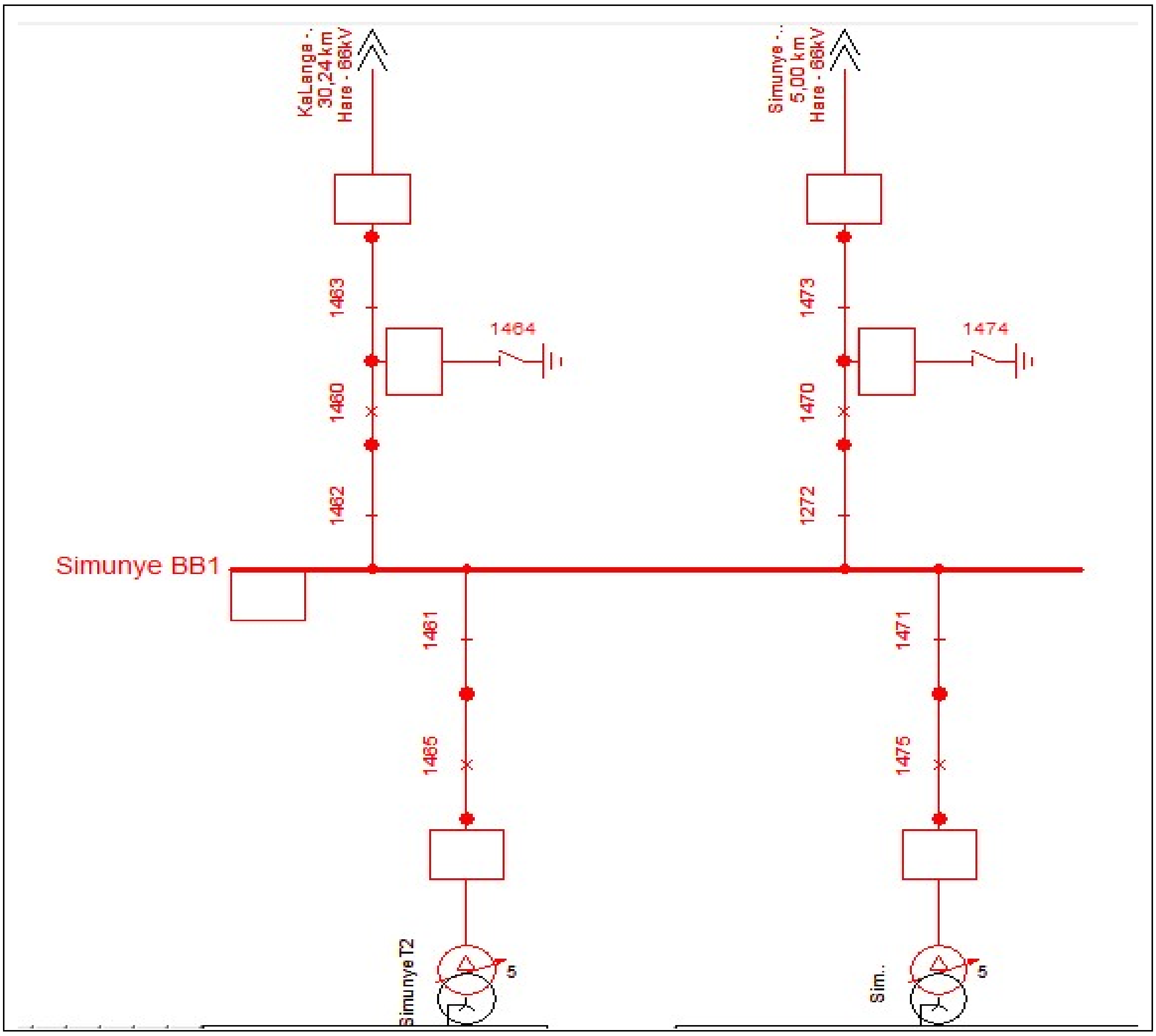

Figure 4.1: Simulated Simunye 66/11 kV substation

Thereafter, all the substations were connected to form one continuous network, a single line diagram is shown in Figure 4.2. This is the model that will be used to verify and validate all dip root-causes by means of emulation.

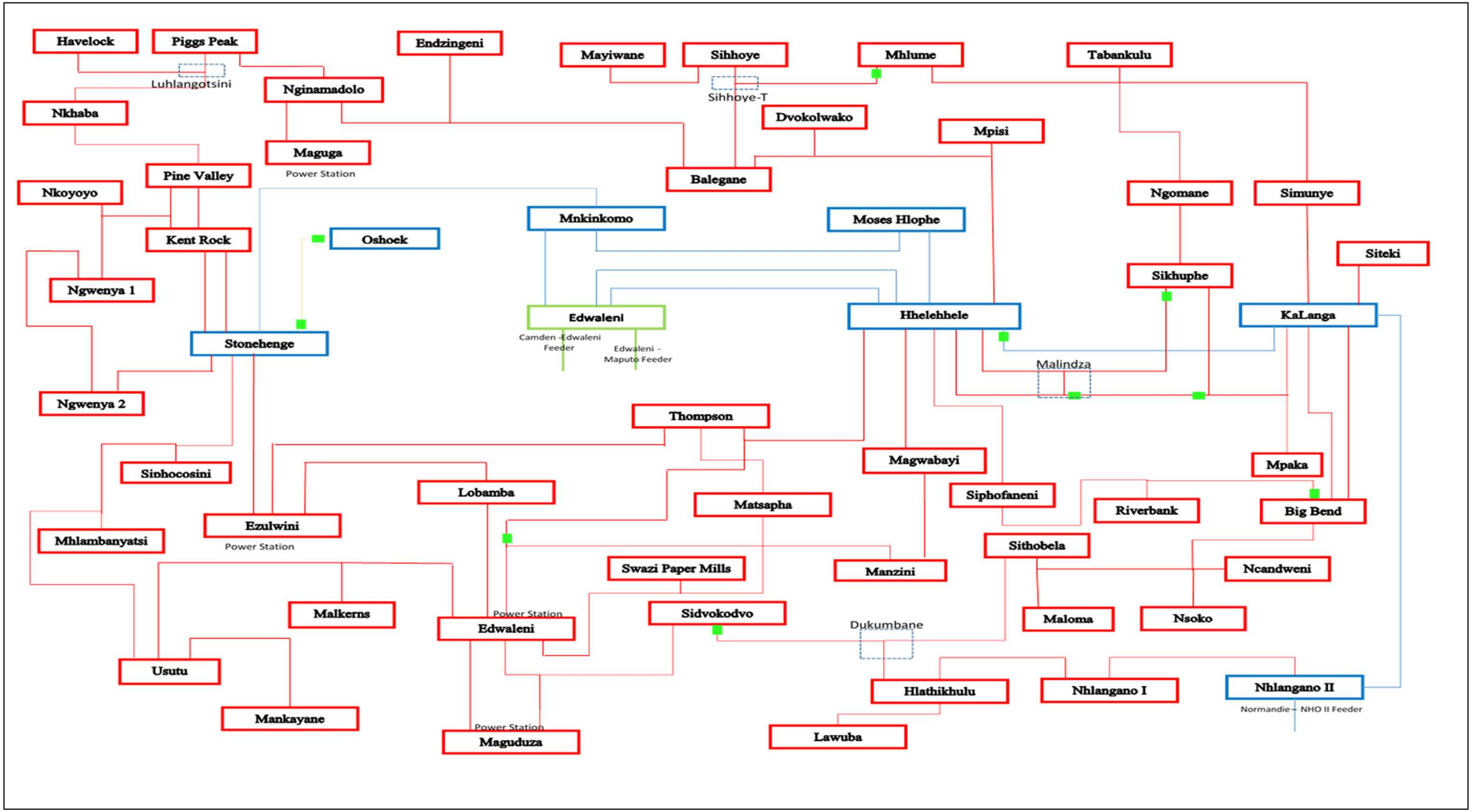

Figure 4.2: A single line diagram of the network with all substations

4.3. Voltage dip simulation conditions/ assumptions

The simulation of voltage dips was done with the following simplifications:

- Only voltage dip events[5] caused by short-circuit or switching events were simulated.
- Repetitive fault conditions were not simulated: The concept of flagging was used to prevent a single event impacting multiple PQ assessments. For instance, without flagging, a dip will be counted under the dip statistics, but could also impact the flicker assessment of the same period, resulting in an additional PQ concern, which does not really exist.
- Phase angle jumps were not considered during the simulation: A voltage dip occurrence does not only cause a reduction in voltage, but it also causes a shift in phase angles. The PQ database do not allow the analysis of phase angle jumps.

4.4. Simulation of voltage dips

A selection of dips was simulated to validate root-causes.

Table 4.1 list the description of root-causes and the number of dips recorded per root-cause, this table served as a reference for the simulation.

Table 4.1: Dip root-cause description and number of dips recorded over a year in the network

No:	Dip root-cause	Description of root-cause	Number of dips recorded
1	Human or Animals	Humans or animals coming in contact with the power system	6
2	Fire	Dips caused by fire, i.e. pollution and damage to pole structures	7
3	Cables	Insulation failure of cable	8
4	Customers	Dips emanating from customer network/premises	21
5	Birds	Birds in contact with the live conductors	22
6	Equipment	Equipment unable to operate as designed	36
7	Jumpers	Broken jumpers	41
8	Storms	Weather	202
9	Conductors	Broken (open-circuit) or clashing (short-circuit) conductors	50
10	Vegetation	Trees touching power lines	51
11	Switching	Network switching & switching of capacitors	17
12	Unknown	Unknown root-causes	104
	Total		**565**

Simulation was done as follows:

- There is a total of 565 dips recorded, excluding Y-dips.
- These dips are divided according to 11 known root-causes (excluding the unknown causes).
- Approximately 5 events were randomly selected from each main root-cause (i.e. 44 dip events spread over 11 root-causes.).
  - o Note that less than 5 events were verified and validated for root-causes with events less than 6, refer to Table 4.2 for the number of events simulated for the different root-causes.

[5] Event in this chapter refers to the number of dips remaining after time aggregation as explained in chapter 3, section 3.3.

Table 4.2: Number of incidents for the different root-causes

Number of root-causes	Number of events recorded	Total number of events to be simulated
1	2	2
2	3	6
4	4	16
4	5	20
Total		**44**

Dips with an unknown root-cause were excluded since their cause could not be determined even after a formal investigation. Verification and validation of the incidents in Table 4.2 was achieved by defining either a short-circuit event or a switching event that result in a similar (to the field data) dip event during the simulation.

Short circuit events were used in verifying and validating dip root-causes which were due to an element providing a path with less or no impedance:

- Two conductors touching causing a bolted fault, hence the impedance becomes zero and the current increases significantly with the voltage approaching zero.
- An element cross phasing between two or more conductors, for instance, a bird. The impedance is not zero due to the impedance of the bird.
- An element touching one or more conductors and ground, for instance a tree touching a phase, the impedance is not zero due to the impedance of the tree.

Switching events were used to emulate dips which were due to interruption of a power circuit:

- Breaking of jumpers or conductors causing an open circuit in either 1 or more phases, leading to infinite impedance and the current becomes zero. This was simulated by opening and closing of a switch after a steady state condition.

4.4.1. Simulation of dips by defining a short-circuit or a switching event

Simulation of dips by defining a short circuit event require knowledge of the type of fault, the duration of the fault, the fault impedance and the exact location of the fault. The required DigSILENT^{TM} parameters are shown in Figure 4.3.

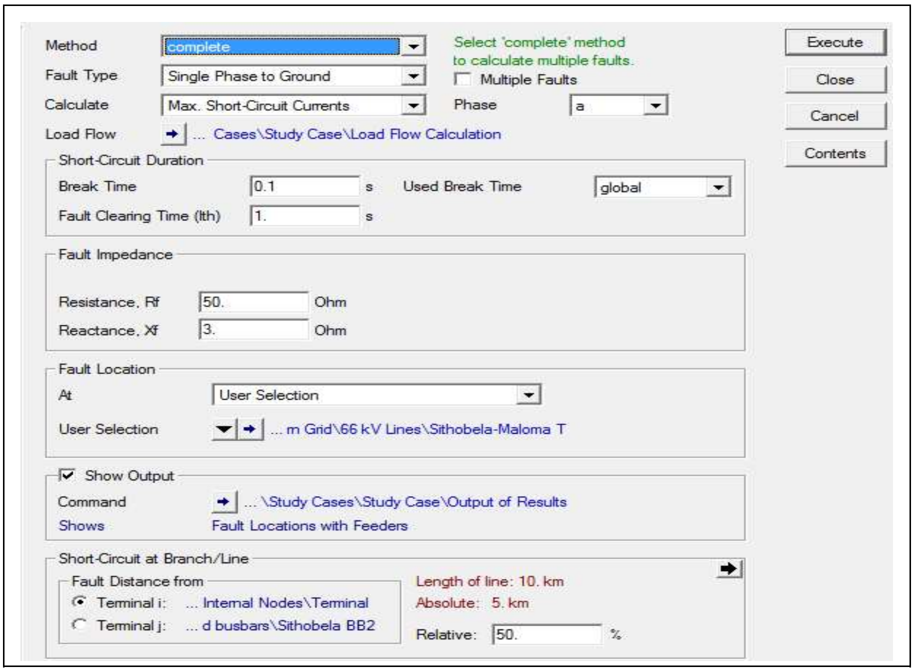

Figure 4.3: Short-circuit window in DigSILENT^{TM}

PQ-portal only report the type of fault, duration of the fault, location of the fault (provided by impedance protection relays) and the residual voltage. The fault impedance is not available, constraining the simulation.

To compensate for the above constraint, some of the field data was first used to determine the range of fault impedances per root-cause in order to validate the remaining field data:

- Four events were selected from each main root-cause, except for instances whereby a root-cause has less than 6 events. In that case, only 2 were used to determine the range of fault impedances:
    - One / two events per main root-cause with the lowest residual voltage and
    - One / two events per main root-cause with the highest residual voltage.
- Table 4.3 shows the range of residual voltages and duration for each main root-cause obtained from field data.
    - These are voltage and duration values forming a boundary (restrictions) which cannot be exceeded by the fault impedance range.

Table 4.3: Range of residual voltages and duration

No:	Root-cause	Residual voltages (%)	Duration (s)
1	Human or Animals	0 - 3	0.81 – 2.08
2	Fire	24 - 77	0.16 – 0.75
3	Cables	0 - 81	0.46 – 0.99
4	Customers	36 - 85	0.08 – 1.08
5	Birds	43 - 84	0.08 – 0.78
6	Equipment	40 - 83	0.69 - 2.14
7	Jumpers	23 - 80	0.13 – 1.75
8	Storm	0 - 82	0.49 – 2.06
9	Conductors	4 - 84	0.12 – 0.81
10	Vegetation Related	24 - 84	0.35 – 0.98

- Some root-cause has events which require both defining a short circuit event and a switching event.
    - For instance, a jumper may break and touch another phase causing a short-circuit (simulated by defining a short-circuit event) or it may break and not touch anything, causing an open circuit (simulated by defining a switching event).
- Per event, a short circuit event was defined at the exact location of the fault in order to obtain the fault impedance value.
    - A random fault impedance value was selected and used for the first simulation. The impedance value was then updated based on the difference between the measured and simulated voltage level until the residual voltage measured by the PQ instruments in the model is the same as the voltage in the practical data. This resulted in several fault impedance values per root-cause, refer to Appendix D.
- The simulation process in DigSILENT^{TM} PowerFactory was as follows:
    - Create an RMS simulation.
    - Solve the initial conditions for the RMS simulation.
    - Define the results variables at the node(s) of interest.
    - Create an event for the fault with the relevant information (location, type of fault and fault impedance).

- ✓ Note the iterations to determine the range of fault impedance during this phase of the project.
  - o Create an event to remove the fault event after the fault duration.
  - o Execute the RMS simulation until the fault has been cleared.

Table 4.4 shows the range of fault impedances obtained per root-cause. Bird related faults had the highest fault impedance when compared to the rest of the root-causes whilst human and animal related faults had the lowest fault impedance range.

Table 4.4: Range of fault impedance values per root-cause

No:	Root-cause	Range of fault impedance (Ω)
1	Human & Animals	(0.08+j0.08) - (1.2+j2)
2	Fire	(0.9+j1.1) - (2.5+j2.8)
3	Cables	(0.01+j0.1) - (1.5+j1.1)
4	Customers	(0.9+j1) - (1.9+j2)
5	Birds	(1.8 + j2) - (8+j9)
6	Equipment	(0.8+j1.5) - (3.1+j2.8)
7	Jumpers	(1.1+j0.1) - (4.1+j2.3)
8	Storms	(0.03+j0.2) - (2.1+j0.9)
9	Conductors	(0.8+j0.35) - (4.3+j2.5)
10	Vegetation	(0.06+j1.3) - (6.5+j4.3)

Fault impedance values in Table 4.4 were then used in verifying and validating the events randomly selected from each main root-cause (i.e. 44 dip events in total). Out of the 44 events, 30 were simulated using short circuits and the remaining 14 events were simulated by defining a switching event.

- Practically, an event can result in voltage dips being recorded by different PQ instruments, but only the PQ instrument with the lowest residual voltage would be of interest since it is closer to the faulted area.
  - o Residual voltages recorded by the other PQ instruments were also of interest to further confirm the validity of the simulated results and the model (propagation of dips through the network).

The simulation process in DigSILENT™ PowerFactory for the simulation of short circuit and switching events was as follows:

- Create an RMS simulation.
- Solve the initial conditions for the RMS simulation.
- Define the results variables at the node(s) of interest.
- Create an event for the fault with the relevant information (location, type of fault and fault impedance).
  - o Use fault impedance values determined in Table 4.4
- Create an event to remove the fault event after the fault duration.
- Execute the RMS simulation until the fault has been cleared

A description of the headers in Table 4.5 and Table 4.6 is as follows:

- **Root-cause**: Indicate the cause of each dip as matched by system operators in PQ Portal.
- **Voltage level**: The voltage level at which the dip occurred.
- **Type of fault**: Whether the fault resulted in a conductor coming in contact with earth or it involved the touching of conductors, causing an over current phase fault or it resulted in an open circuit in either one or more of the phases.
- **Fault description**: Shows the details of the incident and how it eventually caused a voltage dip.
- **Simulation event:** Dips were simulated by either defining a short circuit event or a switching event, the choice of which event to use depends on the description of the type of fault.
- **Fault location:** Shows the exact location of the fault as recorded by the PQ instruments. This was made possible by the implementation of the zones of protection on relays which enable characterisation of the entire network into manageable sections (zones 1, 2 and 3).
- **Fault impedance:** Shows the fault impedances of the events.
- **Duration of event**: Indicate the duration of each event as obtained in PQ-Portal.
- **Point of measurement**: The location where the PQ instruments are installed. This is the location which recorded the lowest residual voltage during an event as obtained from PQ-Portal. The point of measurement does not necessarily imply that the fault occurred along the feeder where the PQ instrument is installed, the fault can emanate far from the point of measurement.
- **Simulation results:** Residual voltage results after the implementation of the simulation settings per root-cause.
- **Practical results:** Voltage results as measured by the PQ instruments, obtained via PQ portal.

Table 4.5: Simulation results of dips caused by conductors

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Conductor	66	Open Circuit Fault	Broken conductor on one phase	Switching	2.6 km on Edwaleni Power Station - SPM Feeder	N/A	2.0616	Matsapha Substation	0	1	1
	66	Phase Overcurrent	Touching of two phases	Short circuit	2.8 km on Simunye - Thabankulu Feeder	3+j1	0.09334	Simunye Substation	6	8	2
	66	Phase Overcurrent	Snapped conductor touches earthed structure	Short circuit	6.5 km on Sikhuphe - Ngomane Feeder	1+j0.35	0.14724	Kalanga Substation	38	39	1
	66	Phase Overcurrent	Touching of two phases	Short circuit	7.2 km on Ngwenya I - Nkoyoyo Feeder	1+j0.95	0.7115	Stonehenge Substation	35	31	-4
	66	Earth Fault	Snapped conductor touches earthed structure	Short circuit	3.8 km on Pine valley - Kent rock	0.9+j0.3	0.81738	Stonehenge Substation	33	31	-2

Table 4.6: Simulation results for dips caused by human or animal faults

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Human or Animals	11	Phase Overcurrent	Monkey cross phasing on two phases	Short circuit	Usuthu Substation - Metering cubicle	1+j0.9	0.60752	Sidvokodvo Substation	36	31	-5
	11	Phase Overcurrent	A snake cross phasing two phases	Short circuit	Kent Rock Substation - 11 kV busbar	0.06+j0.9	0.081156	Stonehenge substation	17	13	-4
	11	Phase Overcurrent	A snake cross phasing two phases	Short circuit	Nhlangano Substation - 11 kV busbar	0.01+j0.2	2.14236	Nhlangano Substation	1	3	2

Tables 4.5 and 4.6 shows the simulation details and results of dips caused by conductor and human or animal faults, refer to Appendix E for results of the other root-causes.

The results in the tables have a combination of events, simulated by defining either a short circuit or switching event. The deviation of simulated results from the practical results is also shown.

Simulation results of all the root-causes were consolidated with much less details and presented in Table 4.7.

