# VOLTAGE DIP PERFORMANCE ANALYSIS

by

**Timothy M Nzimande**

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**Co-Supervisor : Mr R.G. Koch**

**Supervisor : Prof N.M. Ijumba**

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## ABSTRACT

The power quality performance of South African utilities has been regulated through the application of NRS 048-2 standard. The earliest edition of the power quality standard (NRS 048-2:1996) defines compatibility levels for voltage dips in the form of annual dip limits for each voltage dip type. Actual measured utility dip performance has consistently resulted in higher dip numbers than the limits imposed in the standard. On the other hand, the dip limits were considered to be less restrictive by industrial customers. The revised power quality standard addresses the difficulties in managing voltage dip performance based on dip limits as specified in the first edition of NRS 048-2. This new philosophy does not define dip limits; instead, utilities are required to develop specific strategies to manage dip performance according to customer requirements. This research work develops an alternative approach to the management of dip performance as opposed to the application of dip limits. The study analyses measured voltage dip records for a steel-processing plant and a pulp and paper plant. The supply network for each plant is modelled to define dip influence zones as a function of fault locations. The principal results of this study are critical circuits, causes of dips, dip influence zones and the key elements of the proposed approach in communicating dip performance. The optimised approach was presented to and adopted by the customers involved.

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## ABBREVIATIONS

| | |
|---|---|
| a.c. | Alternating Current |
| CIGRE | *Conseil International des Grands Reseaux Electriques* |
| CIRED | *Congrès International des Réseaux Electriques de Distribution* |
| CVT | Constant Voltage Transformer |
| d.c. | Direct Current |
| DPL | DIgSILENT Programming Language |
| DS | Distribution Station |
| DTL | Definite Time Lag |
| DVR | Dynamic Voltage Restorer |
| HV | High Voltage |
| IDMT | Inverse Definite Mean Time |
| IEC | International Electrotechnical Committee |
| IEEE | Institute of Electrical and Electronic Engineers |
| IGBT | Insulated Gate Bipolar Transistor |
| LV | Low Voltage |
| MV | Medium Voltage |
| NEPS | Network and Equipment Performance System |
| NERSA | National Energy Regulator of South Africa |
| PCC | Point of Common Coupling |
| PQ | Power Quality |
| pu | Per Unit |
| PWM | Pulse Width Modulation |
| QMS | Quality Management System |
| QOS | Quality of Supply |
| r.m.s. | Root Mean Square |
| SMES | Superconducting Magnetic Energy Storage |
| STS | Static Transfer Switch |
| TIPPS | Transmission Information Plant Performance System |
| UPS | Uninterruptible Power Supply |
| VSC | Voltage Source Converter |
| VSD | Variable Speed Drive |

## DEFINITIONS

### Eskom

South African electricity utility that generates, transmits and distributes electricity to industrial, mining, residential and agricultural customers and redistributors.

### Eskom Distribution (or Distribution)

A business unit within Eskom that operates networks within the voltage range 380V to 132kV level. Eskom Distribution interacts directly with residential, mining, industrial and agricultural customers and redistributors. Eskom Distribution purchases electricity from Eskom Transmission through internal service level agreements. The interface between Distribution and Transmission is at specific transmission stations, where voltage is stepped down from transmission voltages (765kV – 220kV) to distribution voltages (132kV – 11kV).

### Eskom Transmission (or Transmission)

A business unit within Eskom that operates networks within the voltage range 220kV to 765kV a.c. and 533kV d.c. Transmission sells electricity to Distribution through internal service level agreements. A relatively small number of customers are supplied directly from Transmission instead of being supplied from Distribution (aluminium smelters and some municipalities).

### Eskom Customers (or customers)

'Customer' refers to electricity users who purchase electricity from Eskom Distribution or directly from Eskom Transmission. In the context of this study, reference to Eskom 'customers' excludes neighbouring countries to or from which Eskom sells or purchases electricity.

### SAPPI

A global producer of coated fine paper (used in print publications) and cellulose (used in pharmaceutical products) and premium quality packaging paper. The paper plant involved in this study is situated in Springs (Gauteng province, South Africa).

### Scaw Metals

An international group manufacturing steel products, ranging from rolled steel, wire rope, cast alloy iron and forged steel. The plant involved in this study is situated in Germiston (Gauteng, province, South Africa).

# CHAPTER 1:
# INTRODUCTION

## 1.1 POWER QUALITY

Various publications on the subject of power quality use the term power quality with different meanings. The following set of definitions has been found to be consistent [1], [2], [3]:

- ⇨ Voltage quality is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sinusoidal wave of constant frequency and constant magnitude.
- ⇨ Current quality is concerned with deviations of current from the ideal. The ideal current is again a single-frequency sinusoidal wave of constant frequency and constant magnitude. An additional requirement is that this sine wave is in phase with the supply voltage.
- ⇨ Power quality is a combination of voltage quality and current quality.

The definition of power quality is illustrated in figure 1.1. What is noticeable from the stated definitions is that power quality refers to the interaction between the utility and the customer, or in technical terms between the power system and the load.

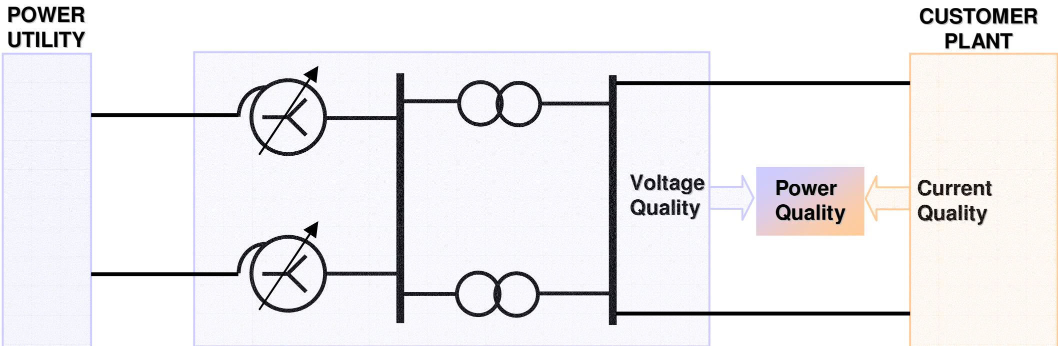



**Figure 1.1:** Power quality is a combination of voltage quality and current quality

Power quality disturbances (deviation of voltage or current or both, from the ideal) generally fall into two categories [1], [2], namely, variations and events. Figure 1.2 shows the categorization of power quality disturbances.

Variations are small deviations of voltage or current from the ideal reference value. Variations are disturbances that can be measured at any instant of time. Events are larger deviations that occur only occasionally. Events are disturbances that start and end with the crossing of a threshold value. Power quality disturbances affect all electricity consumers, from domestic to industrial customers. Customer awareness of power quality issues is increasing due to the more sensitive nature of modern electronic equipment and due to the financial losses associated with lost production time.

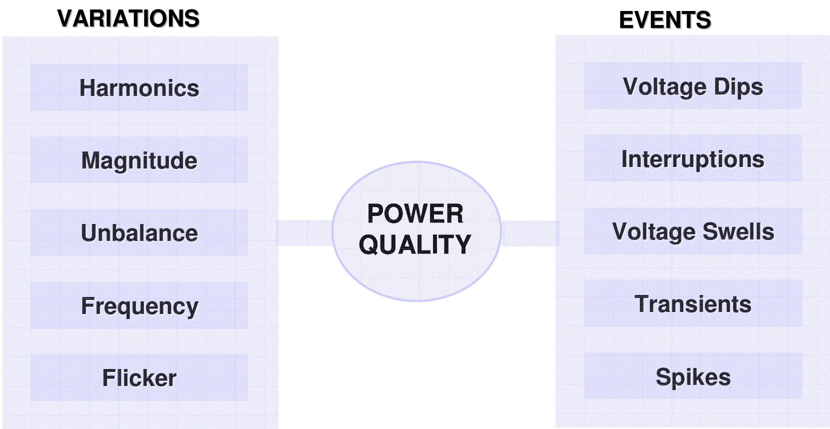



**Figure 1.2:** Power quality disturbances [2]

Voltage dips are recognized as one of the most important aspects of power quality [2], [4], [5]. The interest in voltage dips originates from the problems they cause on several types of common industrial equipment such as variable speed drives, process-control equipment and computers. The impact of a voltage dip on industrial processes may not be as severe as that of an interruption. However, voltage dips occur much more frequently than interruptions and therefore the global impact of dips is still larger [5]. If process equipment is sensitive to these voltage dips, the frequency of problems will be much greater than if the equipment were only sensitive to interruptions.

The management of voltage dips requires active participation of utilities, customers and equipment manufacturers. Utilities around the globe have developed various approaches for managing and reporting voltage dip performance [6]. These methods typically quantify dip performance by defining specific areas on a magnitude-duration plane that represent guidelines on areas where dips are likely to occur, and areas that are likely to affect customers.

The South African utility Eskom performed power quality monitoring throughout its power system to obtain statistical information on the expected number of voltage dips and their characteristics [6], [7]. These measurement results form the basis for dip categorization according to both the expected frequency of occurrence and the impact on customer plant [7]. In 1996, the power quality standard was introduced as a means of evaluating and regulating the electrical product supplied by South African utilities [8].

## 1.2 THE SOUTH AFRICAN POWER QUALITY STANDARD

The first edition of the South African power quality standard [8] specifies compatibility levels for voltage dips in the form of a maximum number of dips per year for each dip category. The voltage dip limits are given for defined network voltage ranges. Table 1.1 reproduced from [8], shows voltage dip limits to be considered as minimum compatibility standard.

The assessment method for voltage dips allows for the extreme 5% of measured values to be discounted when calculating the assessed level. These assessed values are to be compared with voltage dip limits listed in Table 1.1.

**Table 1.1:** Voltage dip limits per year per dip class [8]

| Network Voltage Range | Number of Voltage Dips per Year for each Dip Category | | | | |
|---|---|---|---|---|---|
| | S | T | X | Y | Z |
| 6.6kV to ≤ 44kV | 30 | 30 | 100 | 150 | 20 |
| 6.6kV to ≤ 44kV Rural | 69 | 54 | 215 | 314 | 49 |
| > 44kV to ≤ 132kV | 25 | 25 | 80 | 120 | 16 |
| 220kV to ≤ 765kV | 11 | 6 | 45 | 88 | 5 |

Dip performance studies conducted by Koch, Sigwebela and Geldenhys [7] revealed that actual measured dip performance indicates higher dip numbers than the dip limits specified in Table 1.1. From the utility perspective, the inability to meet the limits imposed by the power quality standard [8] has led to the conclusion that the limits are not achievable without a substantial investment in the electricity supply networks [7].

From the customer perspective, the dip limits were considered to be less restrictive, at the time of adopting the standard. An expectation was present at the time that a revision of voltage dip performance would result in stricter dip limits. Recent improved statistical data shows that the compatibility levels need to allow for even more dip events per annum [7].
The original dip characterization method developed in [8] was based primarily on theoretical considerations. The power quality standard [8] was adopted with an understanding that it will be revised after five years of implementation. The standard was based on limited statistical data obtained from a limited number of power quality instruments. The availability of monitoring instruments was poor, typically failing during lightning seasons when most of the dips would have occurred [7]. Moreover, the definition of voltage dip limits has turned out to have a potentially

negative effect on some of the customers, as the utility may allow acceptable levels of dip performance to deteriorate for the sites that achieve better than acceptable performance.

The National Energy Regular of South Africa (NERSA) recently introduced a new power quality management framework through its power quality directive [9]. The principles defined in the power quality management framework have been adopted in the revised edition of the power quality standard [10]. The initial power quality standard has been revised to overcome the difficulty of managing dip performance based on annual dip limits. The revised standard [10] does not specify dip limits as minimum compatibility levels. The standard recognises the dependence of voltage dip performance on geographical location, network topology and environmental influences.

## 1.3 QUALITY MANAGEMENT SYSTEM IMPLEMENTATION STUDY

The development of NERSA's power quality directive was based on substantial consultation with representatives from various stakeholder categories (utilities, customers, equipment suppliers, standards bodies, consultants etc) [7]. The consultation process highlighted the specific need for each of the parties to appropriately address power quality issues in the design and operation of their plant and equipment.

The new framework recognises that dip performance varies from location to location, and that customer power quality requirements vary. This realization is addressed in the directive through the definition of a quality management system (QMS) as opposed to the application of dip limits. The QMS is a regulatory requirement to implement a standard protocol for:

⇨ Interaction on power quality issues (dips, harmonics, interruptions etc).
⇨ Communication of power quality issues with customers (rights, complaints processes etc).
⇨ Customer recourse to mediation or arbitration of disputes by NERSA.

This research work was initiated as a case study to develop an alternative approach to the management of voltage dips as opposed to compliance to voltage dip limits.

## 1.4 RESEARCH QUESTION

The current practice in dip performance management requires regular interaction forums between Eskom and its industrial customers. The discussions in these forums are centred around the latest dip events and specific actions taken by the utility to reduce the number of dips in line with dip limits specified in [8]. Initiatives to improve dip performance are largely focussed on the utility perspective. Customer involvement is limited to providing feedback on the impact of each recorded dip event in terms of outage duration, financial losses and other difficulties.

The research study examines the following key research question:

- ⇨ **How can communication of dip performance be optimised with a view to ensuring mutual technical responsibility of plant, between the utility and its customers?**

## 1.5 SCOPE OF STUDY

- ⇨ The study analyses voltage dip performance for a selected set of industrial plants, that is, a steel plant and a paper plant (pulp and paper).
- ⇨ Voltage dip analysis is performed from both the utility perspective (location, cause etc) and the customer perspective (dip-related costs).
- ⇨ The supply networks for selected plants are modelled using a power system simulation tool. Various fault types are simulated at different points on each supply network to quantify the sensitivity of busbar voltage at the customer point of supply.
- ⇨ Voltage dip influence zones for each plant are calculated. The results of the analysis and simulations were then presented to the customers participating in this study.

## 1.6 STUDY OBJECTIVES

- ⇨ To quantify voltage dip performance for the selected industrial plants.
- ⇨ To define voltage dip sensitivity zones for the selected plants.
- ⇨ To propose and present to the customers, an alternative approach in communicating dip performance.

## 1.7 MOTIVATION

The following drivers have motivated initiation of this work:

- ⇨ Requirements of the revised power quality management directive.
- ⇨ Mutual dissatisfaction between utility and its customers with the use of dip limits as minimum compatibility standards.

## 1.8 RESEARCH DESIGN AND METHODOLOGY

The process that will be followed in conducting the study is summarized in figure 1.3 below.

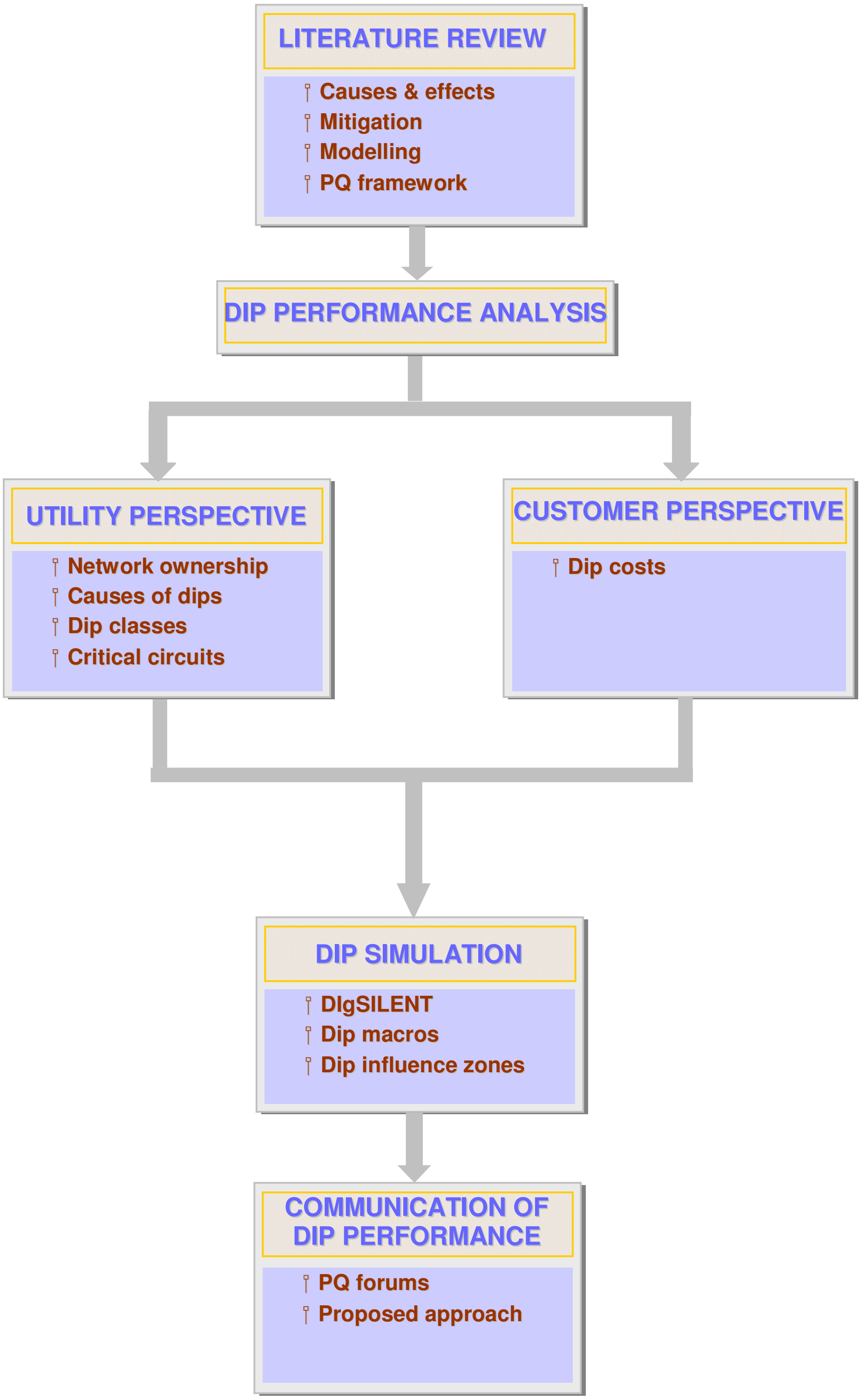



**Figure 1.3:** Process followed in conducting the research study

### 1.8.1 LITERATURE REVIEW

A literature review was conducted to highlight the conceptual framework for the study. Literature was sourced in the form of technical publications such as previous research reports, articles, textbooks, reports by international organisations (CIGRE, IEEE, IEC) and electronic resources. The literature review covered the following areas:

- ⇨ Theory of voltage dips inclusive of point-on-wave characteristics, characterization, causes, effects and possible solutions to dip problems.
- ⇨ Voltage dip modelling techniques.
- ⇨ Initial power quality management framework and experience in the South African context.
- ⇨ Limitations of the initial framework and introduction of the new approach in power quality management.

### 1.8.2 DIP PERFORMANCE ANALYSIS

Voltage dip performance for two industrial plants was analysed (Scaw Metals in Germiston and SAPPI in Springs). The choice of industrial plants was primarily based on historical dip-related plant downtime for the said plants and willingness to collaborate in finding solutions to dip problems. Voltage dip records were obtained from the Eskom quality of supply (QOS) database. A window period of three years has been chosen starting from 1$^{st}$ January 2003 to 31$^{st}$ December 2005. Fault management systems were utilised extensively to determine the root cause of faults and to ascertain circuit breaker trip information.

### 1.8.3 SIMULATION OF VOLTAGE DIPS

Voltage dip simulation was performed using the power system simulation tool DIgSILENT PowerFactory. Dip simulations considered different fault types, position of the fault and resultant dips at the busbar of interest. Previous results from the QMS series of research studies were utilised to calculate dip influence zones.

### 1.8.4 COMMUNICATION OF DIP PERFORMANCE

The regular Eskom-customer power quality interaction forums were utilised as the platform to present the results of dip performance analysis and dip simulations to the industrial customers involved.

## 1.9 CHAPTER OVERVIEW

The study is organised into a number of chapters, each addressing a specific aspect related to voltage dips.

***Chapter 2*** establishes the conceptual framework for the study by reviewing the theory related to voltage dips. The definition of a voltage dip in the context of the study is presented first. The point-on-wave dip characteristics are briefly discussed followed by a discussion on the causes of voltage dips. Various methods of dip characterization are also discussed. Of particular interest is the dip characterization method adopted in South Africa. The chapter further analyses the effects of voltage dips and presents possible dip mitigation options. The discussion on dip simulation techniques includes a brief overview of factors that influence the severity of voltage dips.

The power quality management framework in South Africa has reached important milestones over the past decade. Chapter 2 concludes with an examination of the power quality management framework in the South African context. The discussion focuses on the initial power quality management framework, the experience with power quality monitoring and the new framework.

***Chapter 3*** introduces the power quality monitoring program of Eskom. The causes for recorded dips are determined through a dip-to-trip matching exercise. Chapter 3 presents a brief discussion on the quality of supply database and reporting tools.