Table 4.7: Comparison of simulation and practical results for all root-causes

Root-cause	Voltage Level (kV)	Simulation Results (%)	Practical Results (%)	Variance (%)
Conductors	66	0	1	1
	66	6	8	2
	66	38	39	1
	66	35	31	-4
	66	33	31	-2
Human or Animals	11	36	31	-5
	11	17	13	-4
	11	1	3	2
Cables	11	11	5	-6
	11	15	10	-5
Fire	66	56	55	-1
	66	32	39	7
	66	46	38	-8
Switching	11	86	81	-5
	11	74	80	6
	11	69	78	9
	11	80	72	-8
Customers	66	72	78	6
	66	57	63	6
	66	35	41	6
	66	69	77	8
Birds	66	80	83	3
	66	69	74	5
	66	73	72	-1
	132	47	51	4
Equipment	66	36	42	6
	66	59	65	6
	66	81	74	-7
	66	53	45	8
Jumper	66	24	15	9
	66	53	58	5
	66	64	72	8
	132	58	49	-9
	66	17	10	7
Storm	132	5	2	-3

	400	6	10	4
	132	64	61	-3
	132	69	65	-4
	66	15	8	7
Vegetation	66	78	82	4
	66	54	48	-6
	66	80	76	-4
	66	65	59	-6
	132	58	40	-9
Cable	11	11	5	-6
	11	15	10	-5

The following is noted in Table 4.5, Table 4.6 and Table 4.7:

- The highest statistical variance between simulated and practical results is ± 9% and the lowest statistical variance is ± 1%. A breakdown of the voltage variance error per voltage level is presented in Table 4.8.

Table 4.8: Voltage variance error per voltage level

Voltage Variance (%)	Voltage Variance (kV)	11 kV Frequency (%)	66 kV Frequency (%)	132 kV Frequency (%)
1	0.66		14	
2	1.32	11.1	7.14	
3	1.98		7.14	33.3
4	2.64	11.1	10.7	33.3
5	3.3	44.1	7.14	
6	3.96	11.1	21	
7	4.62		14	
8	5.28	11.1	14	
9	5.94	11.1	3.57	33.3

- The acceptable margin of error which has been in use in research studies [4], [8] is between 0.1% - 8%.
    - 95% of validated data has an error of less than 8% at 66 kV voltage level.
    - 67% of validated data has an error of less than 8% at 132 kV voltage level.
    - 88.1% of validated data has an error of less than 8% at 66 kV voltage level.

- More than 50% of validated data has an error of less than 8% which implies that the simulation is acceptable as a prediction tool.

- The reason for variation is due to factors discussed in section 4.4.2.

- Table 4.5 and Table 4.6 shows the simulation details and results of dips caused by conductor and animal or human faults whereas Table 4.7 shows a summary of all the results for the different root-causes, making it simpler to present and interpret.

Tables 4.5 and 4.6 shows only the lowest residual voltage recorded during an event (conductors and human or animal related faults) whereas Table 4.9 shows the residual voltages recorded by other PQ instruments during the same event. This was done to further verify and validate the practical data.

A description of the headers is as follows:

- **Root-cause:** The primary cause of the dip.
- **Point of Measurement:** Indicate the location of the PQ instruments with the lowest residual voltage.
- **Residual voltages:** Shows practical and simulated residual voltages recorded at the different nodes.
- **Nodes:** Indicate the location of the different PQ instruments (substations) which also recorded dips caused by the same event. Nodes which were not affected by the fault were noted as ‘N/A’.

Table 4.9: Propagation of dips caused by conductors and human or animal faults

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)	Node 5 (%)
Conductors	Matsapha Substation	Practical	1	38	53	68	76
		Simulated	0	31	48	61	69
		Variation	1	7	5	7	7
	Simunye Substation	Practical	8	35	51	68	N/A
		Simulated	6	29	47	63	N/A
		Variation	2	6	4	5	N/A
	Kalanga Substation	Practical	39	52	68	76	N/A
		Simulated	38	59	72	83	N/A
		Variation	1	-7	-4	-7	N/A
	Stonehenge Substation	Practical	31	56	68	79	82
		Simulated	35	61	72	81	89
		Variation	-4	-6	-4	-2	-7
	Stonehenge Substation	Practical	31	54	65	79	79
		Simulated	33	62	73	75	88
		Variation	-2	-8	-9	4	-9
Human or Animal	Sidvokodvo Substation	Practical	31	74	82	N/A	N/A
		Simulated	36	76	85	N/A	N/A
		Variation	-5	-2	-3	N/A	N/A
	Stonehenge substation	Practical	13	36	69	N/A	N/A
		Simulated	17	42	73	N/A	N/A
		Variation	-4	-6	-4	N/A	N/A
	Nhlangano Substation	Practical	3	26	52	68	N/A
		Simulated	1	21	48	61	N/A
		Variation	2	5	4	7	N/A

Propagation of dips depends on network impedance and the vector configuration of interposing transformers. (Discussed in section 3.9). Verification of residual voltages recorded at different points in the network validates the practical data and confirm the network model.

The network is operated in 2 different regions (Northern Central and South Eastern regions). Sectionalising of the network impact dip propagation. Dips occurring in a region will only be recorded by PQ instruments installed in that region since the regions are functioning independently.

Next, the difference between practical and simulated results is analysed.

4.4.2. Earth faults

Earth faults are caused by the reduction of the impedance between the phase conductors and the earth to a value that is below that of the lowest load impedance to the circuit, (i.e. a tree touching the live conductors). The amount of current flowing from the phase conductors to earth will depend on the impedance of the path connecting the phase and earth as well as the impedance of the ground / soil. The impedance of the soil differs drastically due to the difference in the moisture content, chemical content, type of soil and a variation in temperatures [43].

- Moisture content is mainly affected by weather and changes seasonally. Its variation is according to the nature of the sub layers of the earth and the depth of the permanent water table. It is recommended that earth rods are placed deep in the soil where the soil and water are generally stable.
- The chemical content (dissolved salts and minerals) of the soil can enhance conductivity of the soil.
- The type of soil causes different earth resistances as listed in Table 4.10.

Table 4.10: Resistance of the different types of soil [43]

No:	Soil Type	Soil Resistance Range (ohm – cm)
1	Surface Soil	100 - 5000
2	Clay	200 – 10 000
3	Sand and Gravel	5 000 – 100 000
4	Limestone	500 – 400 000
5	Granite	2000 – 100 000

A broken conductor will result in different residual voltages at different locations due to the type of soil it falls upon, also due to changes in climatic conditions which are not included in the simulations.

4.4.3. Phase faults

Phase faults are a result of conductors touching by a physical connection such as a jumper and cause high fault currents. Fault impedance for phase faults are set by the impedance of short-circuit between phases. Direct contact will result in near-zero impedance, but some resistance is normal due to the arcing condition [6].

An arcing fault between phases can be induced by lightning and the fault current is restricted by the high impedance of the air between the conductors. It results in high temperatures with the ability to damage conductors.

Corroded conductors when in touch will have more impedance than when not corroded.

4.5. Conclusion

A simulation model was developed in this chapter using a simulation tool, DigSILENT^{TM}. The model being a true reflection of the network was used to verify and validate the dip root-causes recorded for more than a year, at different voltage levels. Short circuits and switching events were used in emulating the dip root-causes. The only challenge was that it required knowledge of the fault impedance for the simulation of short circuits but this challenge was overcome by using a portion of the data to determine the range of fault impedances, thereafter, verify and validate the remaining data using the pre-determined fault impedances. Verification of practical data (per root-cause) was conducted in two phases:

- Verification of the lowest residual voltage recorded and
- Verification of the dip propagation throughout the network.

The approach aimed at re-assuring the validity of the practical data. Simulation results indicated the following:

- The highest variation between practical and simulated results was ± 9% for both the verified lowest residual voltage and the dip propagation.

- The variation between practical and simulated results was mostly due to the moisture of the soil, chemical content and the type of soil. These factors could not be emulated during simulations due to capability of the simulation tool used and, it is not possible to know all these factors for each dip recorded.

The results of the simulation deem the practical results to be valid after under-going the verification process. In the process, the accuracy of the dip-trip exercise manually conducted by NCC personnel and the model developed were also verified and validated.

Practical data, presented in chapter 3, verified and validated in this chapter reflect a true dip performance of the network and can be used for decision making. That is implementing dip mitigation measures, this can either be in a form of a project or reviewing of current operational processes and procedures. By so doing, the dip performance of the network will improve.

5. Management of voltage dip root-causes

The results presented in chapter 3 and validated in chapter 4 served as inputs to the company strategy and in the planning department. This was an attempt to better manage and improve the performance of the network in terms of dips.

Firstly, present and future measures to mitigate the root-causes of dips (ultimately reducing the impact and frequency of voltage dips), which were highlighted in chapter 3, will be discussed. Thereafter, a discussion of planned capital projects to be implemented in different phases.

5.1. Mitigation of voltage dip root-causes: short term

An effective method of reducing voltage dips will include measures to address the dip root-causes highlighted in Figure 3.9 directly.

Root-cause analysis reveal the opportunity for dip mitigation. Those dips within the SEC network can be contained by measures within the SEC structures. Dips from supply points outside SEC, can also be contained by those responsible for that networks.

Not all dips are under the control of SEC as climatic conditions for example, cannot be controlled. Dip mitigation rely on understanding the root-cause and addressing those opportunities for improvement under the control of SEC, such as improved earthing, maintenance of servitudes and others.

A dip management program must produce the information needed by for example the planning department. Results from root-cause analysis requires integration into business processes, sometimes referred to as the “operationalisation” of dip performance results.

In SEC, the dip performance of the network is disseminated to operational departments on a quarterly and annual basis to be used for network planning. Budgets can be designed to support for example network upgrades and maintenance projects.

Network operation has continuously on-line access to the dip performance and can in near-real-time validate for example how network switching has affected dip performance. The Metering Engineer regularly reports on dip performance to the Southern African Power Pool (SAPP). An annual workshop on the network performance is held in any of the countries which are members (mostly Engineers and Managers of utilities) of SAPP. During subsequent quarterly and annual workshops, progress with mitigation is evaluated.

The results of the root-cause analysis done in the research, reported in this document, were considered by SEC and decisions made on how to address each.

- Note that there are mitigation measures implemented which addresses more than one dip root-cause, for instance, improving maintenance plan will reduce dips caused by overgrown vegetation and sagging conductors.

5.1.1. Mitigation of 67% of dip root-causes discussed in chapter 3

Results of the dip management program were disseminated to operational departments[6] in order to plan and budget for mitigation measures. The results in chapter 3 indicated that almost 67%[7] of the root-causes might be contained through proper maintenance of the electrical network (for instance, dips caused by broken structures, sagging conductors, broken jumpers and trees touching the line). Maintenance plans at SEC are formulated in a way that each feeder is maintained once a year irrespective of the location. Activities performed during feeder maintenance and mitigated root-causes are shown in Table 5.1.

[6] Operational departments refer to Generation, Transmission, Distribution, Planning and System Operation and Control

[7] Normalised values

Table 5.1: Line maintenance activities and mitigated root-cause

Inspected component	Mitigated root-cause
Structures	Storms damaging structures and conductor clearances being compromised
Conductors	Broken conductors and conductor clearances being compromised causing short circuits
Vegetation	Vegetation poorly maintained
Jumpers	Broken jumpers
Equipment	Malfunctioning or failure of equipment[8]
Cables	Failure of cable insulation (underground networks)

Since 2016, SEC formulate maintenance plans according to the location of the feeders or circuits, in order to reduce dips caused by poor maintenance of feeders. For instance, feeders on the Highveld of Swaziland require more maintenance than feeders in the Lubombo region where rainfall is much less.

- Rainfall enhances the growth of vegetation.
- Lightning strikes in the Highveld is the highest (most rain).
- Clearing fault currents from lighting strikes result in more equipment cycles of breakers located in the Highveld region.

However, there are a few feeders in the Lubombo region which also require frequent maintenance due to the Pollution of insulators caused by the seasonal burning of sugar cane fields.

As a result, feeders in the Highveld and a few feeders in the Lubombo regions are now maintained twice a year to improve dip performance.

5.1.2. Mitigation of dips caused by storms

Approximately 90% of the SEC transmission and distribution networks have wooden structures. A decision to replace all wooden structures with steel structures in the transmission network was made in 2016 in order to improve the reliability and stability of the network. Due to the high costs associated with the exercise, it will be implemented in phases. Details of planned projects to be implemented per feeder are provided in section 5.3. Steel structures will be implemented in all future projects in order to reduce those dips caused by broken structures and to reduce the high costs of maintenance on wooden structures.

Plans to replace wooden with steel structures in the distribution network were not realised due to costs. Transmission lines have a total length of 2900 km compared to the 5200 km of distribution lines.

Dips that are a result of storms are usually accompanied by lightning as discussed in section 2.3.4.2. Measures taken by SEC to reduce the impact of lightning on electrical lines are:

- Strengthening insulation levels in transmission lines to withstand higher voltage transients.
- Installation of controllable discharge lightning rod.
- Reducing tower footing resistance.
- Proper implementation of lightning surge arrestors.

5.1.3. Mitigation of dips caused by fire

In 2017, SEC re-evaluated the contract with land-owners on the required clearance of power lines from vegetation and buildings and was adapted to include the following important clauses:

- If a tree is compromising the conductor clearance, SEC has the right to cut it down to prevent faults caused by conductor clearances being compromised.
- During the burning of sugar cane fields, the owner of the fields must notify SEC well in advance so that proper precautions can be taken to ensure that wooden structures are not damaged in the process.

[8] Equipment – Refers to any component part of the electrical system which need to powered to operate.

- If the owner of the fields fails to comply with the above request, the owner must pay for all costs associated with the damage.

The decision of replacing wooden structures with steel structures will also reduce dips caused by burning of sugar cane fields which burn wooden structures, causing them to collapse.

Conductors of feeders cutting through sugar cane fields are to be covered with Polyvinyl Chloride (PVC) in order to prevent degradation of the strength of conductor insulation caused by pollution.

5.1.4. Mitigation of dips caused by birds

Two measures were implemented since 2016 in all new projects to reduce dips caused by birds:

- Insulated PVC pipes are installed on maintained transmission jumpers to prevent bird electrocution when they perch at proximity with the power lines.
- Installing suspension porcelain insulators (which separates the line conductors and supports them electrically) to provide a safe platform for birds to perch. SEC has recently implemented this on new power lines, for instance, Riverbank – St Phillips line and Ka-Langa-Big Bend line. This mitigation measure was implemented in 2016, after close monitoring of line performance, it was noted that the feeder has not recorded any dips caused by birds.

5.1.5. Mitigation of dips caused by humans or animals

The following measures were implemented since 2017:

- Foam inside tunnels used to run cables into the control room (where the control panels are located) to ensure they are tightly sealed, preventing mice or snakes gaining entrance to the control room in substations. In order to minimise dips which are a result of animals causing short circuits in live chambers.
- Relocate existing 11 kV feeders away from main roads to reduce faults caused by cars hitting the structures.
- Steel structures for 66 kV lines along roads to minimise the impact of car accidents.
- Routes for new feeders to be away from forests likely to be inhabited by animals.

5.1.6. Mitigation of root-causes beyond SEC's control

Section 3.6 assigned ownership of dip causes. SEC can only manage dips within its control. Below is a breakdown of what was done to contain dips from outside the SEC network.

Eskom

80% of dips caused by Eskom were recorded at the Normandie - Nhlangano II feeder. The poor dip performance of the feeder was discussed with Eskom and two projects will be implemented by Eskom in collaboration with SEC before the end of the financial year (March 2019) to improve the performance of the feeder:

- Replace wooden structures with steel structures. SEC has conducted a study to assess the loading capacity of the existing line conductors during peak conditions inclusive of future anticipated load growth. Studies indicated that line conductors can handle existing and future loading and does not need upgrade, refer to Appendix F for detailed report.
- Installation of a second 400/132 kV transformer at Normandie substation to increase the fault level improving the sending end 132 kV voltage regulation and voltage harmonic distortion. Reduction of the supply impedance into this feeder will also improve dip performance, refer to Appendix G for a detailed report.

Customer

Customers were responsible for 70% of dips and they emanated from the Simunye – Mhlume feeder where there are two dedicated transformers which connects the Royal Swaziland Sugar Co-operation (RSSC) with SEC. A meeting was held with RSSC to discuss the findings of the feeder's performance with respect to dips.

RSSC requested for another investigation where all the PQ parameters will be assessed, not only voltage dips. The investigation was conducted, and it was discovered that the feeder recorded the 5th highest number of dips in the year 2016.

Thereafter, RSSC revised their maintenance plans, processes and procedures in an attempt to improve dip performance of Simunye – Mhlume feeder, refer to Appendix H for a detailed report of the investigation.

5.2. Long-term planning to improve dip performance

The economic development of the Kingdom of Swaziland depends on the availability, reliability and quality of energy supplied to end-users. Planning in SEC take the electricity demand forecast into account when striving to improve reliability and power quality whilst growing supply capacity.

Swaziland's growth during the 2017-2034 as expected by the Ministry of Natural Resources and Energy was used by SEC to align the demand of electricity with the supply capacity. Transmission and distribution plans to strengthen the network were simulated in DigSILENT using the existing transmission and distribution models as baseline. Load flow and short-circuit studies assessed the performance of the network and identified the need for additional transmission infrastructure projects beyond those already committed. The goals are:

- Compliance to the quality of Service (SZNS 026) and Quality of Supply (SZNS 027-2:2012) standards as required by SERA.
- Ensure adequate electricity is supplied to all current customers and those to be connected.
- Improve network efficiency to reduce operational costs.
- Meet the company's objective, mission and vision statements.

To ensure that SEC comply with the above, a master plan was formulated:

- Conduct a network demand forecast for short, medium and long term for load growth.
- Carry out studies to identify network congestion resulting of the network capacity constraints against the forecasted load demand.
- Conduct system studies to explore solutions in meeting the short, medium- and long-term network requirements based on current constraints and load forecasted.
- Upcoming generation projects are incorporated during the simulations.
- Costs for the different projects to be implemented in the short, medium and long term are allocated for proper planning.

The master plan was reviewed in October 2017, in order to incorporate projects that will address findings of the dip management program. Projects in the master plan are categorised either as a strengthening or a reliability project. The latter aim at reducing the frequency and duration of outages mostly in the distribution network. Projects will be implemented in different terms.

- Short term – 2017 - 2020
- Medium term – 2021 - 2027
- Long term – 2028 - 2034

Short, medium and long-term projects are discussed below with a focus on how the dip performance of the network will benefit. The master plan consists of 55 strengthening and 28 reliability projects. However, only projects identified to mitigate or reduce voltage dips will be discussed below (11 strengthening and 7 reliability projects).

Practical voltage dip data in chapter 3 indicated that 47% of dips were recorded along feeders and substations. Root-causes were mostly jumper and storm related faults:

- **Jumper related faults:** Jumpers which are not properly secured to line conductors can develop hot spots and break when sustaining high fault currents.
- **Storm related faults**: Wooden structures can break and cause conductors to touch and/or fall on the ground, resulting in line-line and/or line-earth faults.

The performance of the feeders is continuously monitored on the SCADA system; hence, the current performance of the feeders is known. For instance, a feeder with an under-voltage problem for a week will be seen by the personnel in the Nation Control Centre and the information will be store in the SCADA system.

- Correlation of the number of dips recorded per feeder against the information of feeder performance stored in the SCADA and PQ databases was made to be certain of dips which were a result of poor voltage regulation.
- Thereafter, simulations were done in the SEC network model developed in chapter 4 to ascertain the projects which can be implemented to improve dip performance.
- The simulation results, before and after implementation of each project are included in Appendix I.
- The voltage dip management program served as motivation to plan and budget for these projects.

5.2.1. Short term projects

Short-term reliability and strengthening projects to be implemented between 2017-2020 period are listed in Table 5.2 and Table 5.3, with a total estimate of R 336.2 million.