Also introduced in this chapter, are the two industrial plants selected for the case study. The analysis of actual measured dip performance for the steel plant and the paper plant is presented.

***Chapter 4*** discusses dip macros developed for the purpose of simulating voltage dips using the DIgSILENT PowerFactory simulation tool. The network model for the selected plants and the simulation methods are described. Chapter 4 quantifies the sensitivity of the busbar voltage at the customer point of delivery by defining dip influence zones. The dip influence zones are computed as a function of fault type.

***Chapter 5*** presents the key elements of the new proposed strategy of communicating dip performance. ***Chapter 6*** analyses the results obtained from dip performance analysis and dip simulations. The study objectives are reviewed with reference to the results.

## CHAPTER 2:
## LITERATURE REVIEW

### 2.1 INTRODUCTION

Voltage dips are widely recognised as the single most important power quality phenomenon when the number of process interruptions is considered [5]. Several definitions of voltage dips exist, differing only in the specification of duration and magnitude thresholds. This chapter reviews some of the theoretical concepts associated with voltage dips such as dip characterization, effects of dips, possible solutions to dip problems and dip simulation techniques. The South African experience with power quality management is also discussed, with particular attention to voltage dips.

### 2.2 THEORY OF VOLTAGE DIPS

#### 2.2.1 DEFINITION OF A VOLTAGE DIP

A voltage dip is defined as a sudden reduction in the r.m.s. voltage, for a period of between 20ms and 3s, of any or all of the phase voltages of a single phase or a polyphase supply [8]. Depth (magnitude) of a voltage dip is the difference between the declared voltage and the residual voltage during a voltage dip event. The duration of a voltage dip is the time measured from the moment the r.m.s. voltage drops below 0.9 per unit of declared voltage to the instant when the voltage rises above 0.9 per unit of declared voltage. Voltage dip parameters are illustrated graphically in figure 2.1 below.

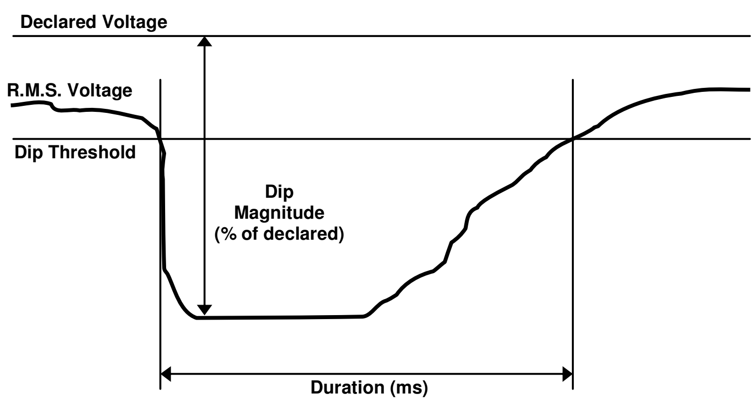



**Figure 2.1:** Definition of a voltage dip [8]

If the voltage dip involves multiple phases, the dip duration is defined as the instant when the voltage on one phase falls below the dip threshold to the instant when all three phases are again above the dip threshold. Similarly the magnitude of the voltage is given by the maximum r.m.s. excursion from the declared voltage.

### 2.2.2 PHASE SHIFT AND POINT-ON-WAVE CHARACTERISTICS

A short-circuit in a power system not only causes a drop in voltage magnitude but also a change in phase angle of the voltage [11]. This change in phase angle is referred to as the phase-angle jump. The phase-angle jump manifests itself as a shift in zero-crossing of the instantaneous voltage. The concept of phase-angle jump associated with a voltage dip is illustrated in figure 2.2.

Phase-angle jumps during three-phase faults are influenced by the difference in the reactance-to-resistance ratio between the source and the feeder. Several other factors also influence phase-angle jumps; type of fault, the distance between the fault and point of observation and the transformation of voltage dips to lower voltage levels [11]. Phase-angle jumps may affect power electronic converters since firing signals are derived from phase-angle information.

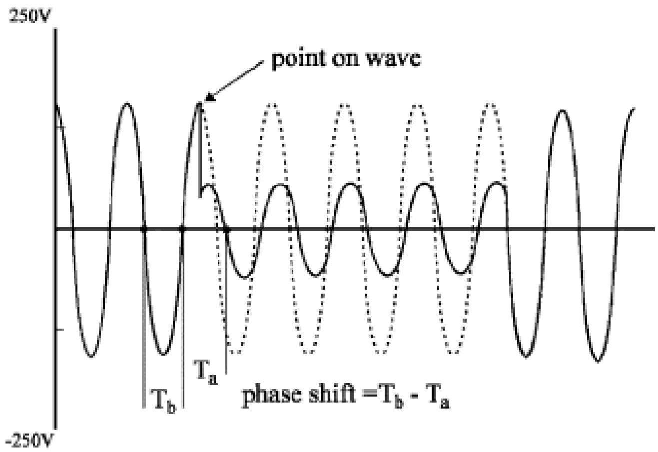


**Figure 2.2:** Voltage dip with phase-angle jump [11]

The points on the sine wave where the dip starts and ends are known to affect dip performance of certain process equipment such as contactors [2], [3], [11]. The point-on-wave of dip initiation is the phase angle of the fundamental wave at which the dip starts. The point-on-wave of dip recovery is the phase angle of the fundamental voltage at which the voltage recovers to 90% of nominal. The positive-going zero crossing of pre-event voltage is often used as the reference point when considering the point-on-wave quantities.

### 2.2.3 CAUSES OF VOLTAGE DIPS

Voltages dips are primarily caused by short-duration overcurrents flowing through the power system. The principal contributions to overcurrents are power system faults, motor starting and transformer energizing.

Power system faults are the most frequent cause of voltage dips, particularly single-phase short-circuits [1]. In the event of a short-circuit, for a large area of the adjacent network, the voltage in the faulted phase drops to a value between 0 and 1pu, depending on the impedance between the point of fault and the point of measurement.

#### 2.2.3.1 Motor Starting

Voltage dips can be experienced on starting of large direct-on-line electrical motors. A starting motor appears as a large load with low power factor, which improves as the motor approaches full speed. A start-up motor could draw five to six times normal full load current [2]. Figure 2.3 shows an example of a voltage dip due to motor starting.

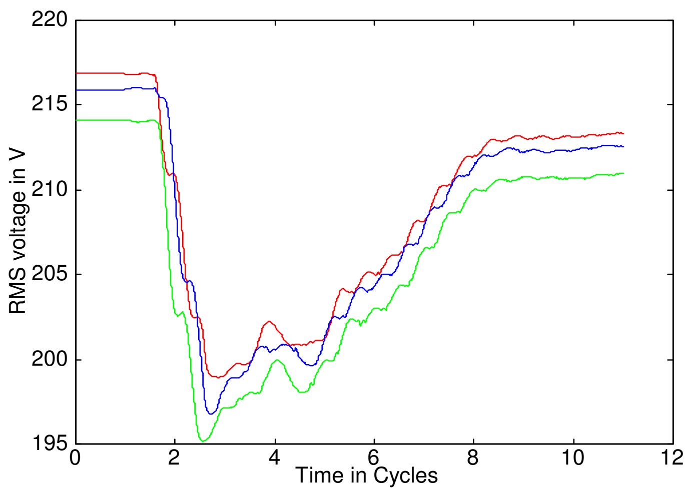



**Figure 2.3:** Voltage dip due to motor starting [12]

The starting of a motor load gives rise to voltage dips characterized by a small sudden drop in voltage, followed by a gradual recovery. Electrical motors are three-phase balanced loads and the associated voltage drops are the same in all phases. The voltage dip lasts until the large current demand decreases or the fault is cleared by a protective device, typically a fuse or a circuit breaker.

#### 2.2.3.2 Transformer Energizing

The energising of a large transformer gives rise to voltage dips characterized by a sudden drop in voltage and a slow recovery. Unlike the case of motor starting, the voltage dip magnitudes are different in the three phases. The inrush current is different in the three phases and is associated with appreciable content of second and fourth harmonic distortion [1]. An example of a voltage dip due to the energising of a transformer is shown in figure 2.4.

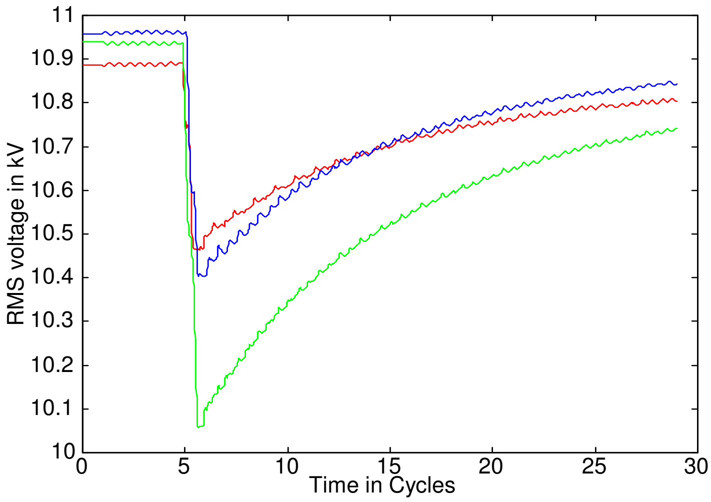



**Figure 2.4:** Voltage dip due to transformer energising [12]

#### 2.2.3.3 Power System Faults

Voltage dips are caused by faults on the utility network or within the customer's plant. A network fault indicates either a short-circuit condition or an abnormal open-circuit condition. The nature of voltage dips can be influenced by the symmetry of a network fault. Two types of voltage dips are depicted in figure 2.5: asymmetrical dip (a) and symmetrical dip (b).

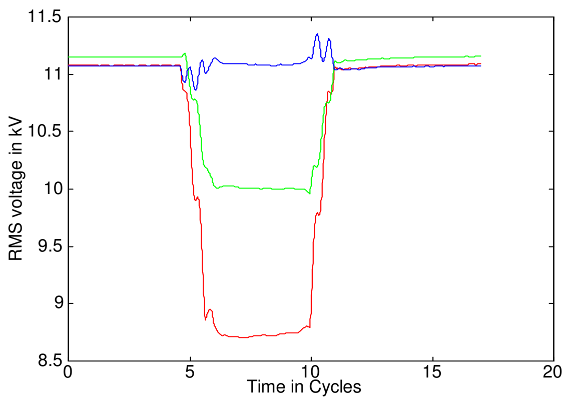



**Figure 2.5(a):** Asymmetrical dip [12]

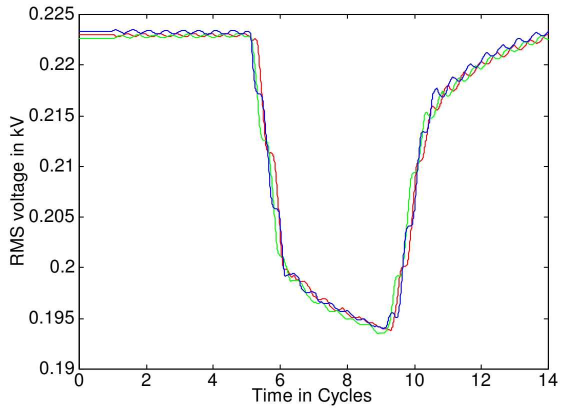



**Figure 2.5(b):** Symmetrical dip [12]

The drop in voltage is a function of the characteristics of fault current and the position of the fault in relation to the point of measurement. The duration of the dip event is a function of the characteristics of system protection and recovery time of the connected loads.

In areas of high lightning activity, dip performance of a utility network is negatively influenced by lightning-induced short-circuits. Lightning-induced faults may arise as a result of the following phenomena:

⇨ Direct lightning strike to one of the phase conductors.
⇨ Indirect lightning strike due to electromagnetic coupling from a strike in the vicinity of the overhead line. When lightning terminates on a grounded structure, an electromagnetic wave is generated, which induces a voltage on adjacent structures.
⇨ Back-flashover from the shield-wire or the steel tower, where the combined impedance of the shield wire, tower and tower footing is sufficiently high to give rise to a voltage drop that exceeds the basic insulation level of the line.

Faults due to insulator pollution occur when a conductive layer of liquid electrolyte is deposited on the insulator surface. Insulator pollution may arise due to bird pollution, marine pollution or industrial pollutants. The flashover mechanism on polluted insulators is briefly discussed in [13]. The insulator becomes coated with a layer of pollution containing soluble salts or diluted acids. In this state the dry pollution layer is non-conductive. In the presence of moisture (fog, mist or light rain), the pollution layer becomes conductive. Surface leakage currents start to flow and the resultant heating effect dries out parts of the pollution layer. The pollution layer never dries out uniformly, and in places the conducting path is interrupted by dry bands. The full phase-to-ground voltage is then established across the dry bands, resulting in air breakdown and bridging of the dry bands by arcs. If the resistance of the wet part of the pollution layer is sufficiently low, the arcs across the dry bands will be sustained. The rise in temperature due to leakage currents results in further drying out of the pollution layer and the arcs continue to extend along the insulator surface. The insulator string is ultimately bridged and a line-to-ground fault is established.

Overhead line structures provide nesting and perching opportunities for many bird species. Bird-initiated electrical faults can take one of three forms, namely, bird electrocutions, bird streamers and insulator pollution as a result of bird droppings. Vosloo [14] conducted research studies on the interaction of birds with power lines. Bird electrocution may occur when birds with large wing-spans are perched or attempt to perch on power line towers or conductors. The bird creates a short-circuit by physically bridging the airgap between live parts or the airgap between live and earthed parts. This causes lethal current to flow through the body of the bird. Large birds that roost on power lines emit watery exctreta, which may sufficiently reduce the airgap strength to cause a flashover between live conductors or between tower and live parts. Research has revealed that the bird streamer mechanism is responsible for the large number of unknown line faults on the Eskom's transmission system [14], [15]. The bird streamer mechanism was not recognised as a significant problem in the electricity industry possibly due to the fact that bird streamer flashovers occur in remote areas and leave little evidence [14].

A significant number of faults on the Eskom transmission system are fire-related faults due to the large number of veld fires during winter [14]. In addition to veld fires, the burning of sugar cane during the harvesting season in South Africa, has also contributed to the large number of fire-related transmission line faults.

The problem that utilities experience with regard to vegetation concerns principally the case of tall trees that may fall on power lines or short trees that grow within the servitude boundaries. The trees encroach on statutory clearances and thus compromise safety. In South Africa, the greatest threat presented by vegetation is the risk of fire [14].

Failures of transmission towers are generally related to extreme weather conditions with a low probability of occurring (for instance, high levels of ice loading in South Africa).

Line hardware failures are relatively uncommon [6]. Typical failures in this category include mechanical failure of jumpers, shield wires, overhead conductor and fibre-optic cables. Vandalism, ageing and interaction with fauna, all play a role in the failure of utility line hardware.

### 2.2.4 VOLTAGE DIP CHARACTERIZATION

Voltage dip characterization is the process of extracting useful information from measurements that describe the dip event without the need to retain every detail of the event. The magnitude and duration are the main characteristics of a voltage dip.

#### 2.2.4.1 The IEC Method

Voltage dips are characterized by the measurement of dip duration below the threshold and by dip magnitude. The IEC 61000-4-30 standard [16] defines voltage dip duration as the instant when the r.m.s. voltage on one phase falls below the dip threshold to the instant when all three phases are again above the dip threshold. The magnitude of the voltage dip is given by the maximum r.m.s. excursion from the declared voltage.

Technical publications on voltage dips [1], [17] have identified a number of limitations of the characterization method specified in the IEC standard [16]. A voltage drop in a single phase is characterized as equally severe as a voltage drop in all three phases, whereas the latter event is typically much more severe for industrial equipment. Methods to characterize non-rectangular dips and assess their effects on equipment operation are not specified. In reality, voltage dips are seldom one-stage rectangular events [17].

The IEC dip classification method [16] does not provide a direct link with customer equipment performance. An additional drawback with this method is that information is lost making it harder to gain insight into the fault characteristics (fault type and location).

#### 2.2.4.2 The ABC Classification Method

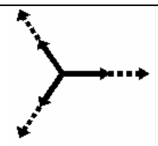
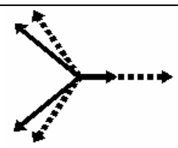
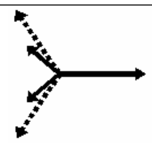
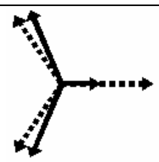
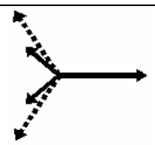
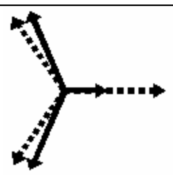
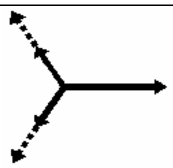
In response to the limitations of the IEC method, Bollen *et al* [1], [4], [17] proposes a more intuitive approach to the characterization of three-phase voltage dips. The ABC classification method distinguishes between seven dip types (A to G) by analysing possible types of short-circuits and the dip propagation through transformers. Table 2.1 summarizes these dip classes as a function of fault type, location and connection of measuring instruments in the a.c. grid.

**Table 2.1:** Dip classes of several faults measured at different locations [1]

| FAULT TYPE | DIP CLASS (measured between phase and neutral) | DIP CLASS (measured between phase and neutral after a Dy or Yd transformer) | DIP CLASS (measured between phases) | DIP CLASS (measured between phases after a Dy or Yd transformer) |
|---|---|---|---|---|
| Three-phase | A | A | A | A |
| Single-phase | B | C | D | C |
| Phase-to-phase | C | D | C | D |
| Two-phase-to-ground | E | F | F | G |

Table 2.2 shows voltage phasors for different dip classes, in which the positive-sequence, negative-sequence and zero-sequence impedances are considered to be equal. The voltage in the faulted phase or between the faulted phases is indicated by $V^*$. The complex pre-fault voltage on *phase a* is indicated by $E$. The reference phasors are denoted by the dotted lines.

**Table 2.2:** The ABC classification method [1]

| Dip Type | Voltages | Phasors |
|---|---|---|
| **A** | $U_a = V^*$<br>$U_b = -\frac{1}{2}V^* - \frac{1}{2}jV^*\sqrt{3}$<br>$U_c = -\frac{1}{2}V^* + \frac{1}{2}jV^*\sqrt{3}$ |  |
| **B** | $U_a = V^*$<br>$U_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$<br>$U_c = -\frac{1}{2}E + \frac{1}{2}jE\sqrt{3}$ |  |
| **C** | $U_a = E$<br>$U_b = -\frac{1}{2}E - \frac{1}{2}jV^*\sqrt{3}$<br>$U_c = -\frac{1}{2}E + \frac{1}{2}jV^*\sqrt{3}$ |  |
| **D** | $U_a = V^*$<br>$U_b = -\frac{1}{2}V^* - \frac{1}{2}jE\sqrt{3}$<br>$U_c = -\frac{1}{2}V^* + \frac{1}{2}jE\sqrt{3}$ |  |
| **E** | $U_a = E$<br>$U_b = -\frac{1}{2}V^* - \frac{1}{2}jV^*\sqrt{3}$<br>$U_c = -\frac{1}{2}V^* + \frac{1}{2}jV^*\sqrt{3}$ |  |
| **F** | $U_a = V^*$<br>$U_b = -\frac{1}{2}V^* - \left(\frac{1}{3}E + \frac{1}{6}V^*\right)j\sqrt{3}$<br>$U_c = -\frac{1}{2}V^* + \left(\frac{1}{3}E + \frac{1}{6}V^*\right)j\sqrt{3}$ |  |
| **G** | $U_a = \frac{2}{3}E + \frac{1}{3}V^*$<br>$U_b = -\frac{1}{2}E - \frac{1}{6}V^* - \frac{1}{2}jV^*\sqrt{3}$<br>$U_c = -\frac{1}{3}E - \frac{1}{6}V^* + \frac{1}{2}jV^*\sqrt{3}$ |  |

The ABC classification method was introduced to describe the propagation of voltage dips through transformers. This method of voltage dip classification is the oldest and the most commonly used, possibly due to its simplicity [17]. The ABC method can also be used to extract information on the fault type from recorded data. The limitation of the ABC classification is the assumption that the sequence impedances are equal. The symmetrical component classification, discussed next, overcomes this limitation.

### 2.2.4.3 The Symmetrical Component Classification

To determine the retained voltage at the point of common coupling (PCC), consider the circuit depicted in figure 2.6. The subscripts 1, 2 and 0 represent positive-sequence, negative-sequence and zero-sequence quantities, respectively. The letter U represents the retained voltage at the point of common coupling. The subscripts *f* and *s* represent fault and source quantities, respectively.