- 2 Reliability projects: R 40.5 million
- 8 Strengthening projects: R 274.1 million

Table 5.2: Short term strengthening projects

<table>
<tr><th>No:</th><th>Planned Year</th><th>Project Name</th><th>Project Description</th><th>Justification</th><th>Estimated Cost (R)</th></tr>
<tr><td>1</td><td>2017</td><td>Edwaleni II - Stonehenge 132 kV - Feeder bays</td><td>4 x132 kV feeder bays at Stonehenge and Edwaleni II</td><td rowspan="2">To provide N-1 reliability and eliminate the possibility of overloading of Mnkinkomo Stonehenge line</td><td>R 5.6 million</td></tr>
<tr><td>2</td><td>2018</td><td>Edwaleni II - Stonehenge 132 kV - Line</td><td>Construct 52 km 132 kV "double circuit" OHL from Edwaleni II to Stonehenge (Equip only one circuit)</td><td>R 117 million</td></tr>
<tr><td colspan="6">Projects number 1 & 2: Currently, there is only one 132 kV feeder at Stonehenge substation, coming from Mnkinkomo substation. The projects will be implemented to relieve the loading of the existing 132 kV line from Mnkinkomo substation. Stonehenge substation is the main source of power in the capital city of Swaziland and neighbouring areas. It has four transformers and six outgoing 66 kV feeders to Ngwenya I, Ngwenya II, Kent Rock, Nkoyoyo, Siphocosini and Mhlambanyatsi. If these substations are fed from an alternative source, they experience a voltage drop (visible on the SCADA system and simulations, refer to Appendix I, Figure I.1), hence, the 132 kV feeder from Mnkinkomo substation is critical. Below is the performance of the 66 / 11 kV substations when fed from an alternative source, this is the worst-case scenario (experienced during the high season).
<table>
<tr><th>Substation</th><th>Mnkinkomo – Stonehenge 132 kV line off</th></tr>
<tr><td>Stonehenge</td><td>63</td></tr>
<tr><td>Ngwenya I</td><td>64</td></tr>
<tr><td>Ngwenya II</td><td>64</td></tr>
<tr><td>Kent Rock</td><td>63</td></tr>
<tr><td>Nkoyoyo</td><td>64</td></tr>
</table>
</td></tr>
</table>

Siphocosini	63
Mhlambanyatsi	62

Also, Stonehenge substation experiences overloading, especially in the winter season when the electricity demand is high, voltage will drop to 64 – 65 kV. An overloading condition result in a slight decrease in the declared voltage, hence the network is susceptible to voltage dip occurrence. Field data in chapter 3 indicated that 4% of dips were recorded along this feeder. The project will not only provide an N-1 and prevent overloading at Stonehenge substation, but it will also boost the voltage at Stonehenge and neighbouring substations. A slightly higher voltage will assist in dip compensation and technical losses, below is the impact of the project as simulated, refer to Appendix I, Figure I.2 for simulations, this is not the worst case scenario).

Substation	**Voltage before project implementation**	**Voltage after project implementation**
Stonehenge	66	68
Ngwenya I	66	67
Ngwenya II	66	67
Kent Rock	65	68
Nkoyoyo	66	67
Siphocosini	66	67
Mhlambanyatsi	65	67

Note: Edwaleni II – Stonehenge 132 kV line and feeder bays is currently in the tendering stage.

3	2018	Lavumisa 66/11 kV -10 MVA substation	Construct new 66/11 kV -10 MVA substation	To improve voltage profile, reduce loading on Nsoko transformer and increase transfer capacity	R15 million
4		Maloma - Lavumisa 66 kV line	Construct 35 km 66 kV OHL from Nsoko to Lavumisa		R 35 million

Projects number 3 & 4: Currently, Nsoko has only one 66 kV incoming feeder, which means that the substation is in isolation with no ring configuration. In the event that a fault occurs along the Ncandweni – Nsoko feeder, the resulting dip will be severely felt at the substation and connected customers since there is no alternative supply to the substation. The projects will also improve the voltage profile since Nsoko substation experiences under voltage problems, especially in the winter seasons, making the feeder susceptible to voltage dips. 1% of dips were recorded along this feeder. Below is the impact evaluation of the project, refer to Appendix I, Figure I.3 for simulations.

Substation	**Voltage before project implementation**	**Voltage after project implementation**
Nsoko	65	67
Maloma	66	66
Ncandweni	66	67

Note: New Lavumisa 66/11 kV -10 MVA substation and Maloma – Lavumisa 66 kV line is currently in the tendering stage.

5	2018	New 132/66, 40 MVA substation, Ncandweni II	Construct a 40 MVA 132/66 kV substation	Reduce loading on Ka-Langa and Nhlangano II 132/66 kV transformers and ensure N-1 contingency	R 33.7 million

Project number 5: Ka-Langa substation is experiencing significant voltage drop (visible on the SCADA system and PQ database) at the moment due to the long Nhlangano II – Ka-Langa feeder (109 km). For instance, the sending voltage at Nhlangano II is usually 133 kV but the voltage will be at 122 kV when it reaches Ka-Langa substation causing the transformers to tap up to the last tapping position in an attempt to output a steady 66 kV supply. The projects will assist in reducing the load on the transformers at Ka-Langa substation thus reducing the probability of a dip occurrence because the voltage regulation will be around 65 kV, see below and also refer to Appendix I, Figure I.4 for simulations. Practical data indicated that Nhlangano II – Ka-Langa feeder and the outgoing 66 kV feeders recorded 8% of the total dips.

Substation	Voltage before project implementation	Voltage after project implementation
Ka-Langa	64	66
Mpaka	66	66
Siteki	65	66

Note: Ncandweni 66/11 kV -10 MVA substation is currently in the tendering stage.

6	2019	66/11 kV 10 MVA substation, Gege	Construct a 10 MVA 66/11 kV substation	Reduce loading on Nhlangano II 66/11 kV transformer	R 18.5 million
7		Nhlangano II - Gege 66 kV Line	Construct 25 km 66 kV line from Nhlangano II to Gege		R 29 million

Projects number 6 & 7: The Gege area is fed via an 11 kV network because there is no HV/MV substation in the area. This 11 kV comes from Nhlangano II substation, but due to the long 11 kV feeders supplying power to Gege, under voltage problems, visible on the SCADA system, increase the probability of dip occurrence. Construction of a substation at Gege and Nhlangano II - Gege 66 kV Line will boost the voltage in the area, refer to Appendix I, Figure I.5 for simulation results.

8	2018	66/11 kV 10 MVA substation, Piggs Peak II	Construct a 10 MVA 66/11 kV substation	To reduce loading of Pigg's Peak substation	R20.3 million

Project number 8: Piggs Peak substation is fed from two incoming 66 kV feeders, the main source being the Maguga power station, an SEC-owned hydro generator. Hydro generation is connected to the grid only during peak times in order to supply the maximum demand. This is due to restricted availability of water. Without the hydro, Piggs Peak experience a voltage drop (visible on the SCADA system in the National Control Centre) as the only source of supply is Edwaleni II Substation, which is more than 100 km away from Piggs Peak substation. The under-voltage problem is very common in winter and the feeder is then susceptible to voltage dips, the number of dips recorded in that feeder during this period are significant. Field data indicated that 18% of dips were recorded along the incoming and outgoing 66 kV feeders. The impact of the substation was simulated and the results are in Appendix I, Figure I.6.

Note: Project will be presented to the Project Approval Committee in November 2018.

Table 5.3: Short-term reliability projects

No:	Planned Year	Project Name	Project Description	Justification	Estimated Cost (R)
1	2019	New Nsoko - Maloma 66 kV - Feeder bays	Construct 2 x 66 kV feeder bays at Maloma and Nsoko	To provide *N*-1 transformer contingency	R 11 million
2	2019	New Nsoko - Maloma 66 kV - line	Construct 25 km 66 kV HARE line from Nhlangano II	To provide *N*-1 transformer contingency	R 29.5 million
Project number 1 & 2: At present, the substations above only has one 66 kV feeder, in the event of a fault, the substation will be lost. These projects will reduce the frequency of dips since the voltage will increase from 64 kV to 66 kV. The impact of the project is similar to the construction of Lavumisa substation, refer to Appendix I, Figure I.3.					

5.2.2. Medium term projects

Medium term reliability and strengthening projects to be implemented between 2021-2027 period are listed in Table 5.4 and Table 5.5, with total estimate of R 94.3 million.

- 2 Strengthening projects: R 20.2 million
- 3 Reliability projects: R 15.1 million

Table 5.4: Medium term strengthening projects

No:	Planned Year	Project Name	Project Description	Justification	Estimated Cost (R)
1	2021	New 66/11 kV 10 MVA substation, Sidwashini	Construct New 66/11 kV 10 MVA substation	To reduce loading of Nkoyoyo substation	R 18.4 million
2		Sidwashini 66 kV lines	2 x 0.6 km 66 kV lines		R 1.8 million
Projects number 1 & 2: Due to the anticipated future expansion in the Sidwashini area, Nkoyoyo substation, capacity cannot meet demand. Construction of substation will reduce loading of Nkoyoyo substation preventing under-voltage problems. Field data in chapter 3 indicated that 2% of dips were recorded in the outgoing 66 kV feeders, refer to Appendix I, Figure I.7 for simulation results.					

Table 5.5: Medium term reliability projects

No:	Planned Year	Project Name	Project Description	Justification	Estimated Cost (R)
1	2021	Maloma re-configuration	1x66 kV busbar Build 2x66 Feeder bays	To provide *N*-1 line contingency	E 7.6 million
2	2021	Maloma re-configuration of lines	Construct 1.5 km 66 kV lines	To provide *N*-1 line contingency	R 1.8 million
Project number 1 & 2: It enable meshing of feeders to reduce severity of a dip, at the same time reducing outages. For, instance, the severity of a dip occurring in one feeder will be reduced at the point of common coupling when compensated by other different feeders (increase the fault level). The impact of the meshing is shown in Table 5.8.					
3	2025	Dvokolwako 66/11 kV Transformer upgrade	New 1x66 kV busbar New 2nd 66/11 kV 2.5 MVA transformer, bay equipments and protection panel	To provide N-1 transformation reliability	R5.7 million
Project number 3: To reduce loading on existing transformers and improve supply to customers. Overloading causes voltage drop to a level where even a less severe fault results in a severe dip. Simulations were done and the impact of the project visible in Table 5.8.					

5.2.3. Long term projects

Long term reliability and strengthening projects to be implemented between the 2028-2033 period are listed in Table 5.6 and Table 5.7. Total cost estimate is R 97.3 million**.**

- 1 Strengthening project: R 23.6 million
- 2 Reliability projects: R 31.7 million

Table 5.6: Long term strengthening projects

No:	Planned Year	Project Name	Project Description	Justification	Estimated Cost (R)
1	2028	Swazi Paper Mill Transformer upgrade	Replace existing 66/11 kV 10 MVA transformer with 66/11 kV 20 MVA transformer	Reduce loading of Swazi Paper Mill Transformer	R 23.6 million
Project number 1: Improve supply to Matsapha industries and reduce the depth of a dip, refer to Table 5.8.					

Table 5.7: Long term reliability projects

No:	Planned Year	Project Name	Project Description	Justification	Estimated Cost (R)
1	2029	New Edwaleni - Mnkinkomo 2nd 132 kV line - Feeder bay	Install 2x132 kV feeder bays	Strengthen Mnkinkomo for *N*-1 reliability	R 6.2 million
2	2029	New Edwaleni - Mnkinkomo 2nd 132 kV line - Line	Construct 2nd 17 km 132 kV Edwaleni 2-Mnkinkomo OHL	Strengthen Mnkinkomo for *N*-1 reliability	R 25.5 million
Project number 1 & 2: Reduce voltage dip depth and enough power to Matsapha industries, refer to Table 5.8.					

5.2.4. Impact evaluation of projects with respect to dip performance

All the projects to be implemented in short-term, mid-term and long-term were simulated in the model developed in chapter 4 to ascertain the impact of the project on the dip performance. As a result, dips recorded and presented in chapter 3, verified and validated in chapter 4 were simulated again in the model with all the proposed projects. The worst 2 dips were simulated again per root-cause and the results are presented in Table 5.8.

Table 5.8: Impact evaluation of the project implementation on dip performance

No:	Root-cause	Residual voltage before project implementation	Residual voltage after project implementation
1	Human or Animals	0	8
		3	15
2	Fire	24	39
		26	41
3	Cables	0	10
		2	15
4	Customers	36	51
		37	56
5	Birds	43	51
		48	61
6	Equipment	40	58
		42	54
7	Jumpers	23	41
		25	39
8	Storm	0	10
		8	18
9	Conductors	4	14
		13	21
10	Vegetation Related	24	39
		28	42

The following is noted in Table 5.8:

- The severity (depth) of the dip is drastically improved.
- The dips change types, some will not become dips, just that the 2 severe dips per root-cause were selected.
- The improvement in dip severity is caused by:
    - Meshing of networks to reduce dip severity at points of common coupling.
    - Improvement in voltage profile, network operating at a voltage higher than the declared voltage in order to compensate for technical losses and assist in dip compensation.
    - Elimination of under-voltage problems caused by long feeders, increase in demand especially in winter or the power stations are out of service.
- The duration of the dips did not change since they are affected by the protection setting of the relays.

5.3. Projects to improve dip monitoring & data analysis

SEC has made plans to improve monitoring and analysis of dips as shown in Table 5.9.

Table 5.9: Improvements on dip monitoring and data analysis

No:	Element	Responsible Person	Due Date	Estimated costs (R)
1	Additional PQ instruments	GM Operations	June 2020	R 19 million
2	Automation of Dip-to-Trip Matching	GM Operations	December 2020	R 0.4 million
3	Hosting a PQ Monitoring System	Transmission Manager	June 2019	R 0.98 million
4	Establishing a PQ Department	GM Operations	January 2019	R 0.47 million
	Total Costs			**R 20.85 million**

Details of how each element in Table 5.9 will contribute towards the improvement of dip monitoring and data analysis is discussed next.

5.3.1. Additional visibility of PQ performance

Management of dips requires the visibility of the network performance, achieved by PQ monitoring at strategic points. SEC has only 11 PQ instruments, 4 at infeed points (monitoring 8 feeders by PQ instruments that measures 2 three-phase channels simultaneously) and 7 at other strategic distribution points of (monitoring 7 feeders).

These are not enough in revealing system technical performance. An additional 52 PQ instruments will be installed at all transmission / distribution points, power stations and key customers. This project was budgeted for in 2018/2019 financial year, it is currently under-going the tendering process. Motivation in adding the instruments was due difficulties faced whilst determining the root-cause of dips when formulating the voltage dip management program. In determining the root-cause, the direction of the dip, whether upstream or downstream must know. If the instruments are not enough in determining the character of the power system, the process of determining the root-cause is time consuming at times. Implementation of the project will enable visibility in all substations making it possible to determine the direction (upstream or downstream) of a dip much faster, hence measures for root-cause mitigation can be implemented timeously.

PQ instruments for investigation will also be increased from 3 to 10 to enable additional analysis of concerns as arising.

5.3.2. Automation of dip-trip matching

Additional PQ data will be too much for the NCC personnel to manually match dips to network incidents recorded by the SCADA system. There is a need to merge PQ data and SCADA data. By comparison of time-stamped data from different sources using a shared time reference, automatic matching of dips should be possible:

- Elimination of human error in matching dips with trips.
- Specialised personnel not needed.
- Inconsistency in matching dips as different operators have different interpretations of root-cause.
- Detailed dip information to be readily available in the dip database supporting prompt of mitigation.

Figure 5.1 present a systems approach to matching dips with network events. Verification by a human operator is needed as final approval of results.

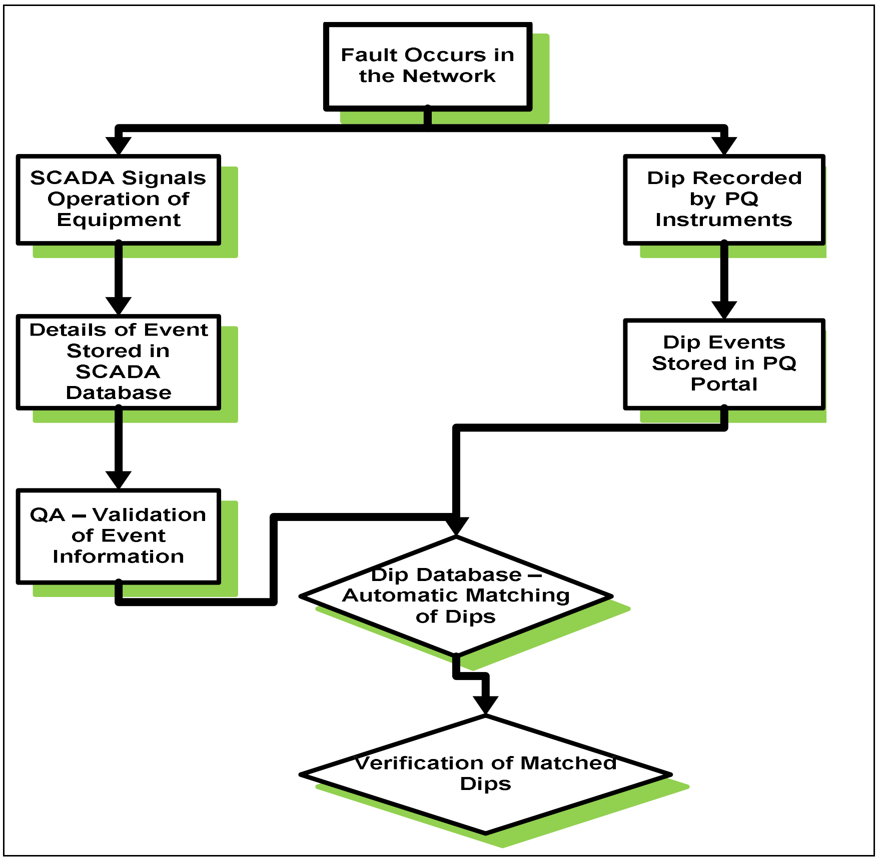

Figure 5.1: Efficient method of dip-trip-matching

Development and implementation of such a dip management tool requires collaboration from the NCC personnel, operation engineers, transmission and distribution technicians.

A PQ database was created in an Excel™ spreadsheet to support the operational aspects of voltage dip management at SEC. Choice of selection was due to ease of the software and ability to interpret the results.

Click the following link to access the database.

https://www.dropbox.com/s/w8kq28raec1zggh/Voltage%20Dip%20Database.xlsm?dl=0

A significant shortcoming of the dip database now is that it is not automated. The reason behind that is due to the inability of Excel™ to conduct time aggregation of waveform events. An explanation of the sub-sections in the dip database is as follows:

- **Menu**: List of options to be selected to access different reports
- **PQ-portal Data**: Data copied from PQ Portal
- **Root-Cause**: The primary cause of the dip against the type of fault and voltage levels
- **Worst 5 feeders**: The worst 5 performing feeders against the voltage levels.
- **Dip Responsibility**: The party responsible against the root-cause and the type of dip.
- **Type of Fault**: The fault type against the type of dip and voltage levels.

Details of how to utilise the dip database is as follows:

- Copy the data from PQ-portal website and paste it on the PQ-portal sheet.
- Data on all the other sheets will automatically be updated.
- Double click at the top right corner of each sheet to view the presentation of results against other parameters.

Figure 5.2 shows the front view of the database with all the available options which can be used to better manage dips. The geographical map which shows mainly the route of the feeders and associated voltage levels can also be used to identify the source of dips, direction of dips and the location of the instrument in the network.

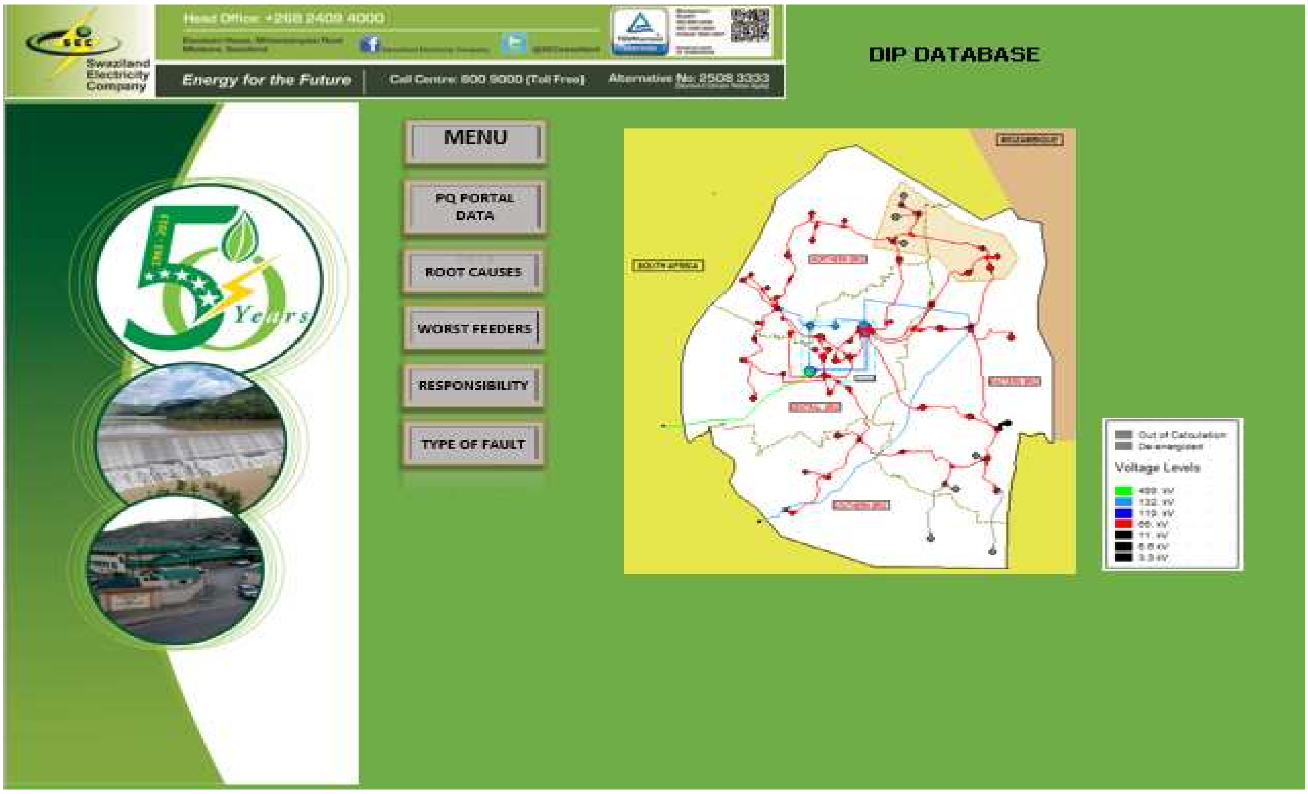

Figure 5.2: Front view of the dip database

Figure 5.3 shows a view of data copied from the PQ-portal website, data in all the other options will automatically be updated.

MAIN MENU

Id	Incident Name	Date	Worst Durati	Worst Residual Voltage %	Cause	Circuit	Voltage Le	Responsible Party	Dip Type	seasons f the y	Month
646794	Earth Fault	2016/11/05 16:25	2.56352	20.58	Weather	Hlathikhulu 66Kv 4750	66kV	SEC	Dip Z2	Spring	November
646959	Phase Overcurrent	2016/11/05 15:59	2.45292	38.52	Weather	Sithobela 66kv 1150	66kV	SEC	Dip Z2	Spring	November
646738	Earth Fault	2016/11/05 14:40	2.0634	3.32	Unknown	Normandie 132kV	132kV	SEC	Dip Z2	Spring	November
646740	Earth Fault	2016/11/05 14:48	2.07554	5.07	Conductor Clashing	Nhlangano 2 11 kv 4240	11kV	SEC	Dip Z2	Spring	November
649947	Phase Overcurrent	2016/11/14 08:17	2.14004	5.34	Unknown	Nhlangano II	66kV	SEC	Dip Z2	Spring	November
647145	Phase Overcurrent	2016/11/06 18:02	2.30086	7.98	Unknown	Hhelehhele 66 Kv	66kV	SEC	Dip Z2	Spring	November
647169	Phase Overcurrent	2016/11/06 19:23	0.09674	8.96	Unknown	Hhelehhele 66 kV	66kV	SEC	Dip T	Spring	November
645649	Earth Fault	2016/11/01 17:00	1.2515	9.73	Unknown	Edwaleni II 400kV	400kV	SEC	Dip Z2	Spring	November
648422	Phase Overcurrent	2016/11/09 20:32	0.54918	11.01	Unknown	Stonehenge 66kV	66kV	SEC	Dip T	Spring	November
651125	Phase Overcurrent	2016/11/17 22:05	0.4872	20.95	Broken Jumper	Sthobela 66KV feeder	66kV	SEC	Dip T	Spring	November
649558	Earth Fault	2016/11/12 20:09	1.26138	24.24	Broken Structure	Sidvokodvo 11 kV	11kV	SEC	Dip Z2	Spring	November
651107	Earth Fault	2016/11/17 21:28	0.08024	24.76	Weather	Hhelehhele Fdr 3580	66kV	SEC	Dip T	Spring	November
647155	Earth Fault	2016/11/06 18:43	0.08008	26.59	Weather	Stonehenge 66kV	66kV	SEC	Dip T	Spring	November

MENU | PQ-PORTAL | ROOT CAUSE | WORST FEEDERS | RESPONSIBILITY | TYPE OF FAULT

Figure 5.3: View of data in the PQ database

Figure 5.4 shows results for one of the options in the menu for data recorded in March 2016. The blue buttons on the top right shows the different options of interpretation available with respect to other elements, which is the root-cause in relation to voltage levels and the resulting voltage dip types.

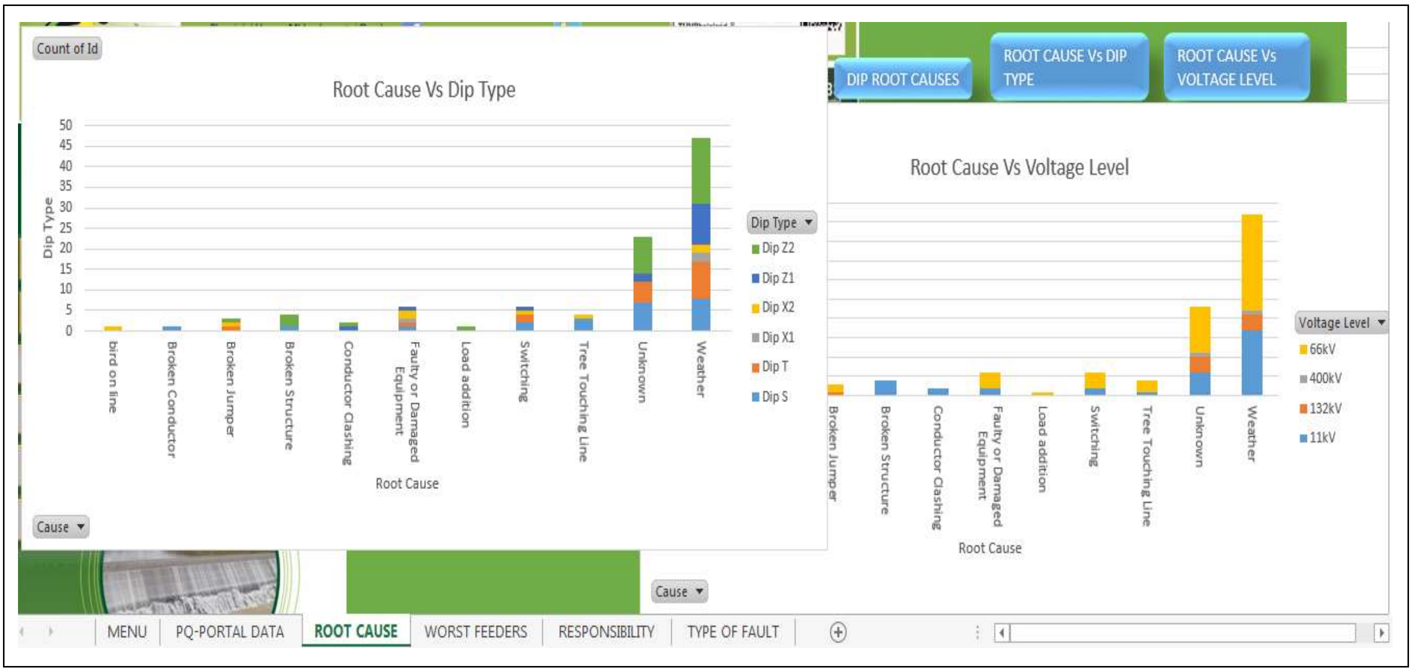

Figure 5.4: An example of results in one of the options in the menu

This Excel^{TM} database will be made available on the SEC Portal for personnel supporting the voltage dip management program. It will be updated daily to ensure prompt attendance to root-causes, for instance, cutting of trees.

5.3.3. Hosting a PQ monitoring system

Now, SEC is outsourcing the services of hosting to CT Lab. The cost of hosting depends on the type of PQ instrument installed. An Impedo DUO (capable of monitoring two feeders) costs R1000.00 per month and a Vecto II (capable of monitoring one feeder) costs R500.00 per month. The total cost of hosting services per financial year is R90 000.000. These costs will increase significantly after the addition of more PQ instruments, hence owning a PQ monitoring system is of paramount importance to reduce costs.

5.3.4. Establishing a PQ department

At the moment, the Metering and National Control Centre departments are responsible for all PQ related issues. However, it will not be possible for these departments to handle PQ related issues efficiently, due to the existing job responsibilities. As a result, addition of the PQ instruments and internal hosting of the PQ monitoring system will require a PQ department dedicated to only manage PQ.

5.4. Conclusion

Installing PQ instruments in the network to monitor dip performance is not enough, information retrieved from this PQ instruments must feed into mitigation measures to be implemented, whether in short, medium or long term to reduce or eliminate voltage dips. This initiative also requires constant monitoring of system performance after implementation of each mitigation measure to ensure that the desired results are obtained.

Implementation of mitigation measures is costly, however, there are less costly measures, for instance, proper implementation of maintenance plans, that is frequent maintenance of circuits which are on the Highveld (because they have a lot of rainfall which leads to overgrown vegetation) and a few circuits in the Lubombo region are susceptible to fire and pollution.

Projects to be implemented in short-term, medium term and long term were simulated in the model developed in chapter 3 in order to ascertain their improvement in system performance. Thereafter, all the projects were simulated in the model and 2 severe dips per root-cause were simulated to quantify their improvement with respect to dip performance. Indeed, the projects reduce the dip depth, especially in substations where the feeders are meshed.

Measures to improve network visibility, dip monitoring and data analysis will be implemented in 2019 and 2020. A PQ database was created in excel, uploaded at SEC portal to enable timeous analyses and attending to dip root-causes.

6. Conclusion and Recommendations

6.1. Conclusion

The decision taken by SEC to monitor the quality of power served to customers is encouraged and commendable. It is informed and guided by SERA and a selection of PQ standards (NRS 048-2:2007, SZNS 026-1:2012 and SZNS 027-2:2012). The decision does not only benefit the customer, but it also assists SEC in containing the operational risks associated with the supply of power. It led to the installation of PQ instruments at infeed points and strategic points of the network to visualise the PQ emissions to benchmark performance against the PQ standards.

The PQ directive provides a process that customers should follow when they experience PQ problems [1]. Amongst others, it requires that they first engage SEC, before it can be escalated to the regulator. Complaints received from customers were mostly dip related; hence the need was identified to conduct a detailed study on how voltage dips can be better managed. A summary of the content discussed per chapter is as follows:

6.1.1. Chapter 2

The theoretical principles of electrical PQ with the focus on dips were discussed in detail in the chapter. Research conducted by other people on the matter were used to bring insight and direction on how best the dip management program for SEC can be formulated. Guidelines on how to install the PQ instruments were discussed to ensure that instruments recorded similar results for comparability purposes. Existing PQ standards (nationally and internationally) were used as a basis against which all measurements and analysis were conducted.

Knowledge of the direction, cause and impact of dips in the electrical network enabled strategic implementation of mitigation measures. Evaluation of the costs associated with the different mitigation measures enables sound decision making (affordability) on which actions to implement. It was found there are cheaper measures which can be implemented, for instance, improvements on maintenance plans and reducing the fault clearing time (adjusting protection settings).

6.1.2. Chapter 3

Voltage dip data, used in determining the dip performance of the network, was recorded by different PQ instruments for the duration of a year. Due to the seasonal impacts of e.g. weather on network faults and dip performance, a minimum of one years' data is required to understand the under-lying behaviour of dips. Data indicated that a significant portion of the dips were weather related.

To ensure that the actual dip performance of the network was not masked by instrument location, data was firstly aggregated using time. Time stamping of recorded data enabled dip-to-trip matching of dips to identify the under-lying root-causes. Automatic time-aggregation of events conducted in PQ-portal significantly decreased the number of dips to reveal the actual performance of the network.

Data was then normalised in order to compare dip performance in all voltage levels. The number of dips recorded per voltage level was critical for planning and implementing mitigation measures. For instance, mitigation of dips recorded in the transmission network is a priority compared to mitigation of dips recorded in the distribution network. Dips recorded in the transmission network tend to propagate downstream, penetrating the network, causing power disturbances to customers; their effect is more severe. Information on dip propagation also verified the sectionalisation of the network. Dips recorded in the north-western section of the network were not visible in the south-eastern section.

Practical results indicated that a high number of dips were caused by vegetation and conductors being the second highest. Dips caused by unknown root-causes pose as a challenge for SEC because it can only manage dips with known root-causes. 56% of dips were recorded in the transmission network and 44% in the distribution network. Dips recorded in the 11 kV network are high compared to those recorded in the 66 kV network despite the fact that the number of instruments are more in the 66 kV network.

The dip characteristic values recorded for 95% and 50% (dips historically recorded by Eskom as per NRS 048 standard) of the monitored sites indicated that dip types X1, T, S, Z1 and Z2 exceeded the dip characteristic historical data in NRS 048-2:2007 standard for voltages less than 220 kV. This was attributed to the high number of dips recorded in the 11 kV and 66 kV networks.

6.1.3. Chapter 4

A network model was simulated in DigSILENT^{TM} PowerFactory. Load flow results of the model were correlated with the actual results of the network to ensure that the model is a true representation of the network. Dip root-causes, as obtained in chapter 3 were simulated in the model for verification and confirm validity. The location of the monitoring PQ instruments in the model and sectionalising of the network (network operating in two independent sections) had an impact on the propagation of dips and the residual voltage recorded at the points of measurement.

Verification and validation of practical data simulated in DigSILENT^{TM} PowerFactory deemed the practical results correct and usable for decision making at SEC. The variance between practical and simulated results were within a reasonable range. Factors behind the variance between practical and simulated results were discussed in detail with the major contributor being environmental conditions.

6.1.4. Chapter 5

Results in chapter 3 indicated that SEC was mostly responsible for the dip occurrences, with a few originating from Eskom, Illovo and customers. The different stakeholders were informed about their contributions to the dip numbers and discussions were conducted to reduce the dip occurrences.

Short, medium and long-term initiatives were put in place by SEC after the dip performance data in order to reduce / eliminate voltage dips in the network. However, the initiatives rely on the availability of funds to be executed. A significant disadvantage is that SEC imports 80% of its power, the cost of the imported unit is more than the cost of sale to customers. The above already pose as a challenge in the availability of funds to implement the projects.

Out of all the initiatives to be implemented by SEC, the most significant initiative was reviewing maintenance plans to ensure feeders are maintained according to location.

Implementation of the initiatives is not sufficient; the effectiveness of the mitigation measures requires quantification which was achieved by comparing dip performance before and after implementation of the mitigation measures.

6.2. Recommendations

The focus of the dissertation was on formulating a voltage dip management program for SEC to improve the dip performance of the network. However, there are other studies which the company can consider in the future to improve the quality of power served to customers.

- Developing a program capable of matching SCADA events with dip occurrences to eliminate human error, this program will be merged with the Excel^{TM} database created for this project.
- Evaluate contingences at different voltage levels for all the root-causes in order to obtain the faults levels which can be expected if a fault occurs in the network. This information will be used by the NCC personnel to verify the root-causes (validation of root-causes).
- Formulate planning levels for the different feeders as specified in NRS 048-2:2007 standard. This planning levels will assist ensuring that the specified compatibility limits of the different PQ parameters (harmonic distortion, flicker and voltage unbalance) are not exceeded. They are also required due to the introduction of IPPs in the network. IPPs are expected to ensure that they supply power with PQ emissions below the emission limits allocated, in order to keep PQ levels below planning levels of a utility. The more the data, the reliable are the results.
- Re-define the dip characteristic values (indicative values) on a yearly basis for benchmarking purposes. Historically, the values have never exceeded 95% and 50% of the monitored sites in South Africa. A year data was used in determining the dip characteristic values in chapter 3, however, it is advisable to use as much data as possible to ensure reliability of the results. The characteristic dip numbers will then be used to benchmark annual dip performance of the network. In the spirit of PQ and ISO9000, SEC will aim at continuously improving the dip performance.

- Formulate management programs for the other PQ parameters, for instance voltage unbalance, flicker and harmonic distortion to ensure a holistic approach to the management of PQ in general.

The recommendations will not only assist SEC in retaining a good relationship with customers, but it will also enable sound decision making with respect to mitigation measures to be implemented.

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Appendix A SAPP Information Sharing Procedure Template

Table A.1: SAPP information sharing procedure template

SAPP QOS DATA REPORTING FORM															
UTILITY	**SUBSTATION**	**VOLTAGE LEVEL**													**REMARKS / COMMENTS**
			VOLTAGE REGULATION		**VOLTAGE UNBALANCE**	**HARMONICS (THD)**	**NO. OF VOLTAGE DIPS**				**UNPLANNED OUTAGES**		**PLANNED OUTAGES**		
			DURATION	**DURATION**	**DURATION**	**DURATION**	**S**	**T**	**X**	**Z**	**NUMBER**	**TOTAL DURATION**	**NUMBER**	**TOTAL DURATION**	
BPC	Francistown	220 kV													
	Phokoje	400 kV													
	Gaborone South	132 kV													
	Segoditshane	132 kV													
CEC	Luano	220 kV													
	Kitwe	330/220 kV													
	Luano	330/220 kV													
EDM	Maputo	400 kV													

	Infulene	275 kV													
	Curomane	110 kV													
	Chicamba	110 kV													
	Songo	220 kV													
ESKOM	Apollo	533 kV													
	Arnot_Maputo	400 kV													
	Camden/Uitkoms	400 kV													
	Matimba	400 kV													
	Spitskop	132 kV													
	Komatipoort	275 kV													
	Aries	400 kV													
	Aggeneis	220 kV													
	Mahamba	132 kV													
	Messina	132 kV													
	Merapi	132 kV													

	Dwaalboom	132 kV													
HCB	Songo	533 kV													
	Songo	330 kV													
	Songo	220 kV													
LEC	Maseru	132 kV													
NamPower	Kokerboom	400 kV													
	Harib	220 kV													
	Katima Mulilo	220 kV													
SEC	Edwaleni - Camden	400 kV	0	0	0	0	0	0	0	0	0	0	0	0	The transmission line is performing well.
	Edwaleni - Maputo	400 kV	0	0	0	0	0	0	0	0		0	0	0	The transmission line is performing well.
	Oshoek	132 kV													Please note that the transmission line is a standby, non-functional at the moment
	Mahamba (Nhlangano II)	132 kV	0	0	0	14 days	0	1	3	0	0	0	0		There are projects which will be implemented in order to improve the performance of the line.
SNEL	Karavia	220 kV													
ZESA	Bindura	330 kV													
	Marvel	220 kV													

	Insukamini	400 kV													
	Mutare	110 kV													
	Beitbridge	132 kV													
	Kariba North	330 kV													
ZESCO	Zambezi	220 kV													
	Kitwe	330/220 kV													
	Luano	330/220 kV													
	Kariba South	330 kV													

Appendix B Practical Results

a) Human or animal

Table B.1: Propagation of voltage dip caused by animal or human faults

	Matsapha - Thompson (66 kV)	Hhelehhele transformer 3 (66 kV)	Stonehenge - Mnkinkomo (132 kV)	Stonehenge transformer (66 kV)
Residual voltage (%)	58	65	78	82
Dip type	X1	S	Y	Y

b) Fire

Table B.2: Propagation of voltage dip caused by fire

	Big-Bend - Illovo incomer 1 (11 kV)	Big-Bend - Illovo incomer 2 (11 kV)	Simunye - Mhlume (66 kV)	Ka-Langa - Hhelehhele (66 kV)	Hhelehhele transformer 3 (66 kV)
Residual voltage (%)	74	73	81	84	88
Dip type	S	S	Y	Y	Y

c) Cable

Table B.3: Propagation of voltage dip caused by cables

	Stonehenge transformer (66 kV)	Stonehenge - Mnkinkomo (132 kV)	Matsapha - Thompson (66 kV)	Hhelehhele transformer 3 (66 kV)
Residual voltage (%)	45	65	67	80
Dip type	X2	X1	X1	Y

d) **Switching**

Table B.4: Propagation of voltage dip caused by switching

	Nhlangano II incomer (11 kV)	Ka-Langa -Hhelehhele (66 kV)	Simunye - Mhlume (66 kV)
Residual voltage	68	79	81
Dip type	X1	Y	Y

e) Customers

Table B.5: Propagation of voltage dip caused by customers

	Stonehenge - Mnkinkomo (132 kV)	Stonehenge transformer (66 kV)	Matsapha - Thompson (66 kV)	Hhelehhele transformer 3 (66 kV)	Big-Bend - Illovo incomer 1 (11 kV)	Big-Bend - Illovo incomer 2 (11 kV)	Edwaleni II-Maputo (400 kV)	Edwaleni II-Camden (400 kV)	Simunye - Mhlume (66 kV)	Ka-Langa - Hhelehhele (66 kV)
Residual voltage (%)	0.3	14.9	33	42	80	80	80	82	84	87
Dip type	Z2	T	T	X2	Y	Y	Y	Y	Y	Y

f) Birds

Table B.6: Propagation of voltage dip caused by birds

	Nhlangano II - Normandie (132 kV)	Nhlangano II incomer (11 kV)	Simunye - Mhlume (66 kV)	Ka-Langa - Hhelehhele (66 kV)
Residual voltage (%)	63	64	71	71
Dip type	X1	X1	Y	Y

g) Equipment

Table B.7: Propagation of voltage dip caused by equipment

	Big-Bend - Illovo incomer 1 (11 kV)	Big-Bend - Illovo incomer 2 (11 kV)	Simunye - Mhlume (66 kV)	Ka-Langa - Hhelehhele (66 kV)
Residual voltage (%)	54	54	72	75
Dip type	Z2	Z2	Z1	Z1

h) Jumpers

Table B.8: Propagation of voltage dip caused by jumpers

	Sidvokodvo sub (11 kV)
Residual voltage (%)	69
Dip type	X1

i) Conductors

Table B.9: Propagation of voltage dip caused by customers

	Stonehenge - Mnkinkomo (132 kV)	Stonehenge transformer (66 kV)	Matsapha - Thompson (66 kV)	Hhelehhele transformer 3 (66 kV)	Edwaleni II- Maputo (400 kV)	Edwaleni II-Camden (400 kV)
Residual voltage (%)	31	56	62	63	83	83
Dip type	T	S	S	S	Y	Y

j) Vegetation

Table B.10: Propagation of voltage dip caused by vegetation

	Simunye - Mhlume (66 kV)	Ka-Langa -Hhelehhele (66 kV)
Residual voltage (%)	22	69
Dip type	X1	T

k) Unknown

Table B.11: Propagation of voltage dip caused by unknown faults

	Stonehenge transformer (66 kV)	Matsapha - Thompson (66 kV)	Hhelehhele transformer 3 (66 kV)	Simunye - Mhlume (66 kV)
Residual voltage (%)	30	51	70	90
Dip type	T	Z2	Y	Y

l) Storms

Table B.12: Propagation of voltage dip caused by storms

	Big-Bend - Illovo incomer 1 (11 kV)	Big-Bend - Illovo incomer 2 (11 kV)	Simunye - Mhlume (66 kV)	Ka-Langa - Hhelehhele (66 kV)
Residual voltage	62	62	80	82
Dip type	X1	X1	Y	Y