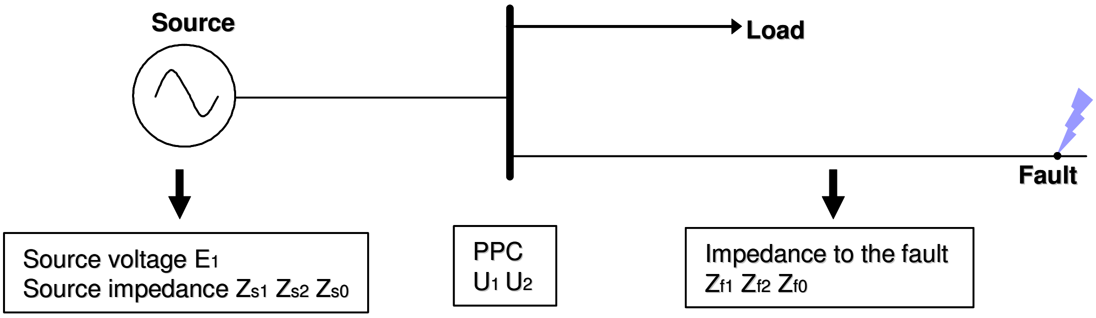
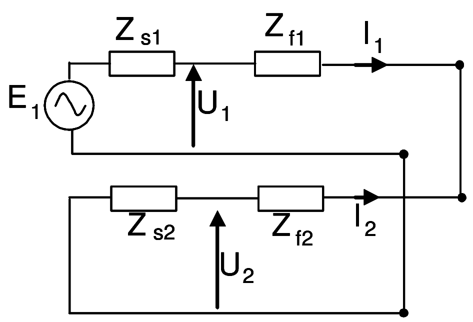



**Figure 2.6:** Voltage divider model

If the fault impedance is zero, the retained voltage is zero at the fault location and non-zero but less than the pre-fault voltage for all other locations. For a three-phase fault at the location indicated by the 'fault symbol' in figure 2.6, the positive-sequence magnitude of the retained voltage at the PCC is obtained from expression (2.1) as follows:

$$U_1 = \frac{Z_{f1}}{Z_{f1} + Z_{s1}} E_1 \qquad (2.1)$$

Equation (2.1) forms the basis for the characterization of voltage dips due to non-symmetrical faults. Consider the equivalent circuit for a phase-to-phase fault shown in figure 2.7 below. For a phase-to-phase fault, the zero-sequence currents and voltage are zero. The negative-sequence and positive-sequence networks are connected in parallel.




$I_1$ = positive sequence current (A)
$I_2$ = negative sequence current (A)
$U_1$ = positive sequence voltage (V)
$U_2$ = negative sequence voltage (V)

**Figure 2.7:** Equivalent circuit for a phase-to-phase fault

The voltage across the fault impedance is defined by the difference between $U_1$ and $U_2$ . Equation (2.2) and (2.3) were derived using the voltage divider rule.

$$U_1 = E_1 - \frac{Z_{s1}}{Z_{s1}+Z_{s2}+Z_{f1}+Z_{f2}} E_1 \quad (2.2)$$

$$U_2 = \frac{Z_{s2}}{Z_{s1}+Z_{s2}+Z_{f1}+Z_{f2}} E_1 \quad (2.3)$$

To characterize the dip event two quantities are introduced. Firstly, the characteristic voltage V is determined by calculating the difference between positive-sequence and negative-sequence voltages, given by equations (2.2) and (2.3). Secondly, the PN factor or positive-negative factor (represented by letter F), is determined by computing the sum of the sequence voltages. The characteristic voltage and the PN factor are expressed mathematically in equation (2.4) and equation (2.5), respectively.

$$V = U_1 - U_2 = \frac{Z_{f1} + Z_{f2}}{Z_{s1}+Z_{s2}+Z_{f1}+Z_{f2}} E_1 \quad (2.4)$$

$$F = U_1 + U_2 = E_1 - \frac{Z_{s1} - Z_{s2}}{Z_{s1}+Z_{s2}+Z_{f1}+Z_{f2}} E_1 \quad (2.5)$$

Equation (2.3) is of the same form as the expression for the retained voltage for a three-phase fault. The voltage dip event described above is referred to as *Ca-type* dip, implying that the main voltage drop is the *phase b* and *phase c* with characteristic voltage according to equation (2.4) and PN factor according to equation (2.5).

The symmetrical component classification distinguishes between dip events with the main voltage drop in one phase and dip events with the main voltage drop in two phases. The symmetrical dip classification method is summarized in Table 2.3. The first column gives voltage dip types. The second column gives the phases that show a severe drop in voltage, for example, a *Cb-type* dip results in severe voltage drop in *phase a* and *phase c*. The third and fourth columns show general expressions for characteristic voltages and PN factors, respectively.

**Table 2.3:** Dip types according the symmetric component method [1]

| Type | Drop in phases | Characteristic Voltage | PN Factor |
|---|---|---|---|
| Ca | bc | $V = U_1 - U_2$ | $F = U_1 + U_2$ |
| Cb | ac | $V = U_1 - a^2U_2$ | $F = U_1 + a^2U_2$ |
| Cc | ab | $V = U_1 - aU_2$ | $F = U_1 + aU_2$ |
| Da | a | $V = U_1 + U_2$ | $F = U_1 - U_2$ |
| Db | b | $V = U_1 + a^2U_2$ | $F = U_1 - a^2U_2$ |
| Dc | c | $V = U_1 + aU_2$ | $F = U_1 - aU_2$ |
| | | | |

The advantage of the symmetrical component method is that its characteristics (for example, voltage drop in each phase) can be extracted from measured data. The symmetrical component method is a systematic approach to the analysis of unbalanced voltage dips. For this reason, it is preferable above the ABC classification method.

### 2.2.4.4 The South African Dip Classification Method

Voltage dip performance in South Africa was traditionally presented in the form of a two-dimensional plot of dip magnitude and duration. In a paper presented at the First Southern African Power Quality Conference, Coney and Johnson [18] reviewed the development of power quality standards in South Africa. Voltage dips due to single-phase, two-phase and three-phase faults are differentiated on the dip chart by use of different symbols. Dips due to single-phase faults are represented by a red circle, two-phase faults (phase-to-phase or phase-to-phase-to-ground faults) by a blue square and dips due to three-phase faults by a green diamond, as shown in figure 2.8.

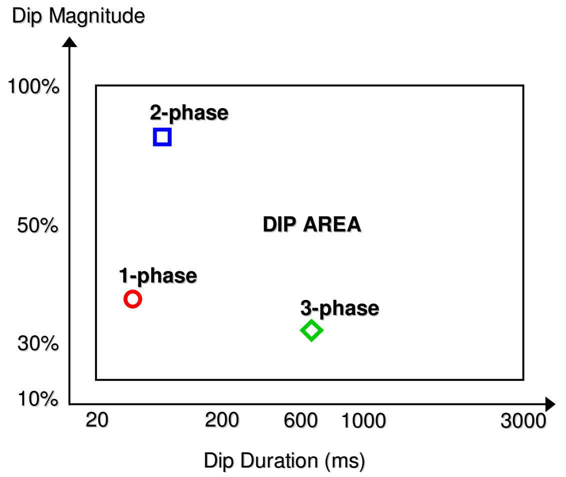



**Figure 2.8:** Two-dimensional plot of dip data [18]

In attempt to improve the reporting of voltage dip performance, the dip window was developed. The dip window is fundamentally similar to the dip chart except that the dip area is now divided into smaller areas labelled A, B, C and D as depicted in figure 2.9.

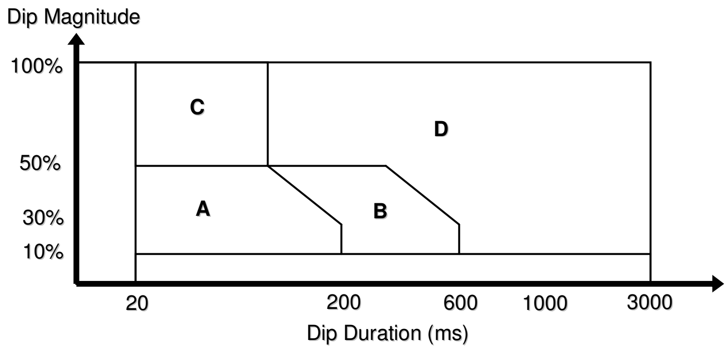



**Figure 2.9:** The ABCD voltage dip window [18]

Voltage dips in *area A* are caused by faults remote from the dip measurement point, which cause significant voltage depression at the point of fault. These faults are rapidly cleared by the correct operation of protection close to the fault.

Voltage dips in *area B* are due to low-magnitude faults (high resistance faults) cleared after a time delay by back-up protection or possibly faults at a lower voltage level where protection times are longer. Dips in *area B* may also result from faults on the customer premises.

Voltage dips in *area C* are caused by severe faults on the network close to the point of measurement. These faults are cleared rapidly by zone 1 protection.

Voltage dips in *area D* are caused by severe faults or faults at the source side of a radial line feeding the PCC or the point of observation. These faults are cleared slowly. Dip *area D* is generally thought to be representing poor or incorrect operation of the protection system [18].

The advantage of this classification is that each dip category can be related to the protection characteristics of the power system. However this method of dip classification is not without drawbacks.

The major problem with this characterization method is that for dips in classes A, B and D, the threshold is 10%. Dips of this nature occur frequently and are largely caused by operation of the customers' equipment [18]. This limitation presented some difficulty in contracting with customers.

In addition, the extent of the network over which dips are recorded is great and would result in large numbers of recorded dips.

Consequently the electricity industry proposed to supplement the ABCD dip window with an additional area, labelled E, for contracting and regulation purposes – shown in figure 2.10. The 30% threshold in *area E*, brought about two effects. Firstly, sensitivity is limited and therefore only localised dips are reported on. Secondly, the 30% dip magnitude represents a higher threshold, which when exceeded, may negatively affect customer production processes.

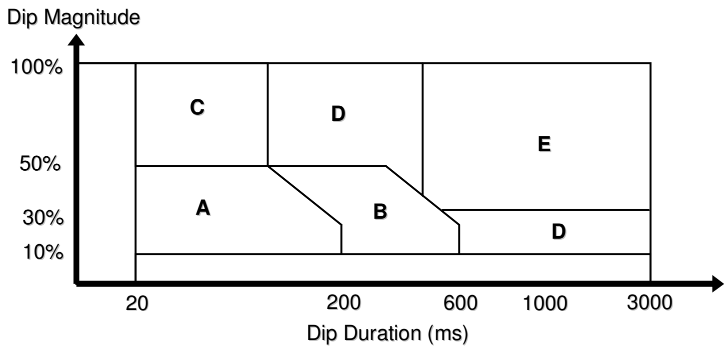



**Figure 2.10:** Supplementing the dip chart with an additional *E* class [18]

In the process of formulating power quality standards, it became clear that the ABCD characterization philosophy was inadequate. In 1996, the power quality standard [8] was introduced for application in the South African power quality context.

The classification of voltage dips, according to [8], is based on a combination of network protection characteristics and customer equipment sensitivity. The standard defines a voltage dip window with rectangular areas named S, T, X, Y and Z. The voltage dip window is shown in figure 2.11.