Appendix C DigSILENT PowerFactory Class Library

Table C.1: SEC standard transformer sizes

Description of transformer	Rating (MVA)	Vector group configuration	Number of steps	Nominal position
11/3.3 kV	4	Dyn11	4	0
16/0.4 kV	5	Dyn11	4	0
66/3.3 kV	4	Dyn11	4	0
	15	Dyn11	5	0
66/11 kV	2	Dyn11	4	0
	2.5	YNd1	4	0
	3	Dyn11	17	5
	3	Dyn11	4	0
	5	Dyn11	17	5
	5	Dyn11	4	0
	6	Dyn11	4	0
	7.5	Dyn11	17	5
	7.85	YNd1	4	0
	10	Dyn11	17	5
	10	Dyn11	5	3
	12	Dyn11	5	0
	20	Dyn11	17	5
132/11 kV	20	YNd1	17	5
	40	YNd11	17	5
132/66 kV	20	YNa0d1	17	5
	40	YNa0d1	17	5
	63	YNa0d1	17	7

400/132 kV	250	YNa0d1	17	5
	250	YNa0d1	17	5

Table C.2: Existing conductors on SEC network

Name		**per bundle**	**mm2**	**kV**	**A**	**Ohm/km**
			Transmission System			
Mink	ACSR	1	73.65	66	260	0.4546
Raccoon	ACSR	1	91.97	66	300	0.3622
Pigeon	ACSR	1	99.3	66	320	0.3371
Hare	ACSR	1	122.48	66	360	0.2733
Leopard	ACSR	1	148.21	66	410	0.2184
Wolf	ACSR	1	194.94	132	481	0.1828
Lynx	ACSR	1	226.2	132	528	0.1576
Tern	ACSR	4	431.6	400	830	0.0718
			Distribution System			
Fox	ACSR	1	42.8	11	190	0.7822
Mink	ACSR	1	73.65	11	260	0.4546
Hare	ACSR	1	122.48	11	360	0.2733
ABC - 35mm2	N/A	3C-Al	35	11	145	0.868
ABC – 70mm2	N/A	3C-Al	70	11	221	0.443

Table C.3: Description of towers installed in the SEC network

Voltage Level	Description of Towers
66 kV	Tower G68/128-C
	Tower G68/76-A
	Tower G68/78
	Tower G68/79-B
132 kV	Tower 255A-J
	Tower 255A-K
	Tower G68/50-D
400	Tower 524

Table C.4: Capacity of hydro generators

Power Station Name	Generator Number	Generator Size (MVA)
Edwaleni	1	2.5
	2	2.5
	3	2.5
	4	2.5
	5	5
Ezulwini	1	10
	2	10
Maguga	1	10
	2	10

Appendix D Range of fault impedance results

Table D.1: Impedance range of dips caused by human or animal faults

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Human & Animal Related	11	Earth Fault	A mouse touching phase & ground	Short circuit	Kent Rock Substation – 11 kV busbar	1.2+j2	2.07734	Stonehenge Substation	32	32
	11	Phase Overcurrent	Monkey cross phasing two phases	Short circuit	Sidvokodvo Substation - 11 kV busbar	0.08+j0.08	0.81156	Sidvokodvo Substation	0	0

Table D.2: Impedance range of dips caused by fire

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Fire Related	66	Earth Fault	Burnt Porcelain	Short circuit	1.9 km on Sikhuphe Ngomane Feeder	2.5+j28	0.36746	Simunye Substation	77	77
	66	Phase Overcurrent	Flashover between two phases	Short circuit	1.3 km on Usuthu - Mhlambanyatsi Feeder	1.3+j1.5	0.54684	Stonehenge Substation	70	70
	66	Phase Overcurrent	Flashover between two phases	Short circuit	2.1 km on Usuthu - Mhlambanyatsi Feeder	0.9+j1.1	0.16042	Stonehenge Substation	48	48
	66	Earth Fault	Flashover between phase & earth	Short circuit	5.6 km Balegane - Endzingeni Feeder	1+j1.2	0.7514	Nginamadvolo Substation	24	24

Table D.3: Impedance range of dips caused by cables

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Cable Related	11	Phase Overcurrent	Damaged Insulation	Short circuit	Nsoko Substation	0.07+j0.03	0.99258	Big Bend Substation	81	81
	66	Earth Fault	Damaged Insulation	Short circuit	Edwaleni Power Station	1.5+j1.1	0.62172	Matsapha Substation	77	77
	66	Phase Overcurrent	Damaged Insulation	Short circuit	Stonehenge Substation - 66 kV power cables	0.01+j0.1	0.46394	Stonehenge Substation	0	0
	11	Earth Fault	Damaged Insulation	Short circuit	Nhlangano Substation - 11 kV outgoing cables	1.1+j0.3	0.62186	Nhlangano Substation	3	3

Table D.4: Impedance range of dips caused by customers

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Customer Related	66	Phase Overcurrent	Broken jumper touches another phase	Short circuit	1.3 km on Mankayane - Usuthu Feeder	1.1+j1.3	0.7145	Stonehenge Substation	85	85
	66	Phase Overcurrent	Two phases touching due to sagging conductors	Short circuit	0.5 km on Sihhoye - Mhlume T	0.9+j1	1.07728	Simunye Substation	79	79
	66	Earth Fault	Broken jumper touches earth	Short circuit	0.5 km on Simunye - RSSC Feeder	1.3+j0.8	0.08008	Simunye Substation	36	36
	66	Phase Overcurrent	Damaged cable insulation	Short circuit	5 km on Ncandweni - Nsoko Feeder	1.9+j2	0.64492	Big Bend Substation	40	40

Range of fault impedance results

Table D.5: Impedance range of dips caused by birds

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Bird Related	66 kV	Earth Fault	Bird touches conductor and earth	Short circuit	1 km on Kent Rock - Stonehenge Feeder	8+j9	0.77884	Stonehenge Substation	84	84
	66	Phase Overcurrent	Bird Streamers	Short circuit	3 km on Ndzingeni T - Balegane Feeder	1.8+j2	0.08368	Nginamadvolo Substation	43	43

Table D.6: Impedance range of dips caused by equipment

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Equipment Related	66	Earth Fault	Flashover between two phases	Short circuit	2.8 km on Mpisi - Hhelehhele Feeder	3.1+j2.8	0.68874	Hhelehhele Substation	83	83
	66	Phase Overcurrent	Arching between two phases	Short circuit	3.8 km on Hhelehhele - Ngwane Park T	0.8+j1.5	2.14004	Hhelehhele Substation	40	40

Table D.7: Impedance range of dips caused by jumpers

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Jumper Related	66	Earth Fault	Broken jumper touched earthed stay wire	Short circuit	1.9 km on Balegane - Endzingeni Feeder	1.1+j0.1	0.54496	Nginamadvolo Substation	80	80
	66	Earth Fault	Broken jumper touched earthed stay wire	Short circuit	3 km on Nsoko - Ncandweni Feeder	1.5+j1.1	0.4985	Big Bend Substation	79	79
	66	Phase Overcurrent	Broken jumper touched another phase	Short circuit	0.42 km on Ncandweni - Big Bend Feeder	2.3+j1.9	1.75302	Big Bend Substation	23	23
	132	Phase Overcurrent	Broken jumper touched supporting gantry structure	Short circuit	2.54 km on Ngomane - Thabankhulu T Feeder	4.1+j2.3	0.13332	Simunye Substation	34	34

Table D.8: Impedance range of dips caused by storms

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Storm Related	66	Earth Fault	Snapped conductor touched earth	Short circuit	6.3 km on Dvokolwako - Balegane Feeder	2.1+j0.9	0.6931	Nginamadvolo Substation	82	82
	132	Earth Fault	Lightning struck phase & earth	Short circuit	20 km on Stonehenge - Mnkinkomo Feeder	1.9+j2.5	1.06166	Stonehenge Substation	77	77
	66	Phase Overcurrent	Broken structure - which led to the touching of two phases	Short circuit	1.3 km on Kent Rock - Stonehenge Feeder	0.06+j0.8	2.06328	Stonehenge Substation	0	0
	400	Phase Overcurrent	Lightning struck two phases	Short circuit	0.01 km on Camden - Normandie Feeder	0.01+j0.2	0.4888	Edwaleni II Substation	1	1

Table D.9: Impedance range of dips caused by for conductors

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Simulation Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Conductor Related	66	Earth Fault	Snapped conductor touches earthed structure	Short circuit	8 km on Nhlangano I - Hlatikhulu Feeder	4.3+j2.5	0.6267	Nhlangano II Substation	84	84
	66	Phase Overcurrent	Touching of two phases	Short circuit	1.5 km on Dvokolwako - Balegane Feeder	0.9+j1.3	0.12322	Nginamadvolo Substation	76	76
	66	Phase Overcurrent	Touching of two phases	Short circuit	1.5 km on Thabankulu - Mhlume T	0.8+j0.35	0.4836	Simunye Substation	4	4
	66	Phase Overcurrent	Touching of two phases	Short circuit	2.3 km on Pine Valley - Kent Rock Feeder	1.3+j0.95	0.81738	Stonehenge Substation	7	7

Table D.10: Impedance range of dips caused by vegetation

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)
Vegetation Related	66	Phase - Ground	Tree touching one phase	Short circuit	2 km on Ezulwini Power Station - Thompson Feeder	6.5+j4.3	0.34604	Matsapha Substation	84	84
	66	Phase - Ground	Tree touching one phase	Short circuit	1.8 km on Lobamba - Ezulwini Power Feeder	3+j2.6	0.46904	Stonehenge Substation	83	83
	66	Phase - Ground	Tree touching one phase	Short circuit	2.8 km on Balegane - Endzingeni Feeder	2+1.7	0.97534	Nginamadvolo Substation	24	24
	66	Two Phases - Ground	Tree touching two phases	Short circuit	1.3 km on Edwaleni Power station - SPM Feeder	0.06+j1.3	0.63946	Matsapha Substation	44	44

Appendix E Voltage dip simulation results

Table E.1: Verification results for dips caused by fire

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Fire	66	Earth Fault	Burnt Structure - snapped con 69ductor touched the ground	Short circuit	1.9 km on Simunye-Mhlume feeder	2+j2.2	0.0498	Simunye Substation	56	55	-1
	66	Phase Overcurrent	Flashover between two phases	Short circuit	3 km on Mhlume-Thabankulu T	2+j2.4	0.07378	Nginamadvolo Substation	32	39	7
	66	Phase Overcurrent	Flashover between two phases	Short circuit	14 km on Balegane-Mhlume feeder	1+j2	0.07374	Nginamadvolo Substation	46	38	-8

Table E.2: Propagation of dips caused by fire

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)
Fire	Simunye Substation	Practical	55	68	72	N/A
		Simulated	56	65	69	N/A
	Nginamadvolo Substation	Practical	39	43	68	75
		Simulated	32	39	62	69
	Nginamadvolo Substation	Practical	38	61	73	N/A
		Simulated	46	68	81	N/A

Table E.3: Verification results for dips caused by switching

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	DigSILENT Results (%)	Practical Results (%)	Variance (%)
Switching	11	Phase Overcurrent	Capacitor switching	Switching	Sidvokodvo Substation – 11 kV Busbar	N/A	0.54722	Sidvokodvo Substation	86	81	-5
	11	Phase Overcurrent	Capacitor switching	Switching	Nhlangano II Substation – 11 kV Busbar	N/A	0.47096	Nhlangano II Substation	74	80	6
	11	Phase Overcurrent	Capacitor switching	Switching	Simunye Substation – 11 kV Busbar	N/A	1.05902	Simunye Substation	69	78	9
	11	Phase Overcurrent	Capacitor switching	Switching	Big Bend Substation – 11 kV Busbar	N/A	0.57006	Big Bend Substation	80	72	-8

Table E.4: Propagation of dips caused by switching

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)
Switching	Sidvokodvo Substation	Practical	81	N/A	N/A
		Simulated	86	N/A	N/A
	Nhlangano II Substation	Practical	80	N/A	N/A
		Simulated	74	N/A	N/A
	Simunye Substation	Practical	78	84	N/A
		Simulated	69	80	N/A
	Big Bend Substation	Practical	72	82	N/A
		Simulated	80	91	N/A

Table E.5: Verification results for dips caused by customers

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Customer	66	Earth Fault	Broken jumper touches earth	Short circuit	1.5 km on Thompson - Matsapha Feeder	4+j3	0.59506	Matsapha Substation	72	78	6
	66	Earth Fault	Broken jumper touches earth	Short circuit	1.6 km on Simunye - RSSC Feeder	5+j3	0.18706	Simunye Substation	57	63	6
	66	Phase Overcurrent	Two phases touching due to sagging conductors	Short circuit	0.98 km on Simunye - RSSC Feeder	1+j0.3	0.3032	Simunye Substation	35	41	6
	66	Earth Fault	Damaged cable insulation	Short circuit	Stonehenge Substation	6+j4	1.76308	Stonehenge Substation	69	77	8

Table E.6: Propagation of dips caused by customers

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)
Customer	Matsapha Substation	Practical	78	82	N/A	N/A
		Simulated	72	76	N/A	N/A
	Simunye Substation	Practical	63	75	81	N/A
		Simulated	57	69	75	N/A
	Simunye Substation	Practical	41	61	74	82
		Simulated	35	56	69	78
	Stonehenge Substation	Practical	77	83	N/A	N/A
		Simulated	69	78	N/A	N/A

Table E.7: Verification results of dips caused by bird

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Bird	66 kV	Earth Fault	Bird touching phase and earth structure	Short circuit	2 km on Ngwane Park - Thompson Feeder	7.9+j6	0.57684	Matsapha Substation	80	83	3
	66 kV	Phase Overcurrent	Bird bridge air gap between conductors	Short circuit	4 km on Edwaleni Power Station - Ngwane Park T	7+j6.5	0.89116	Matsapha Substation	69	74	5
	66 kV	Earth Fault	Bird touching phase and earth structure	Short circuit	2 km on Balegane - Endzingeni Feeder	7+j4	0.21256	Nginamadvolo Substation	73	72	-1
	132 kV	Phase Overcurrent	Bird Streamers	Short circuit	51.2 km on Nhlangano II - Ka Langa Feeder	2+j1	0.09034	Nhlangano II Substation	47	51	4

Table E.8: Propagation of dips caused by birds

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)
Bird	Matsapha Substation	Practical	83	N/A	N/A	N/A
		Simulated	80	N/A	N/A	N/A
	Matsapha Substation	Practical	74	82	N/A	N/A
		Simulated	69	78	N/A	N/A
	Nginamadvolo Substation	Practical	72	83	N/A	N/A
		Simulated	73	86	N/A	N/A
	Nhlangano II Substation	Practical	51	62	75	78
		Simulated	47	58	70	71

Table E.9: Verification results of dips caused by equipment

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Equipment	66	Open Circuit Fault	Faulty breaker - one phase could not close	Switching	Balegane - Endzingeni Feeder	N/A	0.09676	Nginamadvolo Substation	36	42	6
	66	Earth Fault	Arching of Insulator	Short Circuit	2.5 km on Sihhoye T - Mhlume Feeder	1.8+j1.5	0.06666	Simunye Substation	59	65	6
	66	Phase Overcurrent	Arching of two phases	Short Circuit	1.5 km on Nkhaba - Pine Valley Feeder	2.3+j1.5	0.92694	Stonehenge Substation	81	74	-7
	66	Open Circuit Fault	Isolator did not close properly	Switching	5.3 km on Balegane - Endzingeni Feeder	N/A	1.39376	Nginamadvolo Substation	53	45	8

Table E.10: Propagation of dips caused by equipment

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)
Equipment	Nginamadvolo Substation	Practical	42	78	72
		Simulated	36	71	65
	Simunye Substation	Practical	65	79	N/A
		Simulated	59	72	N/A
	Stonehenge Substation	Practical	74	82	N/A
		Simulated	81	87	N/A
	Nginamadvolo Substation	Practical	45	75	79
		Simulated	53	82	86

Table E.11: Verification results of dips caused by jumpers

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Jumper	66	Open Circuit	Broken jumper on one phase	Switching	2.9 km on Sihhoye - Mhlume T Feeder	N/A	0.07976	Simunye Substation	24	15	9
	66	Earth Fault	Broken jumper touched earthed stay wire	Short circuit	0.75 km on Simunye - Thabankulu Feeder	1.3+j1.98	0.59364	Simunye Substation	53	58	5
	66	Phase Overcurrent	Broken jumper touched another phase	Short circuit	0.42 km on Dwaleni-Lobamba Feeder	3.7+j5.9	1.39366	Matsapha Substation	64	72	8
	132	Earth Fault	Broken jumper touched supporting gantry structure	Short circuit	0.54 km on Nhlangano 2 – Ka Langa	0.04+j0	0.32394	Nhlangano II Substation	58	49	-9
	66	Open Circuit	Broken jumper on one phase	Switching	1.3 km on Ngomane - Thabankhulu T Feeder	N/A	0.4765	Simunye Substation	17	10	7

Table E.12: Propagation of dips caused by jumpers

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)
Jumper	Simunye Substation	Practical	15	40	52	79
		Simulated	24	48	61	86
	Simunye Substation	Practical	58	69	80	N/A
		Simulated	53	61	73	N/A
	Matsapha Substation	Practical	72	83	N/A	N/A
		Simulated	64	78	N/A	N/A
	Nhlangano II Substation	Practical	49	61	72	77
		Simulated	58	68	76	82
	Simunye Substation	Practical	10	42	59	79
		Simulated	17	49	68	86

Table E.13: Verification results of dips caused by storms

Root-cause	Voltage Level (kV)	Type of Fault/Condition	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Storm	132	Phase Overcurrent	Lightning struck two phases	Short circuit	29 km on Mnkinkomo - Stonehenge Feeder	0.02+j0.06	1.07194	Stonehenge Substation	5	2	-3
	400	Phase Overcurrent	Lightning struck two phases	Short circuit	0.01 km on Camden - Edwaleni II Feeder	1.2+j2	1.2515	Edwaleni II Substation	6	10	4
	132	Phase Overcurrent	Broken structure - which led to the touching of two phases	Short circuit	4 km on Nhlangano II - Ka-Langa Feeder	0.02+j0.3	0.07006	Nhlangano II Substation	64	61	-3
	132	Earth Fault	Snapped conductor touched earth	Short circuit	15 km on Nhlangano II - Ka Langa Feeder	1+j0.8	0.06662	Ka-Langa substation	69	65	-4
	66	Open Circuit	Broken conductor on one phase	Switching	2.3 km on Ncandweni - Big Bend Feeder	N/A	0.38898	Big Bend Substation	15	8	7

Table E.14: Propagation of dips caused by storms

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)	Node 5 (%)	Node 6 (%)
Storms	Stonehenge Substation	Practical	2	15	38	62	64	N/A
		Simulated	5	21	43	68	71	N/A
	Edwaleni II Substation	Practical	10	16	29	35	53	71
		Simulated	6	10	21	29	46	65
	Nhlangano II Substation	Practical	61	76	79	82	N/A	N/A
		Simulated	64	81	86	90	N/A	N/A
	Ka-Langa substation	Practical	65	72	81	N/A	N/A	N/A
		Simulated	69	80	87	N/A	N/A	N/A
	Big Bend Substation	Practical	8	35	59	75	83	N/A
		Simulated	15	41	66	81	91	N/A

Table E.15: Verification results of dips casued by vegetation

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Vegetation	66	Phase - Ground	Tree touching one phase	Short circuit	0.02 km on Ngwenya II - Ngwenya Feeder	5+j5.3	0.0839	Stonehenge Substation	78	82	4
	66	Two Phases - Ground	Tree touching two phases	Short circuit	2.3 km on Edwaleni - Swazi Paper Mills Feeder	4+j3	0.68234	Matsapha Substation	54	48	-6
	66	Phase - Ground	Tree touching one phase	Short circuit	3.8 km on Lobamba - Ezulwini Feeder	4+3.7	0.83152	Matsapha Substation	80	76	-4
	66	Phase - Ground	Tree touching one phase	Short circuit	6.3 km on Pine Valley - Kent Rock Feeder	1+j1.2	0.97534	Stonehenge Substation	65	59	-6
	132	Phase - Ground	Tree touching one phase	Short circuit	0.32 km on Nhlangano II - Kalanga Feeder	0.08+j0.1	0.67156	Nhlangano II Substation	58	40	-9

Table E.16: Propagation of dips caused by vegetation

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)	Node 5 (%)
Vegetation	Stonehenge Substation	Practical	82	N/A	N/A	N/A	N/A
		Simulated	78	N/A	N/A	N/A	N/A
	Matsapha Substation	Practical	48	65	79	N/A	N/A
		Simulated	54	71	83	N/A	N/A
	Matsapha Substation	Practical	76	82	N/A	N/A	N/A
		Simulated	80	90	N/A	N/A	N/A
	Stonehenge Substation	Practical	59	69	78	N/A	N/A
		Simulated	65	76	82	N/A	N/A
	Nhlangano II Substation	Practical	40	56	68	79	82
		Simulated	49	59	72	83	89

Table E.17: Verification results of dips caused by cables

Root-cause	Voltage Level (kV)	Type of Fault	Fault Description	Event	Fault Location	Fault Impedance (Ohm)	Duration of Fault (s)	Point of Measurement	Simulation Results (%)	Practical Results (%)	Variance (%)
Cable	11	Phase Overcurrent	Damaged Insulation	Short circuit	0.1 km on Edwaleni Power Station	0.002+j0.03	0.46394	Sidvokodvo Substation	11	5	-6
	11	Earth Fault	Damaged Insulation	Short circuit	Stonehenge Substation	0.09+j0.08	0.7533	Stonehenge Substation	15	10	-5

Table E.18: Propagation of dips caused by cables

Root-cause	Point of Measurement	Residual Voltages (%)	Node 1 (%)	Node 2 (%)	Node 3 (%)	Node 4 (%)	Node 5 (%)
Cable Related	Sidvokodvo Substation	Practical	5	53	73	N/A	N/A
		Simulated	11	59	78	N/A	N/A
	Stonehenge Substation	Practical	10	29	69	68	72
		Simulated	15	35	74	76	81

Appendix F Normandie – Nhlangano II, 132 kV Transmission Line Simulation Report

1. INTRODUCTION

1.1. Background Information

The Normandie – Nhlangano II feeder has been performing poorly in terms of voltage dips for the past 3 years. Eskom was notified and measures to improve the performance were formulated. After surveying the line, it was discovered that the integrity of the line has been compromised (for instance, sagging conductors and leaning structures were discovered. As a result, a decision to upgrade the line from wooden structures to steel structures was made by Eskom, in collaboration with SEC. This brings about an opportunity to also upgrade the capacity of the line depending on the current peak loading and future anticipated load growth.

1.2. Objectives

The aim of this report is to achieve the following objectives:

- Perform an assessment of Mahamba – Nhlangano II 132kV line
- Draw conclusions and recommendations based on the study results and analyses

2. METHODOLOGY

The following method was applied in evaluating whether upgrading the transmission line from wooden structures to steel monopoles should be combined with uprating its phase conductors:

a. Identify possible conductor options that can be explored to efficiently and reliably transmit power from Normandie to Nhlangano II substation.
b. Evaluate each option's technical capability to meet the power requirements. This entails completing the following tasks:
    - Updating the SEC Transmission Network Base Case pfd file
    - Using load forecast results to evaluate the proposed options' sustainability beyond year 2032
    - Conducting steady state load flow analysis
    - Choosing the best option that meets the requirements
c. Draw conclusions and make recommendations

3. ASSUMPTIONS

The following assumptions are applicable:

- SEC Transmission Network Base Case pfd file shall be used for this study
- The 400/132kV transformer at Normandie shall be set to output 1.01 pu (133kV)
- Peak loading is experienced in the 17nth hour of each day as per the 2014 – 2034 load forecast

4. EXCLUSIONS

The following aspects will be excluded from this study

- Power quality assessment such as harmonics, flicker, etc
- Network stability studies
- Contingency Analysis

5. PLANNING CRITERIA

For the purposes of this study the following planning criteria shall be applicable:

- Operating voltage must be ±5% of nominal under steady state condition
- Thermal ratings of overhead lines will be used as initial check of line overloading. A rating based on 75°C ambient for normal conditions or 90°C (if available) for contingency conditions will be used.

6. POSSIBLE SUPPLY OPTIONS

There are two possible options for conductors that were explored for the upgrading of Normandie – Nhlangano II 132kV transmission line

- Maintain Wolf Conductor
- Uprating to Lynx Conductor

7. LOAD FLOW RESULTS AND ANALYSES

The simulations were run under pre-contingency network configuration with normally open switches at Ka-Langa (**6020**), Sidvokodvo (**320**), Ngwane Park (**474**), Mhlume (**1420**), Sikhuphe (**6640**), and Malindza (**6666**). Simulation results were tabulated and analysed in the following subsections. The voltage regulation results were monitored at the receiving end i.e. Nhlangano II substation's 132kV busbar.

7.1. Maintaining Wolf Conductor

Load flow simulations were carried with the Normandie – Nhlangano II 132kV transmission line conductor maintained as Wolf conductor. Table 7.1 below shows the simulation results of this scenario.

Table 7.1: Maintaining Wolf Conductor

Regulated Parameters	Results			
	2017	2022	2027	2032
Voltage Regulation (p.u.)	1.00	0.99	0.98	0.98
Conductor Loading (%)	30.52	35.00	45.84	54.34

Observations:

- There are no voltage regulation violations experienced
- There is no loading violations in the transmission line.

7.2. Upgrading to Lynx Conductor

Load flow simulations were carried with the Normandie – Nhlangano II 132kV transmission line conductor uprated to Lynx conductor. Table 7.2 below shows the simulation results of this scenario.

Table 7.2: Uprating to Lynx Conductor

Regulated Parameters	Results			
	2017	2022	2027	2032
Voltage Regulation (p.u.)	1.00	1.00	0.99	0.98
Conductor Loading (%)	28.01	32.05	42.02	49.86

Observations:

- There are no voltage regulation violations experienced
- There are no loading violations in the transmission line.

8. CONCLUSIONS

Based on the above results and analyses then the following conclusions can be drawn:

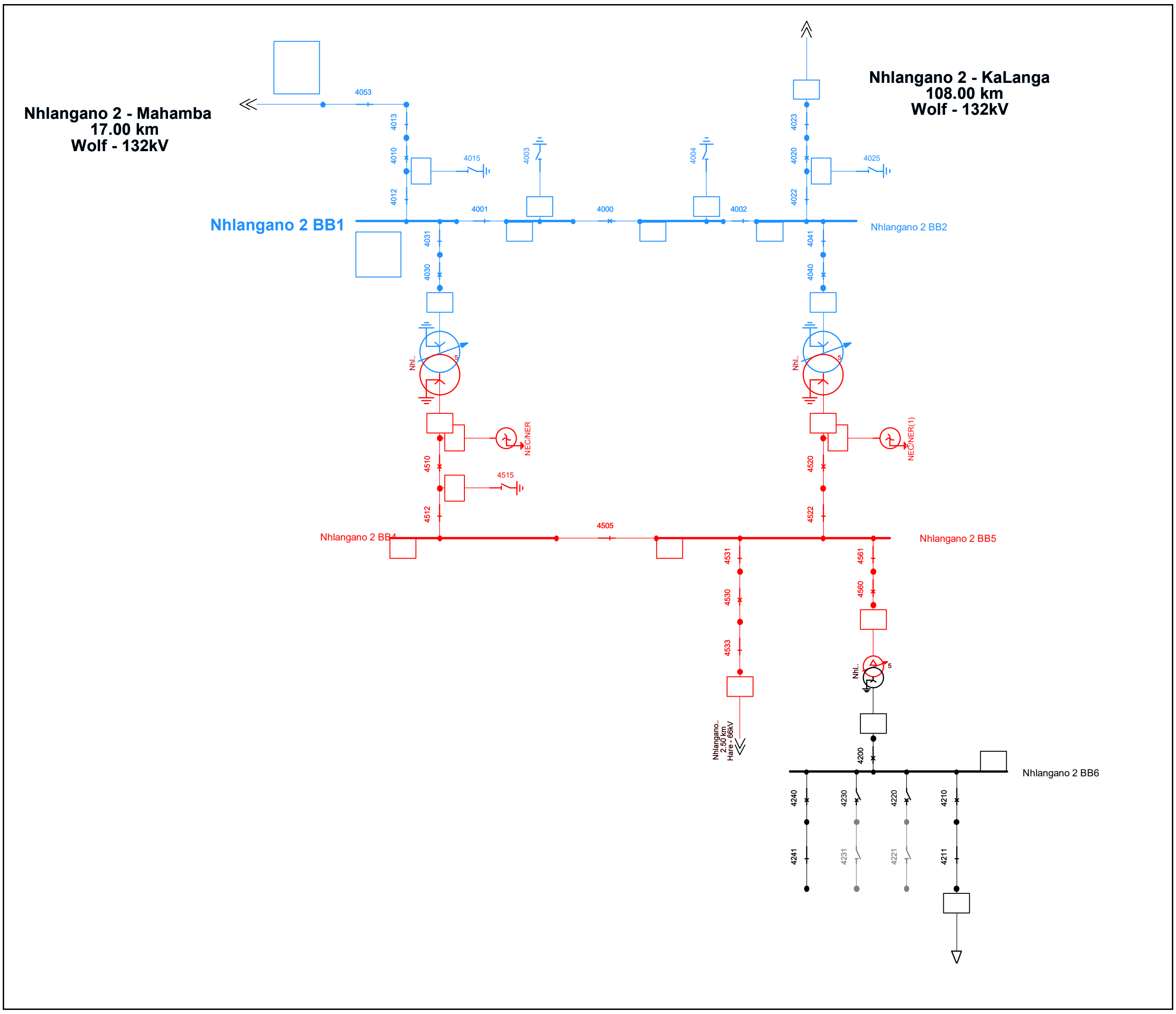
a) The new steel monopole Normandie – Nhlangano II 132kV transmission line can use either Wolf or Lynx phase conductors
b) There are no voltage regulation and loading violations experienced when using either Wolf or Lynx phase conductors

9. RECOMMENDATIONS

Based on the conclusions drawn above the following recommendations can be made:

a) Maintain Wolf phase conductors in the new design for the Normandie – Nhlangano II 132kV transmission line as it will be able to meet the required loading requirements. Uprating to Lynx conductor will not bring significant improvement to quality of supply.

Nhlangano II Substation Single Line Diagram



The load forecast results used when performing this analysis are shown in Table 7.3.

Table 7.3: Load Forecast Results

Substation Name	Load Forecast Results			
	2017	**2022**	**2027**	**2032**
Balegane	4.008185	4.676798	6.102396	7.023945
Big Bend	7.586269	7.74458	7.967076	8.147642
Dvokolwako	1.524653	1.646579	1.898206	2.059213
Edwaleni PS	1.288353	1.528296	4.358872	7.608751
Endzingeni	0.257434	0.313302	0.43411	0.5113
Ezulwini	3.011505	3.271936	3.876403	4.039704
Hlathikulu	2.760669	3.253242	4.26452	4.943899
Ka-Langa	6.546433	7.400749	9.171984	10.41217
Kent Rock	13.73767	14.6363	15.2063	15.34696
Lawuba	1.74299	2.217164	3.247764	3.906301
Lobamba	10.55553	11.42074	12.16215	12.72628
Magwabayi	6.401245	7.170035	9.000783	10.55032
Malkerns	6.564499	6.838194	7.365671	7.716499
Maloma	3.727148	4.408858	5.848377	6.983745
Mankayane	2.462843	2.946198	4.183943	5.156345
Manzini	12.17034	13.2205	14.8512	16.12715
Matsapha	6.833485	6.955227	7.199547	7.456407
Mayiwane	1.431463	1.615004	2.003702	2.252346
Mhlambanyatsi	1.322134	1.494977	1.874789	2.117809
Mhlume	4.195205	4.46604	4.992196	5.350233
Mnkinkomo	15.22268	15.79492	18.34295	21.23431
Moses Hlophe	12.12089	12.71341	13.84611	14.3754
Mpaka	1.526541	1.869544	2.629249	3.204627
Mpisi	3.549642	3.980755	4.900568	5.491035
Ncandweni	0.510227	0.539081	0.596813	0.633762

New Ngwenya	0	0	0	0
Ngomane	3.76438	3.859919	3.958468	4.059072
Nhlangano1	7.644267	8.981878	11.4088	12.97442
Nhlangano2	2.076634	2.385317	3.033144	3.452264
Nkhaba	1.703677	1.810221	2.028292	2.166319
Nkoyoyo	6.567558	9.848233	16.98351	18.36766
Nsoko	5.489264	5.743365	6.231537	6.55666
Old Ngwenya	2.024651	2.133295	2.904086	3.751995
Pigg's Peak	7.934093	8.405762	9.268593	9.922248
Pine Valley	1.874174	2.410296	3.482838	3.754562
Riverbank	5.451808	6.455841	7.522344	8.217883
Sidvokodvo	2.184596	2.349746	2.673632	2.886755
Sihhoye	4.893438	5.784152	7.676129	8.893732
Sikhuphe	1.187167	1.363821	1.734102	1.976231
Simunye	5.697043	6.17533	7.070233	7.695411

Appendix G Normandie – Nhlangano II Voltage Harmonic Investigation

1. EXECUTIVE SUMMARY

A complaint was sent to Eskom by Swaziland Electricity Company (SEC) with regards to the high voltage harmonics at Mahamba 132kV infeed point from Eskom. Mahamba is a 132kV switching substation located just before the Swaziland border, near the town of Piet Retief. Mahamba is supplied from Transmission's Normandie substation via a single line 132kV line. An investigation was launched by ESKOM in response to the complaint and Power quality recorders were installed at Normandie substation on the 132kV busbar to evaluate the levels of harmonic distortion at the site.

The site assessment showed that the voltage THD is below the NRS048:2 compatibility level of 4% but just over the planning level of 3%. It also showed that the 5th harmonic is marginally exceeded; the 95th percentile value is 3.14% vs a limit of 3%. Interrogation of the data showed that the planning level and 5th harmonic is exceeded during low loading periods i.e. reduced damping, typically late at night and early morning. No specific feeder or source could be identified by the measurements, which would account for the harmonic distortion.

A solution for the harmonic distortion, however, will come in the form of a second 400/132kV transformer at Normandie. Harmonic impedance plots show that the transformer will reduce the overall harmonic impedance which will reduce the harmonic distortion on the 132kV busbar and also improve the dip performance of the feeder.

2. INTRODUCTION

This report sets out the results of the investigation in response to the complaint sent to ESKOM regarding the high voltage harmonic distortion on Mahamba 132kV infeed point. The objectives of the investigation were:

- To evaluate the extent of the high voltage harmonic distortion
- To evaluate Eskom's regulatory objectives
- To identify possible sources of the harmonic distortion
- To evaluate possible solutions for the voltage harmonic distortion.

Normandie substation is situated near Piet Retief and is one of the supply points into the SEC's network at 132kV supply voltage. Figure 1 shows the Normandie substation single line diagram.

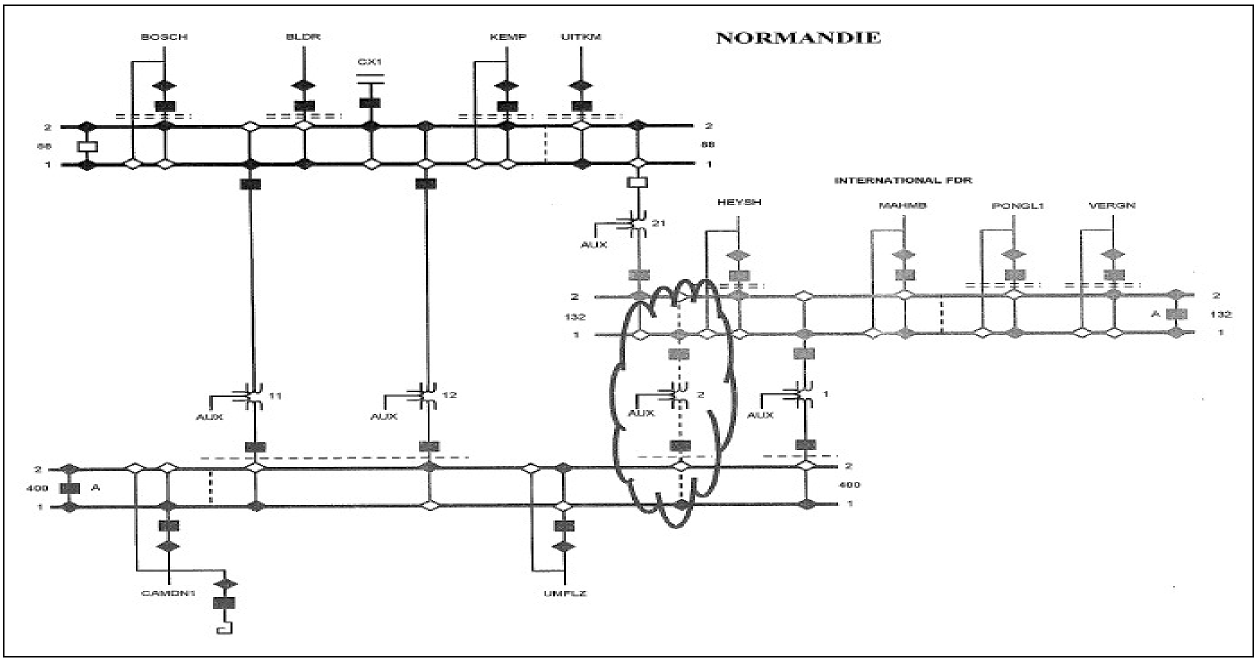


Figure G.1: Normandie substation single line diagram

3. METHOD

Three power quality recorders (each capable of recording 2 feeders simultaneously) were installed on the 132kV busbar at Normandie to record the voltage and current harmonic distortion on all of the outgoing 132kV feeders as well as the 400/132kV supply transformer. The recorders were GPS time stamped to ensure simultaneous measurements.

The recorded data was benchmarked against the NRS048:2 2007 compatibility levels to determine if there are any voltage harmonic violations.

4. RESULTS

4.1. Voltage THD

Figure 2 shows the 132 kV voltage THD over the measurement period on the 132kV Normandie busbar.

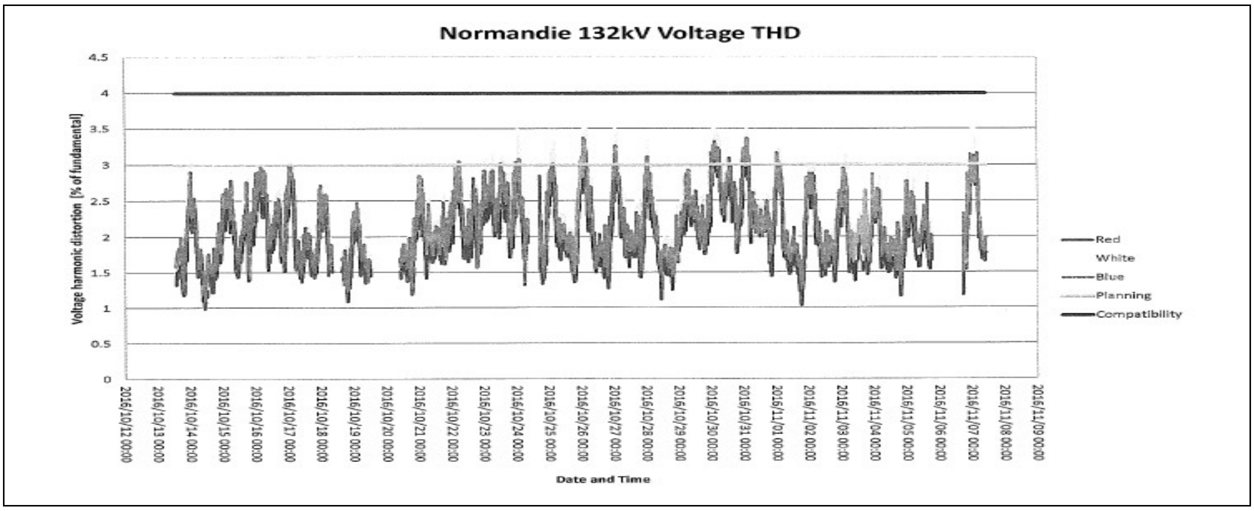


Figure G.2: Normandie 132 kV voltage THD profile

Figure 2 shows that the voltage THD levels are below the NRS048:2 compatibility level for the THD but above the planning level.

Figure 3 shows the analysed harmonic spectrum over the assessed period.