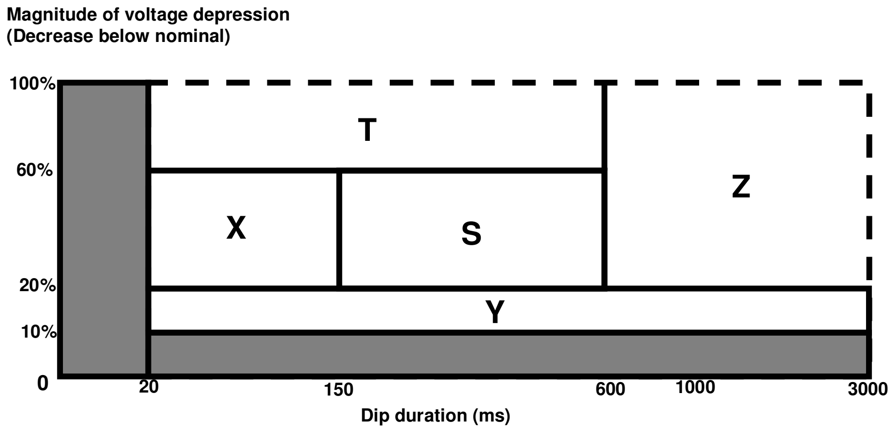



**Figure 2.11:** Voltage dip window according to NRS 048-2:1996 [8]

The vertical line at 20ms blocks off events below 1 cycle as such events are not generated in interconnected networks and have no effect on customers' equipment. The horizontal line at 20% marks the onset of possible problems with variable speed drives. Customer motor control contacts drop out in the presence of dips with magnitude in the range 20% to 60% and duration of 20ms to 150ms [8].

The compatibility levels for voltage dips are given in the form of a maximum number of voltage dips per year for each voltage dip class [8]. As measured data became available, inherent shortcomings of specifying dip limits were highlighted and the standard was subsequently revised in 2003. Figure 2.12 shows the dip window according to the revised standard [10]. In figure 2.12, U is the retained voltage at the PCC or point of measurement. ΔU is the change in voltage expressed as a proportion of declared voltage. Declared voltage is defined in [10] as the voltage officially communicated by the utility to its customers (declared) as the voltage at the point of supply.

<table>
<tr><th rowspan="2">Range of Dip Depth<br>ΔU<br>(expressed as a % of declared voltage)</th><th rowspan="2">Range of Dip Depth<br>U<br>(expressed as a % of declared voltage)</th><th colspan="3">Duration<br>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 < ΔU ≤ 15</td><td>90 > U ≥ 85</td><td rowspan="3"></td><td rowspan="2">Y</td><td></td></tr>
<tr><td>15 < ΔU ≤ 20</td><td>85 > U ≥ 80</td><td rowspan="2">Z1</td></tr>
<tr><td>20 < ΔU ≤ 30</td><td>80 > U ≥ 70</td><td rowspan="3">S</td></tr>
<tr><td>30 < ΔU ≤ 40</td><td>70 > U ≥ 60</td><td>X1</td><td rowspan="3">Z2</td></tr>
<tr><td>40 < ΔU ≤ 60</td><td>60 > U ≥ 40</td><td>X2</td></tr>
<tr><td>60 < ΔU ≤ 100</td><td>40 > U ≥ 0</td><td colspan="2">T</td></tr>
</table>

**Figure 2.12:** Revised voltage dip window [10]

The shaded area in the dip chart of figure 2.12 represents minimum dip immunity requirement for customer plant. The reasoning for various dip classes is listed in Table 2.4 below.

**Table 2.4:** Basis for the definition of dip categories [10]

| Dip category | Values of duration and depth | | Basis for definition |
|---|---|---|---|
| **Y** | Duration | > 20 ms to 3 s | Dip definition (20 ms to 3 s) |
| | 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 1 clearance (no pilot wire) |
| | Depth | 30 % to 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 1 clearance (no pilot wire) |
| | Depth | 40 % to 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<br>Also some distribution faults |
| | Depth | 20 % to 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 % to 100 % | Plant compatibility (contactors trip > 60 %) caused by close-up faults on the licensee network |
| **Z1** | Duration | > 600 ms to 3 s | Back-up and thermal protection clearance or long recovery times (transient voltage stability) or both |
| | Depth | 15 % to 30 % | Remote faults<br>Post-dip motor recovery without stalling |
| **Z2** | Duration | > 600 ms to 3 s | Back-up and thermal protection clearance |
| | Depth | 30 % to 100 % | Closer faults<br>Potential motor stalling |

### 2.2.5 EFFECTS OF VOLTAGE DIPS

Electrical equipment operates best when the r.m.s. voltage is constant and equal to nominal voltage. For each piece of industrial equipment, it is possible to determine how long it will continue to operate in the presence of a voltage depression or an interruption. Voltage dips can have the following effects on customer equipment:

⇨ Tripping of computers and process-control equipment as a result of operation of undervoltage protection.

⇨ Motor contactors can drop out due to lack of voltage to the magnetic coils that keep the contactors connected.

⇨ Variable speed drives can trip due to operation of undervoltage protection and overcurrent protection.
⇨ Stalling of directly-fed motors.
⇨ Partial or complete extinguishing of lamps.

Voltage dip performance is not a standard specification on industrial equipment [2]. Consequently, customers are largely unaware of the potential dip sensitivity problems when purchasing such equipment. It follows that equipment testing is probably the most efficient way to assess equipment sensitivity to voltage dips. The end result of voltage dip testing of equipment is a voltage-time curve called voltage tolerance curve for that specific type of equipment. A voltage tolerance curve describes the sensitivity of equipment to changes (reduction) in supply voltage.

Different categories of equipment and even different brands of equipment within a category may have significantly different sensitivities to voltage dips [5]. This makes it difficult to develop a single standard that defines the sensitivity of industrial process equipment. The effects of dips on common industrial equipment are discussed next.

#### 2.2.5.1 Computers and Process Control Equipment

The power supply of a computer normally consists of a diode rectifier along with a voltage regulator [2]. A simplified configuration of a power supply to a computer is shown in figure 2.13.

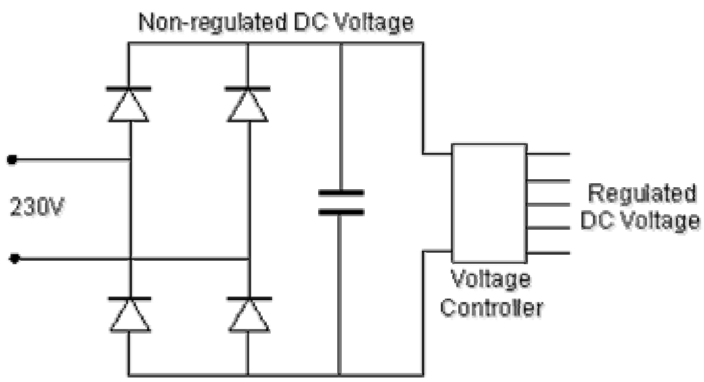



**Figure 2.13:** Computer power supply [2]

The capacitor connected to the non-regulated d.c. bus reduces the voltage ripple at the input of the voltage regulator. The voltage regulator converts the non-regulated d.c. voltage of a few hundred volts into a regulated d.c. voltage suitable for electronic components.

If the input a.c. voltage drops, the voltage on the d.c. side of the rectifier drops. The voltage controller is able to keep its output voltage constant over a certain range of input voltage levels. If the voltage at the d.c. bus becomes too low, the regulated d.c. voltage will also start to drop and ultimately errors may occur in the digital circuits. Tripping of a computer during a voltage dip is attributed to the d.c. bus dropping below the minimum input voltage for which the voltage controller can operate correctly.

#### 2.2.5.2 Motor Contactors

The purpose of the contactors is to control high magnitudes of voltages and currents with small control voltages and currents to facilitate local or remote control of electrical motors and other machinery. Contactors can easily be integrated with other process circuits to perform more complex functions such as coordinated protection and process automation. A contactor typically consists of three parts, namely, the control coil, the magnetic circuit and the spring-loaded mechanical link that controls the main and the auxiliary contacts.

The supply voltage is used to set up the field in the magnetic circuit, which keeps the contacts in position via a spring action. In the event that the supply voltage fails, the contacts open preventing uncontrolled restarting of the motor when the supply is available again. This is acceptable for long interruptions where the unexpected starting of motors can be dangerous. However, contactors also drop for voltage dips, where such behaviour is not always desirable.

Djokić, Milanović and Kirschen [11] conducted comprehensive studies to analyse the behaviour of contactors during voltage dips and short interruptions. The point-on-wave of dip initiation, the phase shift during the voltage dip and deviations of pre-dip voltage supply from ideal conditions, have a profound influence on the behaviour of a.c. coil contactors [11]. The voltage tolerance curves have distinct shapes for 0˚ and 90˚ points-on-wave of dip initiation. The voltage tolerance curves for other points-on-wave lie between these two extreme cases. Typical voltage tolerance curves for the contactors tested are shown in figure 2.14.

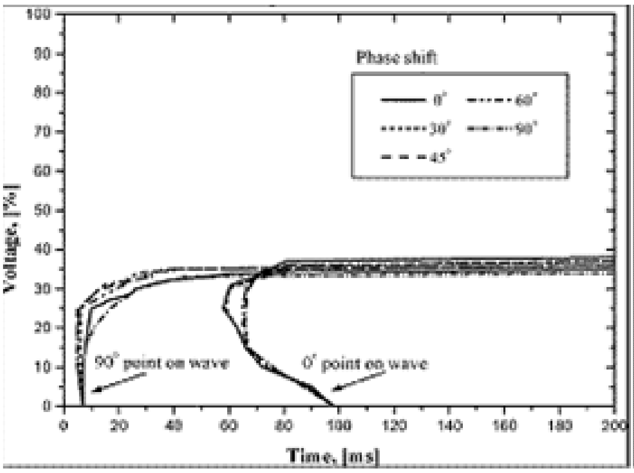



**Figure 2.14:** Typical voltage tolerance curves for an a.c. contactor [11]

A consistent remarkable phenomenon is that, for small points-on-wave at dip initiation (0˚ to 30˚), the voltage tolerance curve becomes better for more severe dips [2], [11]. Bollen [2] explains this phenomenon by stating that it is not the voltage but the current through the magnetic coil that creates the magnetic force to keep the contactor engaged. During a voltage dip, the contactor circuit, being mainly inductive, maintains currently flow for a brief period.

#### 2.2.5.3 Variable Speed a.c. Drives

Adjustable speed drives are fed through a three-phase diode rectifier or through a three-phase controlled rectifier. Figure 2.15 shows one of many configurations of variable speed drives.

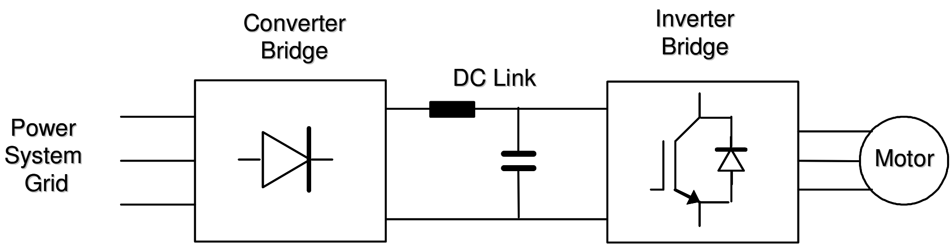



**Figure 2.15:** An example of variable speed drive configuration [2]

The d.c. voltage is inverted to an a.c. voltage of variable frequency and magnitude. Tripping of variable speed drives can occur due several phenomena:

- ⇨ The drive control circuitry detects abnormal operating conditions and trips the drive to prevent malfunctioning of power electronic components.
- ⇨ The drop in d.c. bus voltage can cause malfunctioning of the drive control circuitry.

⇨ The increased a.c. currents during the voltage dip causes an overcurrent trip or blowing of fuses protecting power electronic devices.

#### 2.2.5.4 Variable Speed d.c. Drives

Variable speed d.c. drives typically consist of a three-phase controlled rectifier powering the armature winding and a single-phase controlled or non-controlled rectifier for the field winding. The most sensitive part of the d.c. drive is the three-phase rectifier [2]. A typical configuration of a d.c. drive is presented in figure 2.16.

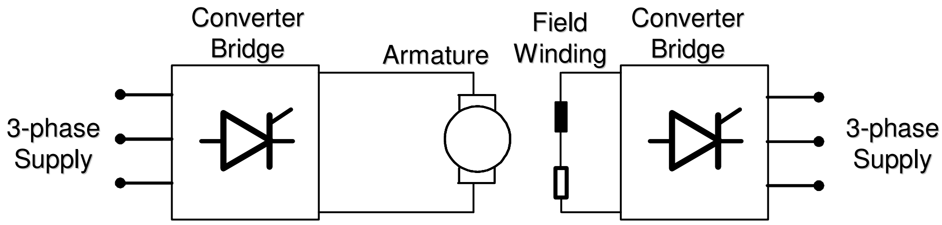



**Figure 2.16:** d.c. Drive with separately excited armature and field windings [2]

A voltage drop on the a.c. supply leads to a direct drop in armature voltage, which, in turn, leads to a decay in armature current. In the event of an unbalanced dip on the a.c. supply, the drops on the armature voltage and the field voltage are not the same [2]. This situation is undesirable because d.c. drives are often used for processes in which very precise speed and positioning are required.

For d.c. drives, commutation failure is a major problem during asymmetrical dips or symmetrical dips with a significant phase-angle jump at the instant of dip commencement [2]. Commutation failure may result in d.c. current flowing through the thyristor stack and the a.c. mains.

#### 2.2.5.5 Directly-fed Induction Motors

Induction motors are largely insensitive to voltage depressions [1], [2]. However, the following phenomena may lead to process interruption in the presence of voltage dips:

⇨ Voltage dips lead to severe torque oscillations at dip commencement and at voltage recovery. The torque oscillations are more severe when the dip is associated with a phase-angle jump.

⇨ When the voltage recovers, the motor draws a high inrush current to build up the airgap field and to re-accelerate. This inrush current can cause a post-fault dip that can lead to operation of undervoltage or overcurrent protection.

- ⇨ For asymmetrical dips, the motor is subjected to both positive-sequence and negative-sequence voltages at the terminals. The negative-sequence voltages cause a torque ripple and large negative-sequence current.

#### 2.2.5.6 Directly-fed Synchronous Motors

The effects of voltage dips on synchronous motors are similar to those on induction machines, that is, overcurrents and torque oscillations [2]. In the case of large voltage disturbances (dips of large magnitude), the additional problem with synchronous motors is that they may lose synchronism with the a.c. supply voltage. When a synchronous motor loses synchronism, it has to be stopped and the load has to be removed before it can be brought back to nominal speed again.

#### 2.2.5.7 Lighting

In the presence of a voltage dip, certain types of lamps may extinguish completely and take several minutes to recover [1]. In industrial settings, where a large number of people are gathered, this can lead to dangerous situations.

### 2.2.6 SOLUTIONS TO VOLTAGE DIP PROBLEMS

Intermittent short-circuit faults are the underlying events that cause tripping of customer equipment. At the fault position the voltage drops to zero or to a value close to zero.

Figure 2.17 shows the magnitude and duration of voltage dips resulting from various power system phenomena. The origin of voltage dips is the basis on which various mitigation strategies can be investigated:

- ⇨ Voltage dips due to short-circuits in the transmission network are characterized by short durations. At transmission voltage levels (220kV to 765kV in South Africa), system improvements to limit the severity of voltage dips are often found not to be feasible. Feasible options to improve dip performance could include installation of mitigation equipment or improving equipment immunity.
- ⇨ The duration of dips due to distribution system faults is a function of the type of protection used and recovery characteristics of the connected load. For severe long-duration dips, equipment improvement becomes more difficult and system improvement easier. Reduction of fault-clearing time and alternative design configuration could be considered as possible options.

⇨ Voltage dips in remote distribution systems and dips due to motor starting are not expected to lead to equipment trips for shallow dips. Solutions for dips in this category could include both equipment improvement and system improvement.

⇨ For long-duration events, equipment improvement is no longer feasible. System improvements in combination with installation of mitigation equipment can be considered as possible solutions.

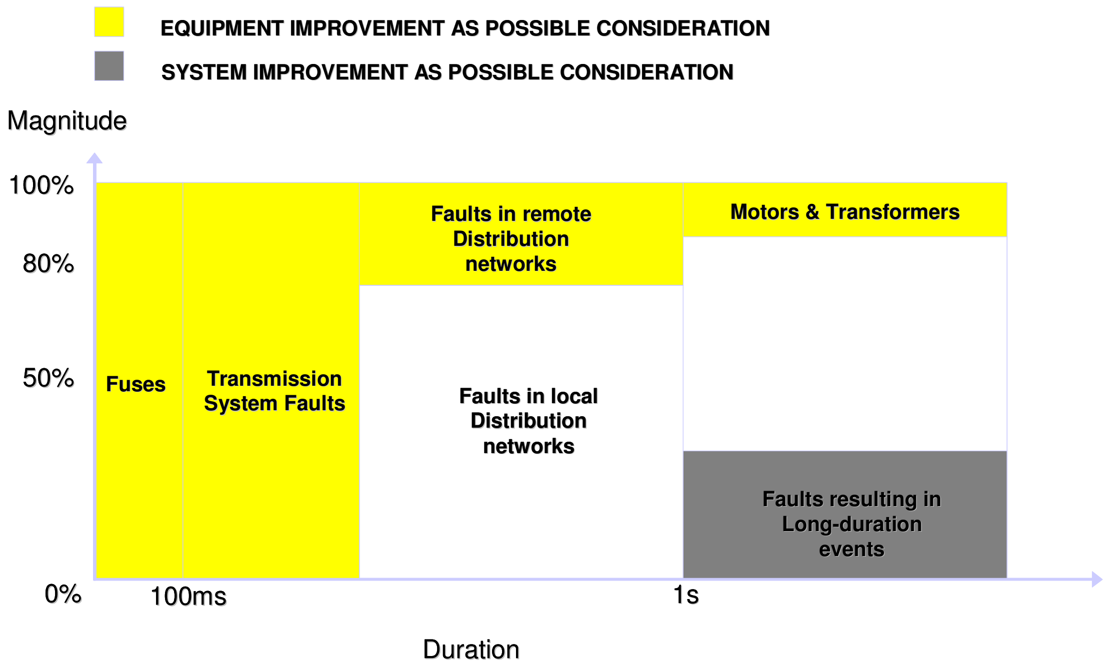



**Figure 2.17:** Origin of voltage dips [2]

A distinction can be made between various methods of voltage dip mitigation. Dip mitigation options invariably include one or more of the solutions summarized in figure 2.18. Each of these solutions will now be discussed.

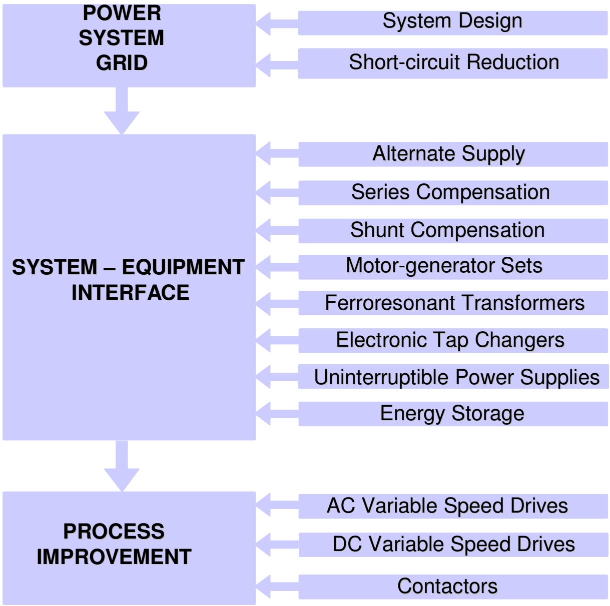



**Figure 2.18:** Various methods of dip mitigation [2]

### 2.2.6.1 Power System Grid

Dip mitigation methods in this category include reducing the frequency of short-circuits and re-configuration of the power system.

#### (a) System Design

Reconfiguration of the power supply may result in voltage dips being less severe. Some examples of voltage dip mitigation methods are:

⇨ Splitting of busbars or substations in the supply path to limit the number of feeders in the dip influence zone.

⇨ Installing current-limiting reactors at strategic points in the system to increase the electrical distance to the fault. Current-limiting reactors have the effect of limiting fault level and therefore may make the dips more severe for other customers.

⇨ Supplying the busbar with sensitive equipment from two or more substations. A voltage dip in one substation will be mitigated by the infeed from the other substations.

⇨ Installing a generator near the sensitive load. The generators will maintain the voltage during a voltage dip due to a remote fault.

⇨ Improving fault-clearing time reduces the severity of the dip. Fast fault-clearing does not reduce the number of dips but can significantly limit the dip duration. To limit the number of long-duration dips on radial systems, a recloser on the main line can be used in conjunction with expulsion fuses on the lateral feeders.