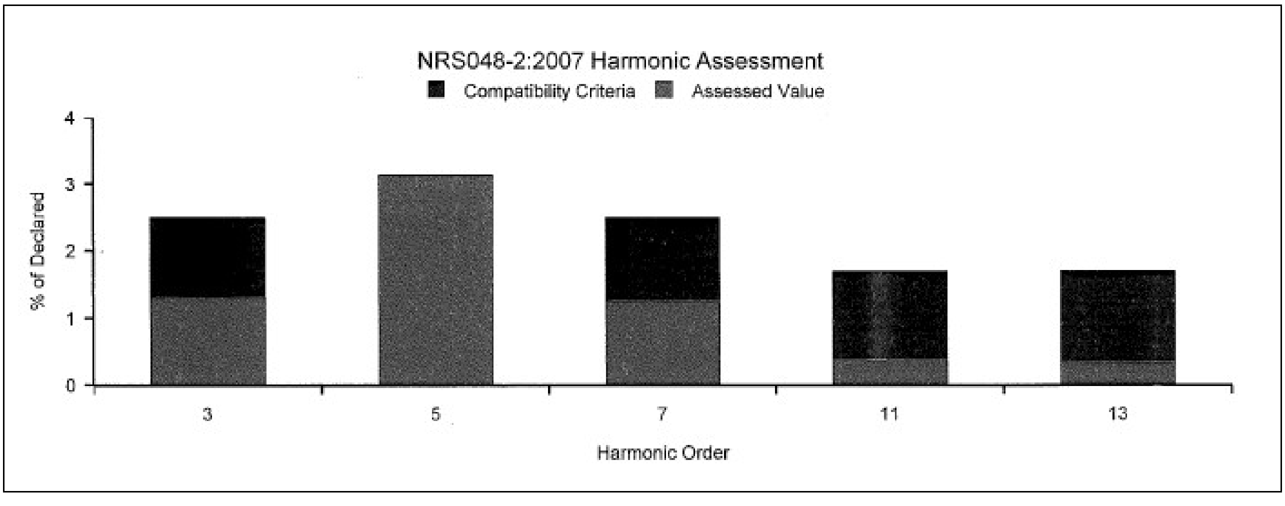


Figure G.3: Voltage harmonic spectrum on the 132kV Normandie busbar

Figure 3 shows that the major contributor towards the voltage THD at the Normandie is the 5th harmonic. The 95th percentile value for the 5th harmonic over the assessed period is at 3.14% against a compatibility level of 3% for the 5th harmonic, thereby marginally exceeding the individual harmonic limit.

Figure 4 shows the voltage THD against the loading of the feeders over 3 days within the measurement period. Figure 4 shows that the voltage THD planning level violations occur at night when the loading (damping) on the network is greatly reduced (compared to the day time).

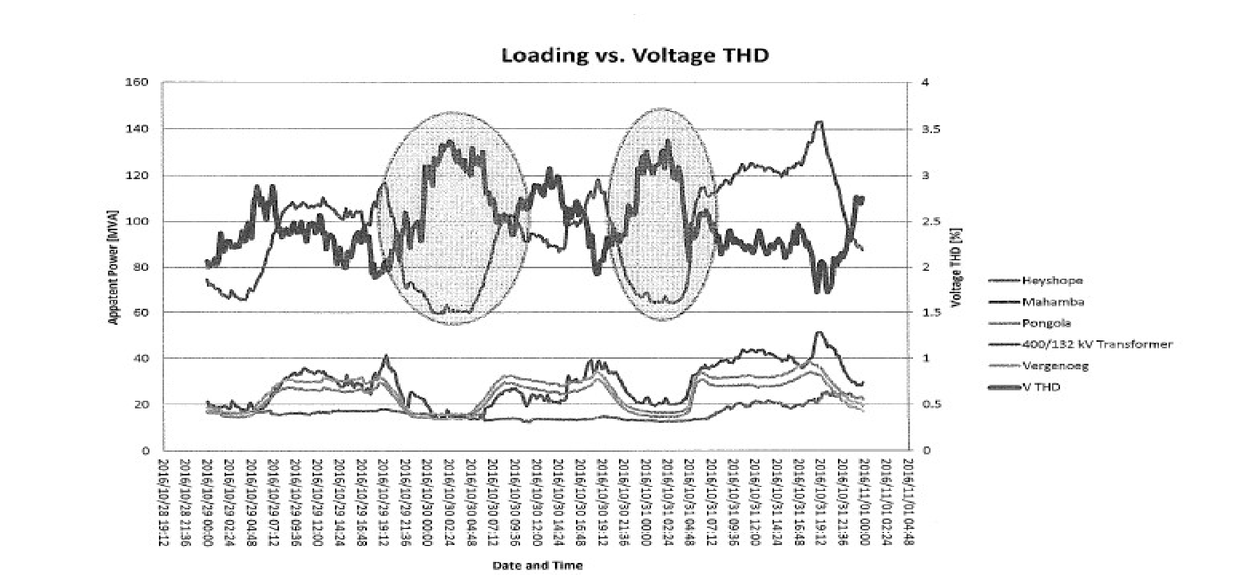


Figure G.4: Feeder loading vs Voltage THD

The loads supplied from Normandie on the 132 kV network consist mainly of rural towns, farms, dams (on the Heyshope feeder), small industry and a sugar mill. There is a small capacitor bank installed at Pongola substation, but the unit has been out of service since 2015.

4.2. Frequency sweep

Presently there is only one 400/132 kV transformer in service as per Figure 1 at Normandie, with back up capabilities via a 132/88 kV transformer.

In 2015, a second 400/132 kV transformer, as highlighted in Figure 1, was to be installed at Normandie, however the unit failed during commissioning testing and was subsequently removed from site for repairs. The repair plan shows that the unit was scheduled for completion in June 2017, however, due to internal problems, the completion date has been postponed to March 2018. Thereafter, the transformer will be taken to site for installation and commissioning.

Figure 5 shows a frequency sweep of the Normandie 132 kV busbar with one transformer (present) and with 2 transformers in service (future). The frequency sweep shows a reduction in the overall harmonic impedance which will translate into a reduction on the harmonic distortion measured on the Normandie 132 kV busbar.

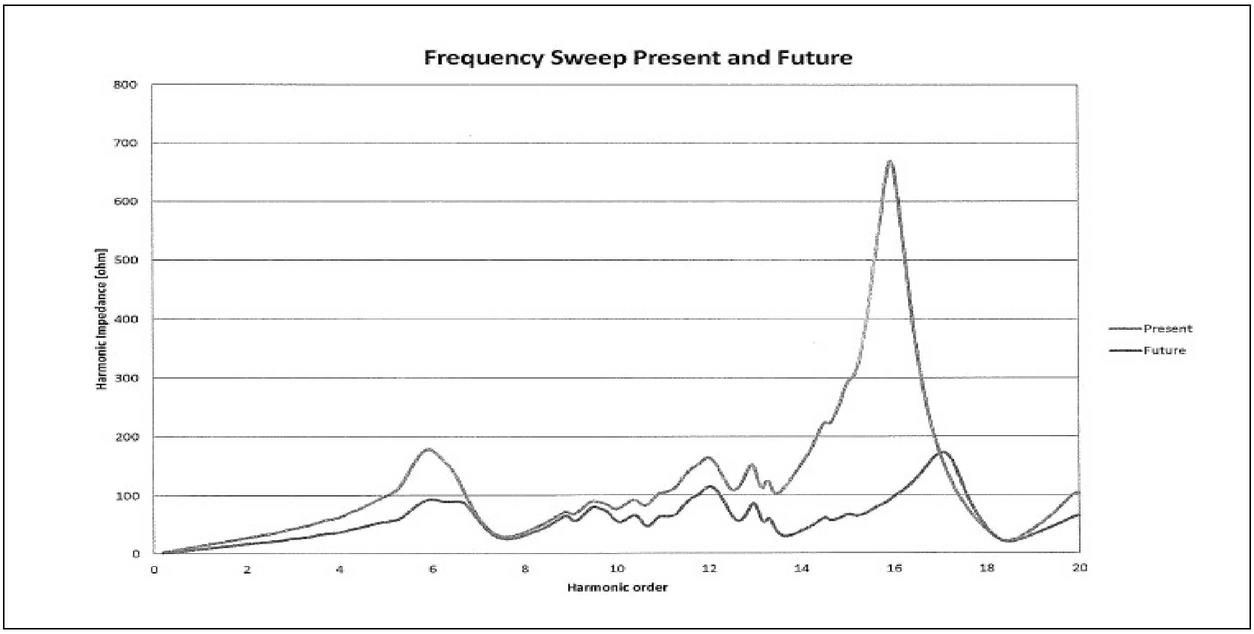


Figure G.5: Normandie 132kV frequency sweeps

5. CONCLUSION

The voltage THD at Normandie is within the NRS048:2 compatibility levels. Presently there is no specific Power Quality agreement between SEC and Eskom regarding the Mahamba infeed point. There is a marginal violation of the individual voltage harmonics on the 5th harmonic, however, this violation occurs mainly at night when the damping on the network has been reduced by a factor of 2.

A second 400/132kV transformer is planned for reinstallation at Normandie before the end of March 2019. Simulations have shown that this transformer will reduce the harmonic impedance on the 132kV busbar resulting in reduced distortion on the 132kV busbar and also improve dip performance of the feeder.

6. RECOMMENDATIONS

It is recommended that the voltage THD and dip performance be re-assessed after the installation of the second transformer.

Appendix H Simunye – Mhlume PQ Assessment

1. INTRODUCTION AND BACKGROUND

This report details the results of the power quality analysis performed for Simunye – Mhlume Feeder 1470, which has a power quality instrument installed at Simunye Substation.

The analysis of this feeder was done as a response to the 2016 SZNS027 Quality of Supply Compliance Report and also responding to a request from RSSC. In this report, it was noted that 1470 power quality required further investigation mainly in the following aspects:

- Event Incidence – this site recorded the 5th highest number of events for the calendar year 2016
- THD – this site had a voltage THD of 7.19%, which was 3.19% above the limit
- Voltage Magnitude – lower limits of voltage magnitude on this site was below 0.95pu

With regards to voltage unbalance, the site was within limits and there were no cases of customer complaints directly linked to this line.

2. DATA AVAILABILLITY

The analysis performed for this report entailed looking at month-to-month power quality data for the site for the period January 2016 to April 2017. Data availability for this period is as follows:

Month, Year	Jan 16	Feb 16	Mar 16	Apr 16	May 16	Jun 16	Jul 16	Aug 16	Sep 16	Oct 16	Nov 16	Dec 16	Jan 17	Feb 17	Mar 17	Apr 17
Data Valid for Stat Analysis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	☹	☹	☹
Data Valid for Investigation	✓	☹	✓	☹	✓	✓	✓	✓	✓	✓	✓	✓	☹	☹	☹	☹

Due to damage on the power quality instrument on this site, no data was collected for the months of February – April 2017. With regards to statistical analysis (which is being used for this study), there was sufficient data in the 13 remaining months.

3. EVENT INCIDENT

According to the monthly reports generated from PQ Portal, this site experienced 195 events in 2016 alone. This is an average of 0.5 events per day. Included in these events are interruptions, voltage dips (except y dips), swells, under- and over- voltage. The distribution of these can be seen in Figure H.1.

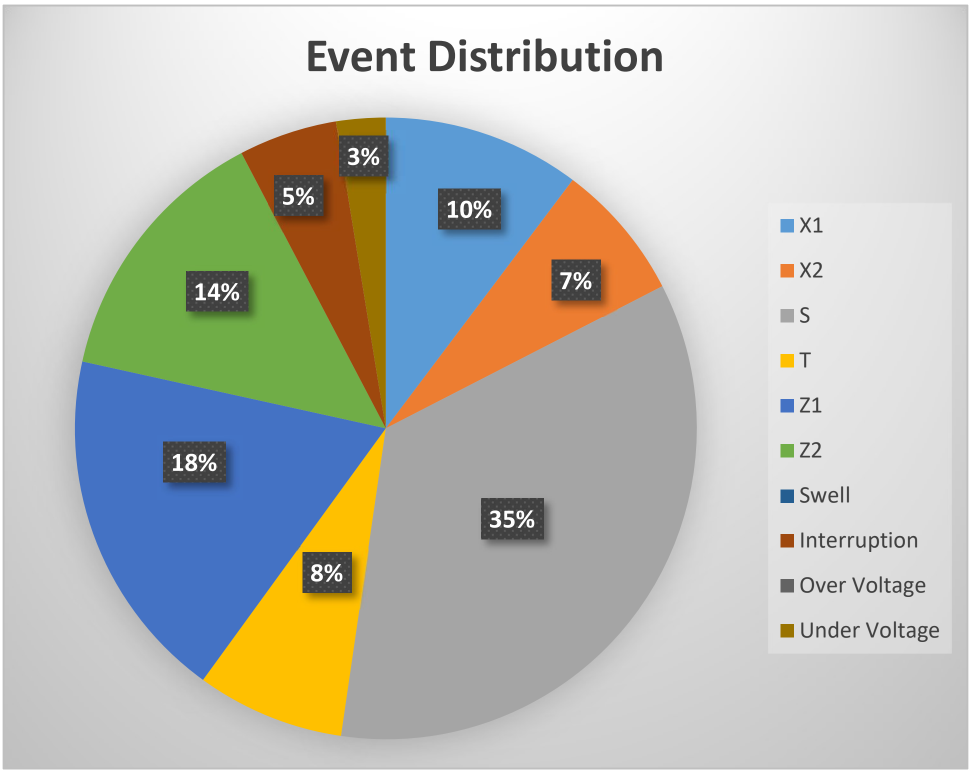


Figure H.1: Event Distribution for Simunye 1470

Dip Type	Count	Comment
X1	20	• should be reduced
X2	14	• should be reduced
S	68	• prevalent where impedance protection schemes used and where voltage recovery is delayed
T	15	• close-up faults and not expected regularly • should be minimised
Z1	36	• reflects sensitive protection operation
Z2	27	• reflects sensitive protection operation; should be actively limited
Swell	0	-
Interruption	10	• 99% of these occurred between October 2016 and January 2017 which can be attributed to weather
Over Voltage	0	-
Under Voltage	5	• 99% of these occurred between October 2016 and January 2017 which can be attributed to weather

3.1. S Dips

A prevalence of S dips in HV networks is usually seen in a system where impedance protection schemes are used and where voltage recovery is delayed. Simunye feeder 1470 uses impedance protection, and a look at the voltage profile of the site indicates that voltage recovery may be compromised due to an unstable fault impedance. This should be addressed.

3.2. T Dips

T dips are not expected to appear regularly on a power system, especially in HV networks. When they do occur, these require in-depth investigation to find the root-cause. The T-dips recorded at this site were as follows:

Date	Time	Incident #	Recorded/Probable Cause
13 – 09 – 2016	00:46:42	631720	• Phase-to-ground fault (downstream[9]) • LA copper strand snapped and touched transformer casing • LV breaker 1360 and transformer breaker 1465 operated
15 – 10 – 2016	19:59:36 19:59:39	638403	• Overcurrent fault (yellow phase) • Broken structures and damaged equipment (downstream) • Weather related
	20:01:07 20:01:48	638405	
	20:26:13	638417	
	20:43:47	638426	
	21:24:48	638432	
24 – 10 – 2016	17:49:30 17:49:33	643545	• Overcurrent fault - all phases (downstream) • Broken structures • Weather related
	19:22:35	643532	• Weather related (possible lightning strike)
29 – 10 – 2016	18:27:13	644750	• Dip recorded on closing of 1470 after overcurrent fault • Weather related trip at 17:28
06 – 11 – 2016	18:09:05	647146	• Broken structures on adjacent circuits • Weather related
09 – 12 – 2016	16:51:29	657729	• Overcurrent and earth fault, Ngomane 1480 (downstream) • Weather related
10 – 12 – 2016	15:18:04	657977	• Overcurrent fault (downstream) • Broken conductor on KPF 1416 • Weather related

As can be seen, a majority of the T dips are weather related occurring on the monitored circuit or on adjacent circuits. There were dips which were caused by RSSC. 80% of the recorded events were coincidental with damage to structures and equipment. A high number of dips were weather related, which is either lightning strike or wind causing clash of conductors. It is important to note that Swaziland has one of the highest lightning incidence rates in the world (approximately 12 strikes per sqkm).

3.3. Z Dips

Z dips are said to be uncommon in HV systems. For this feeder however, we see a total of 63 Z dips in the analysed period, 60% of which occurred during the months of October 2016 – January 2017. There were 27 Z2 type dips in this period, and according to the quality of supply standards, these types of dips should be specifically limited. Analysis of the Z2 dips was performed.

[9] Downstream – dips emanating from RSSC network

Date	Time	Incident #	Recorded/Probable Cause
07 – 04 – 2016	21:17:01	593044	• ARC operated
03 – 05 – 2016	19:32:54	602631	• Cane field fires (RSSC)
03 – 08 – 2016	23:11:14	623496	• Equipment failure
12 – 09 – 2016	22:03:09	631683	• Unknown (Unprocessed)
21 – 10 – 2016	11:58:32	641834	• ARC operated (downstream)
24 – 10 – 2016	18:00:33	643546	• Unknown (Unprocessed)
	18:03:51	643542	• Unknown (Unprocessed) • Possible fault at Ka-Langa
29 – 10 – 2016	18:20:06	644748	• Weather related • Overcurrent trip in the network
	18:25:27	644749	• Weather related (possible lightning strike)
01 – 11 – 2016	20:13:40	645681	• Weather related (possible lightning strike)
05 – 11 – 2016	14:40:44	646738	• ARC operated • Weather related
	14:48:43	646740	• Weather related
06 – 11 – 2016	18:02:19	647145	• Overcurrent • Weather related
14 – 11 – 2016	08:17:49	649947	• ARC operated (downstream) • Weather related
24 – 12 – 2016	13:50:07	661859	• Broken structures in the network • Weather related
	13:53:23	661860	
	13:59:55	661861	
27 – 12 – 2016	12:24:23	662605	• Voltage regulation issues due to high load (downstream)
	13:21:16	662617	
	18:03:22	662695	
06 – 01 – 2017	07:32:39	664727	• Broken jumper
	12:26:25	664747	• Under voltage event from Normandie
17 – 01 – 2017	07:10:38	666186	• Overcurrent • Cause unknown
20 – 01 – 2017	17:48:55	666736	• Overcurrent (downstream) • Cause unknown

According to the SZNS027, the company is obliged to manage protection performance times such that the number of S type dips should be less than the number of X type dips. In this case, we see that the S dips are 2 times the number of X type dips which means attention should be given to this line.

4. COMMENTS AND RECOMMENDATIONS

As has been mentioned, the majority of the events on this line coincide with weather phenomena. It is important for this line to be patrolled and studied further by the relevant departments in order to determine why it is highly prone to voltage events, especially during weather activity. This can include patrols to check servitudes, hotspots, conductor spacing, line span and a further look at the equipment in the substation (including VTs). However, the contribution of RSSC cannot be ignored, relevant measures must be taken by RSSC to improve the dip performance of the feeder.

Compiled by:

Metering Engineer – Goodness Maziya

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Appendix I Simulation Results Before and After Project Implementation

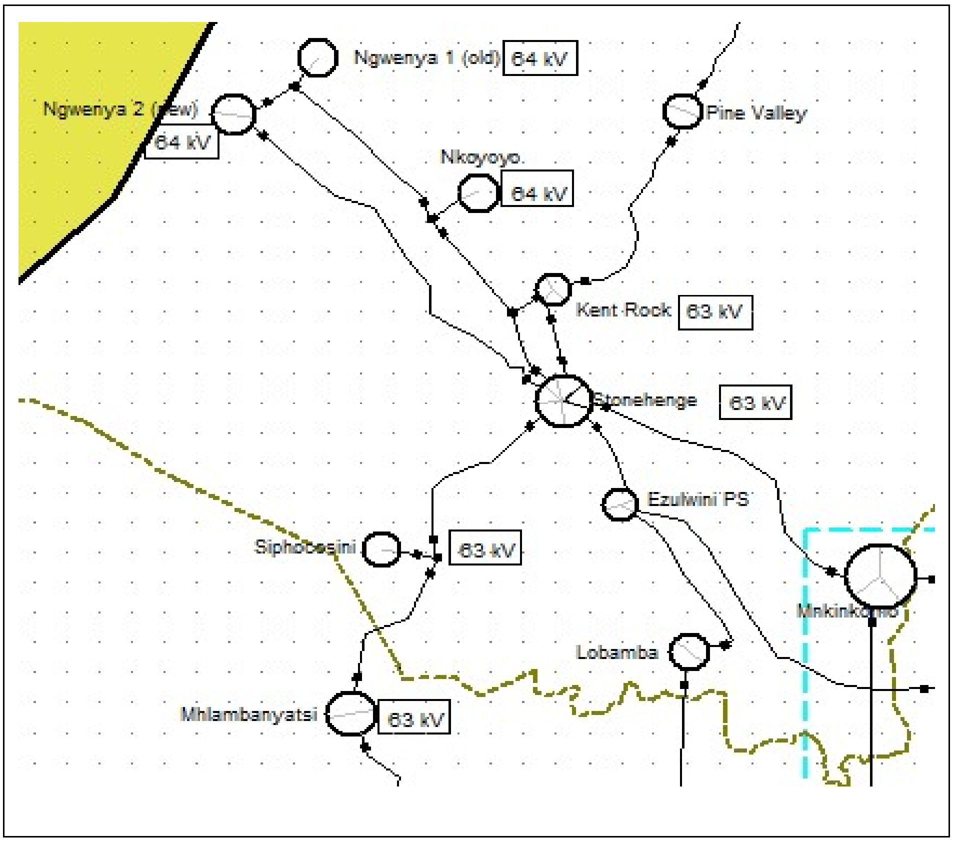


Figure I.1: Substation performance if Mnkinkomo – Stonehenge 132 kV line is off

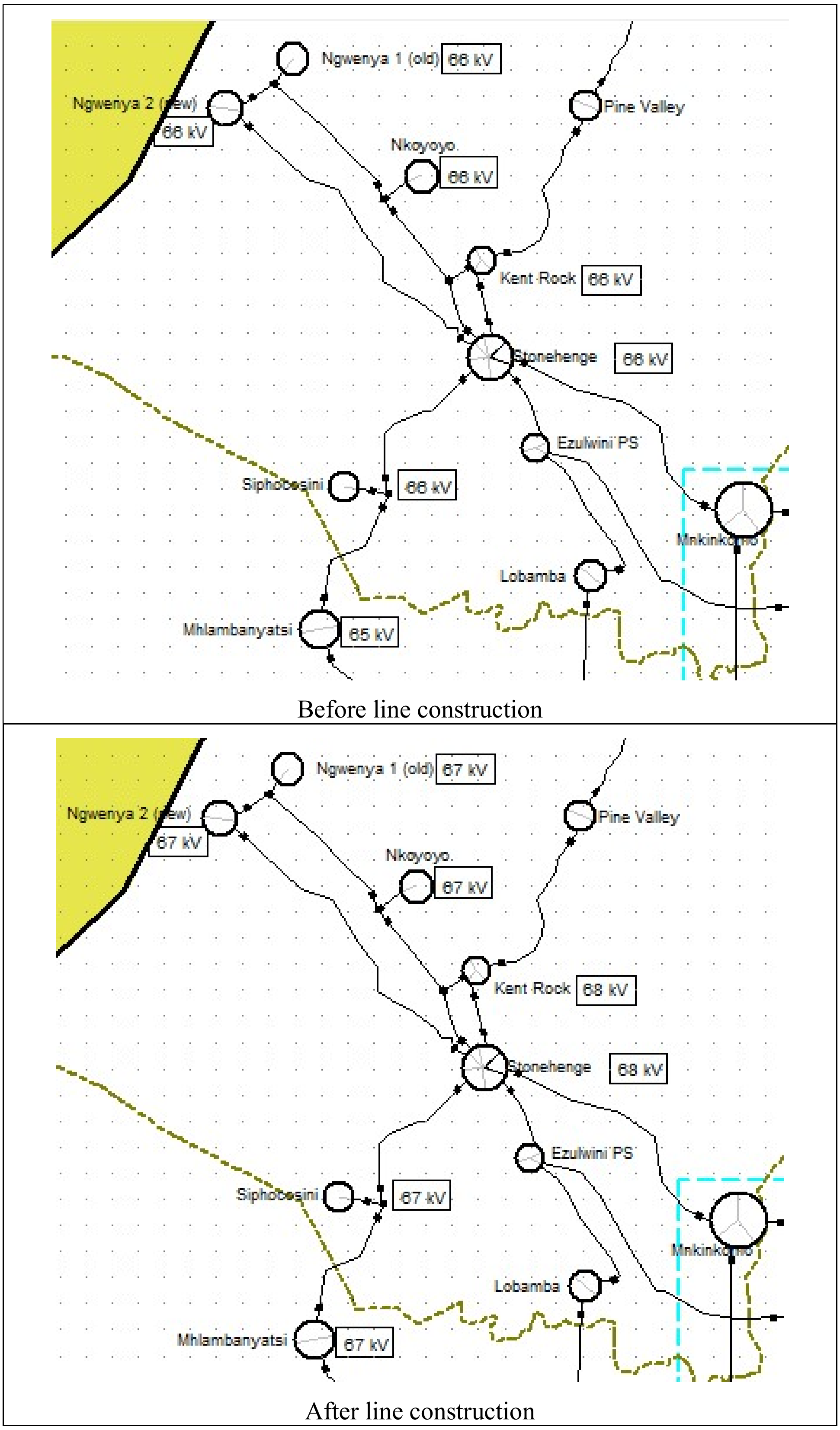
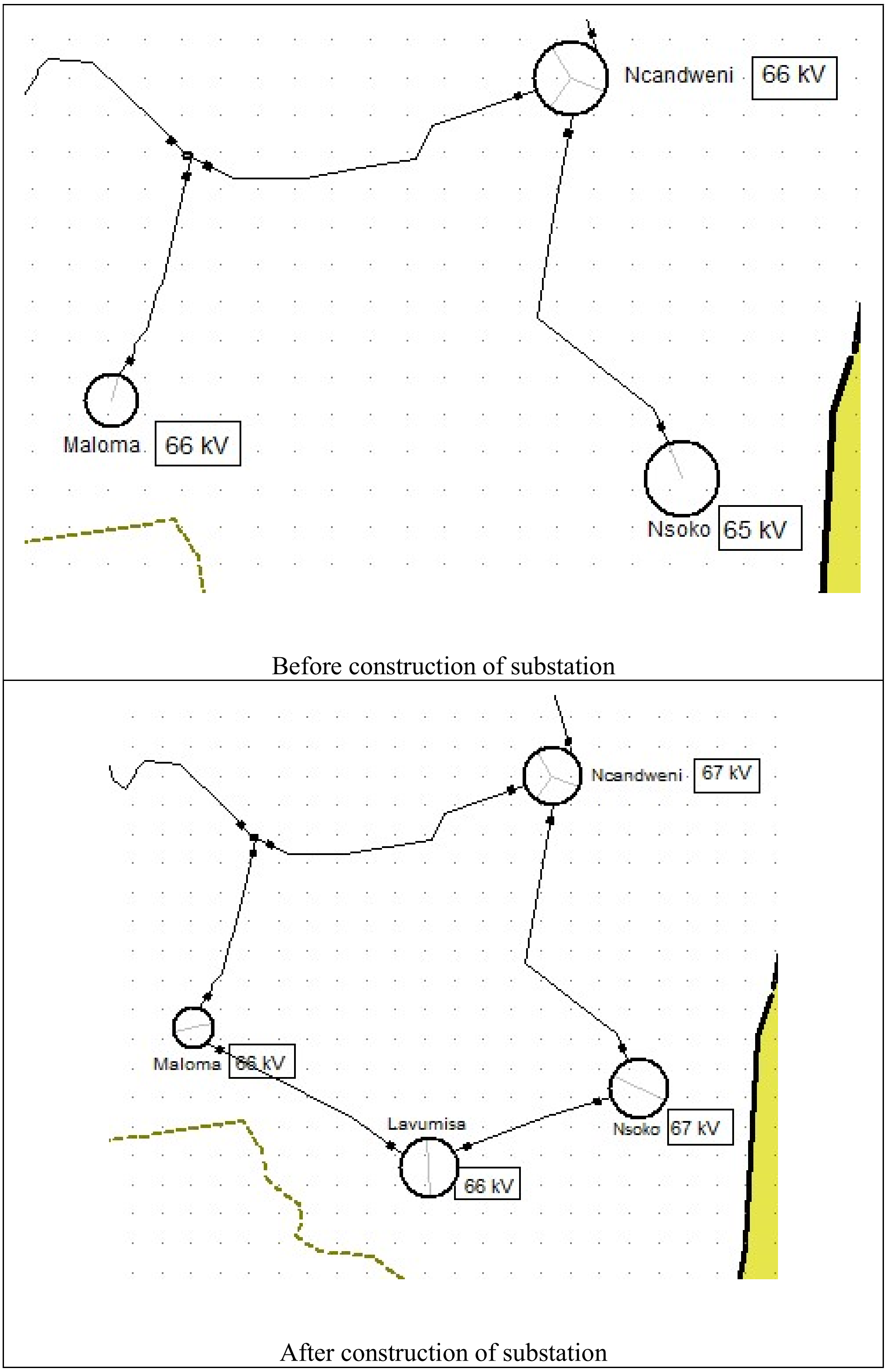


Figure I.2: Substation performance before and after construction of Edwaleni II – Stonehenge 132 kV line



Before construction of substation

After construction of substation

Figure I.3: Substation performance before and after construction of Lavumisa 66/11 kV -10 MVA substation

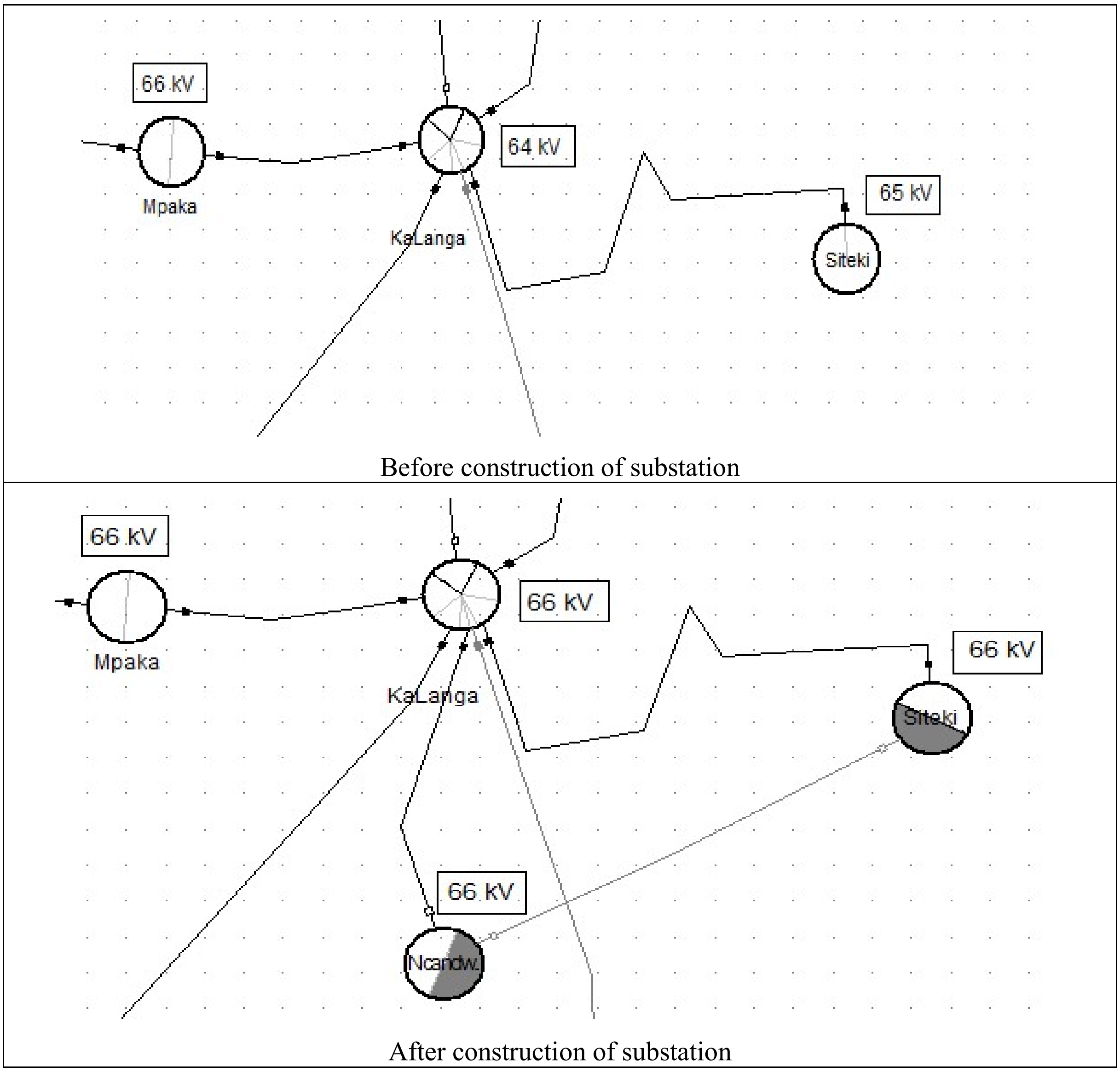
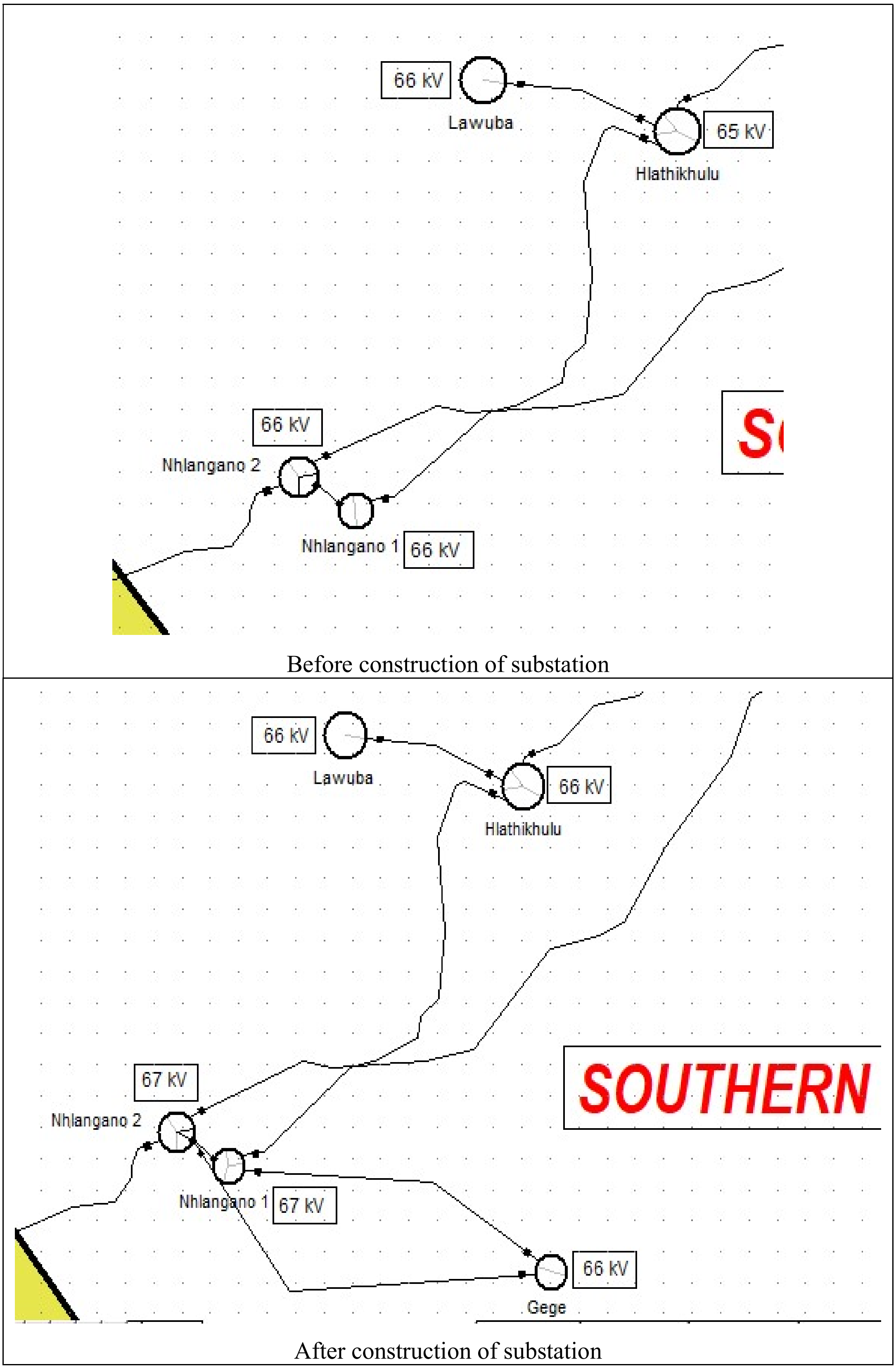


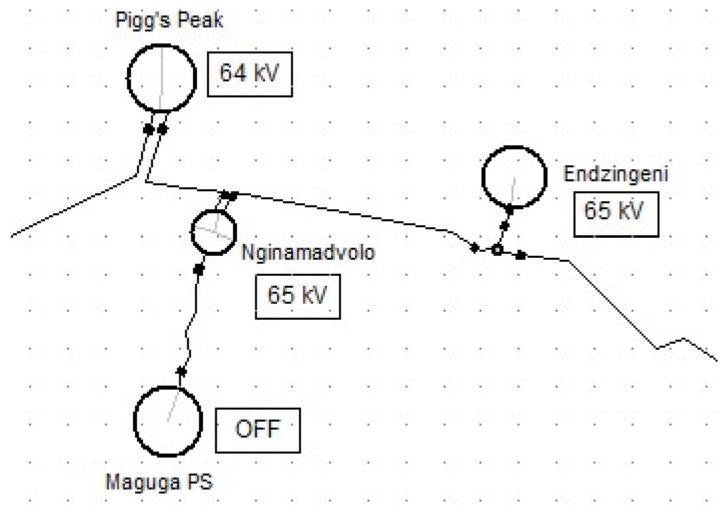
Figure I.4: Substation performance before and after construction of Ncandweni II 66/11 kV -10 MVA substation



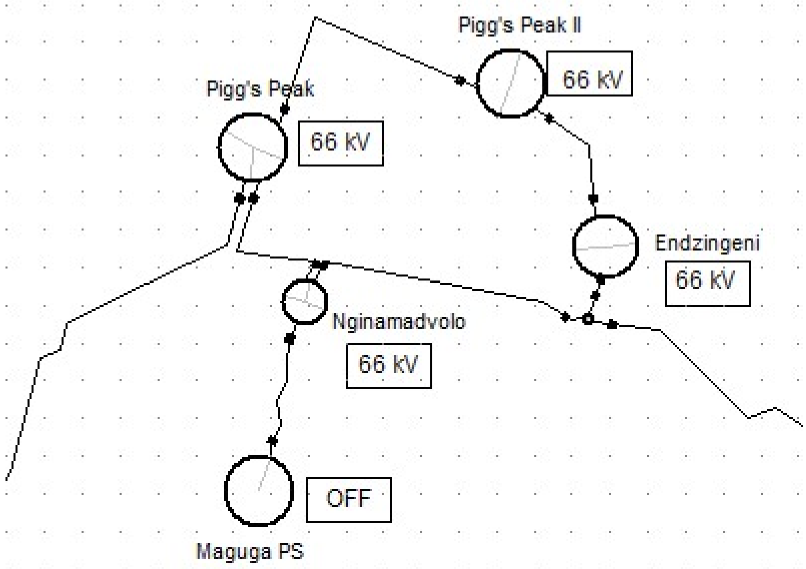
Before construction of substation

After construction of substation

Figure I.5: Substation performance before and after construction of Gege 66/11 kV -10 MVA substation

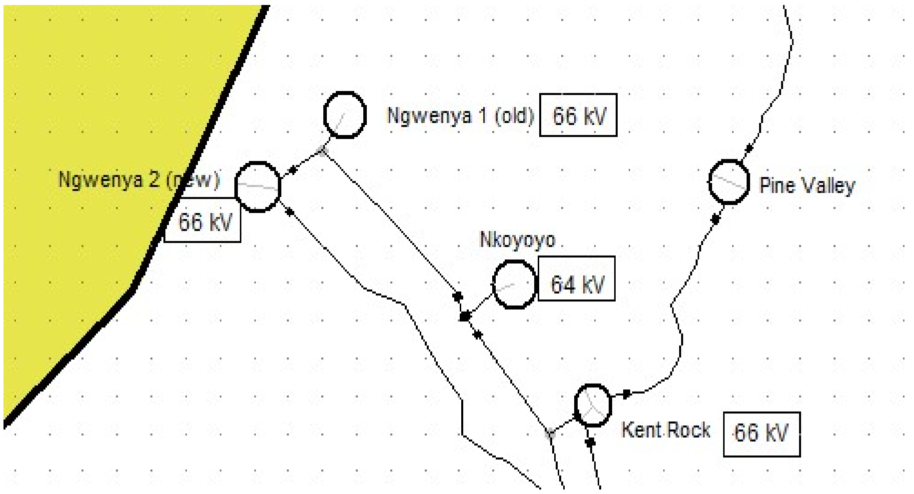


Before construction of substation

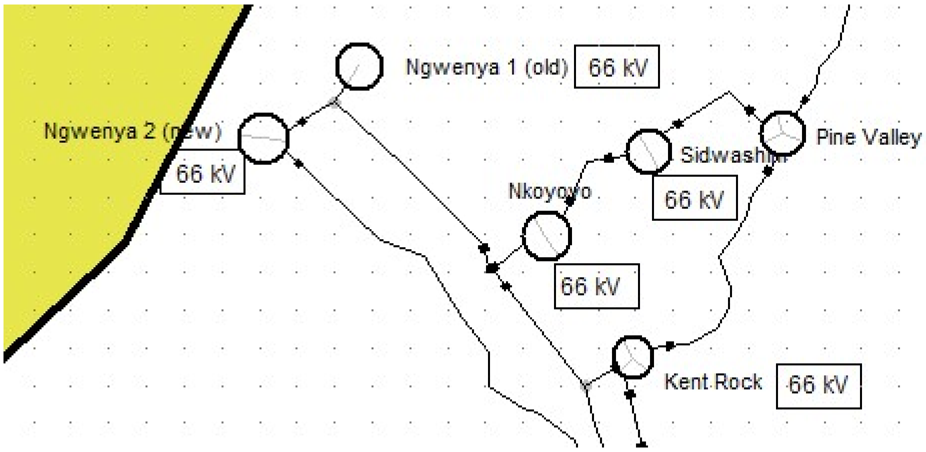


After construction of substation

Figure I.6: Substation performance before and after construction of Piggs Peak II 66/11 kV -10 MVA substation



Before construction of substation



After construction of substation

Figure I.7: Substation performance before and after construction of Sidwashini 66/11 kV -10 MVA substation