### (b) Short-circuit Reduction

Voltage dip performance can be greatly enhanced by reducing the number of short-circuit faults. A short-circuit not only leads to a voltage dip or interruption at the customer interface but may also cause damage to utility equipment. The following are examples of fault mitigation strategies:

- ⇨ Implement a strict policy of vegetation management. During heavy loading of the line, the heating of the conductors increases their sag, making contact with trees more likely.
- ⇨ Apply industry-standard maintenance practices such as reliability-centred maintenance. Maintenance generally reduces the risk of faults through proactive identification of line hardware that is prone to failure.
- ⇨ Improve lightning performance of overhead lines that have been proven to trip during lightning activity. In general, this encompasses installation of line arresters, improvement of tower footing resistance and increasing the basic insulation level of the towers.
- ⇨ Install bird-guards or other devices to discourage bird activity on parts of the towers where a bird perching on the line is likely to cause a flashover.
- ⇨ Replace insulators with hydrophobic insulators in areas where pollution is known to be a problem.
- ⇨ Develop programs to manage fire. This may include veld fires and cane fires.

### 2.2.6.2 The System–equipment Interface

The interface between the power system and the equipment is the most important place to mitigate voltage dips [1]. To compensate for loss of active power supplied by the system, most of the mitigation techniques are based on the injection of power.

### (a) Alternate Supply Source

Load transfer from the faulty supply to a healthy one is an important consideration in mitigating long-duration dips and interruptions. The transfer operation needs to take place very fast in order to effectively limit the duration of the voltage dip at the load terminals. Load transfer can take place by use of a mechanical switch or a static switch.

A static transfer switch (STS) consists of two sets of static switches. Each set is, in turn, made up of two anti-parallel thyristors per phase as depicted in figure 2.19. When the disturbance is detected on the primary source, the firing of switching unit 1 is disabled and the firing of switching unit 2 enabled. The resultant effect is that the load current commutates to the alternate supply within half a cycle of detecting the disturbance.

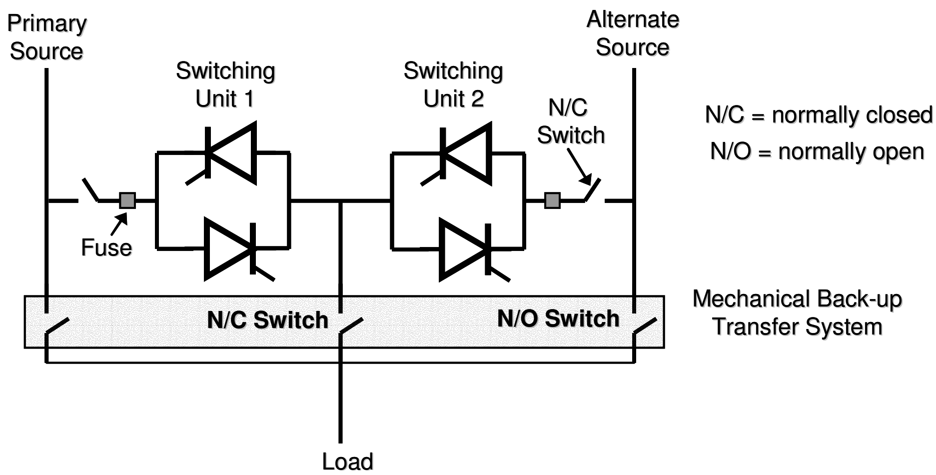



**Figure 2.19:** Commonly used transfer switch topology [2]

This solution is inexpensive for installations where the secondary source of supply is already available. Therefore the application of static transfer switches is particularly attractive for installations which still use a mechanical transfer system. The STS is not effective in mitigating against voltage dips originating from the transmission system since these would also affect the alternate supply source.

### (b) Series Compensation

A static series compensator is a voltage source converter (VSC) connected in series to the distribution feeder. The output voltage of the series compensator adds to the supply voltage to obtain the desired voltage. One of the most widely used series compensation devices is the dynamic voltage restorer [1]. A typical configuration for a dynamic voltage restorer (DVR) is depicted in figure 2.20.

The DVR monitors each phase of the incoming voltage. A converter transformer is used to connect the output of the voltage source converter to the system. In case of a dip, the device determines the change in voltage supply and calculates the required voltage correction to restore the input voltage to its rated level and waveshape. The required level of voltage correction is obtained by using a pulse-width modulation switching pattern.

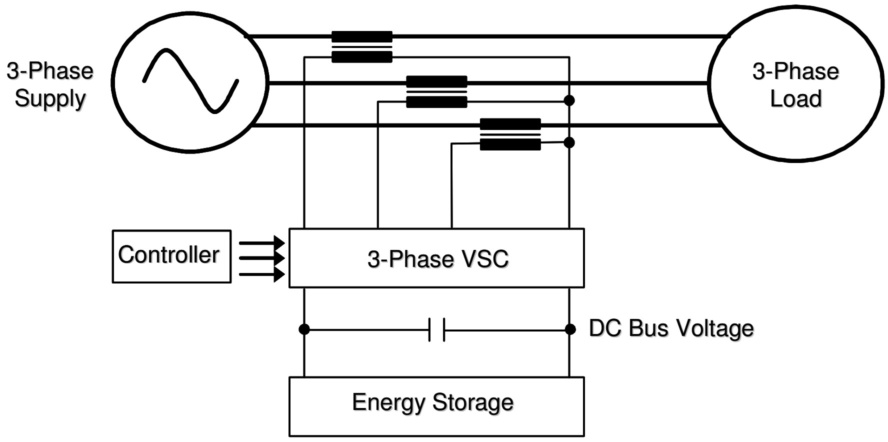



**Figure 2.20:** Dynamic voltage restorer [2]

This device is typically designed for a certain maximum dip duration and a certain maximum dip magnitude. The use of DVRs is very attractive for large sensitive industrial loads, since protection for the entire facility can be achieved through installation of a single device. However this solution is costly and cannot protect the load against interruptions.

### (c) Shunt Compensation

A static shunt compensator (static compensator or StatCom) has the same basic configuration as the series compensator, but it is connected in a shunt configuration. In case of a voltage dip, the shunt compensator injects voltage at the secondary terminals of the transformer. If this voltage is greater than the system voltage required, current is then injected. Therefore the voltage at the load terminals is a superposition of supply voltage and the additional voltage resulting from the injected current. The principle of operation of a shunt voltage compensator is illustrated in figure 2.21.

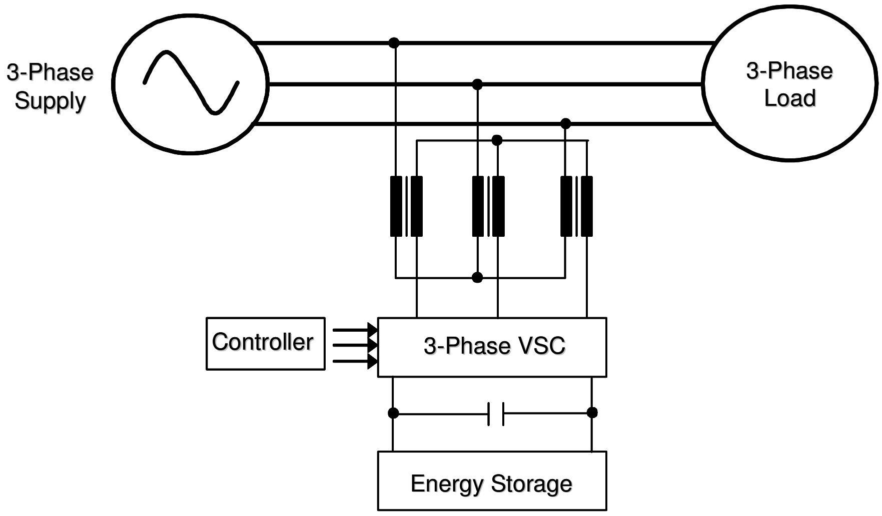



**Figure 2.21:** Shunt voltage compensator [2]

The principal limitation of a static shunt compensator is that the source impedance is greatly reduced for faults at the same voltage level close to the load. In this instance, the shunt compensator requires large currents to mitigate such voltage dips. The shunt compensator is, however, effective in mitigating voltage dips due to faults upstream of the supply transformer.

### (d) Motor-Generator Sets

The basic principle of operation of a motor-generator set is illustrated in figure 2.22. A motor and a generator are connected to a common shaft together with a flywheel. In the event of a voltage dip, the inertia of the machines and the flywheel maintains power supply to the load.

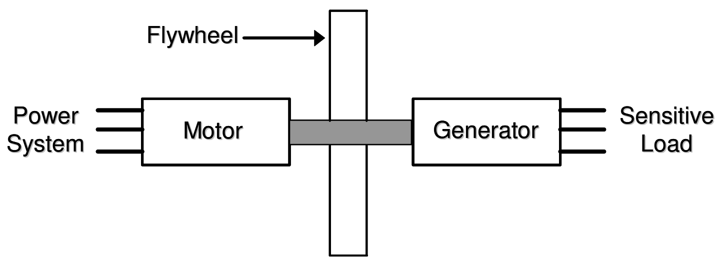



**Figure 2.22:** Principle of motor-generator set [2]

In some installations, the noise and maintenance requirements of a motor-generator set may be of concern. Under normal operating conditions, the losses in the configuration of figure 2.22 may be very high [2].

### (e) Ferroresonant Transformers

A ferroresonant transformer (also known as CVT – constant voltage transformer) is designed to maintain a constant output voltage over a wide range of input voltages [6]. The third winding of a three-winding transformer is connected to a capacitor, thus forming a resonant circuit. The energy stored in the capacitor provides ride-through capability during voltage dips. Overrating the CVT provides a significant improvement in the output voltage characteristics for a given input voltage range [6].

An important disadvantage of the ferroresonant transformer is that its output voltage is dependent on load changes. Industrial loads with high inrush currents also present a problem to CVTs due to the tuned circuit.

#### (f) Uninterruptible Power Supplies (UPS)

The uninterruptible power supply (UPS) is one of the most common devices used to mitigate voltage dips and short interruptions [2]. A UPS consists of a converter connected to an inverter. The energy storage device is usually a battery bank connected to the d.c. bus. The basic configuration of a typical UPS is shown in figure 2.23.

During normal operating conditions, input power from the a.c. grid is rectified and then inverted. The battery bank remains in standby mode and only serves to keep the d.c. voltage constant. The load is supplied via the inverter which generates a sinusoidal voltage using a PWM (pulse-width modulation) switching technique. In case the inverter fails, a static transfer switch connects the load directly to the a.c. grid.

During a voltage dip, the energy released by the battery bank maintains the voltage at the d.c. bus. The batteries can supply the load for several minutes or hours depending on battery size.

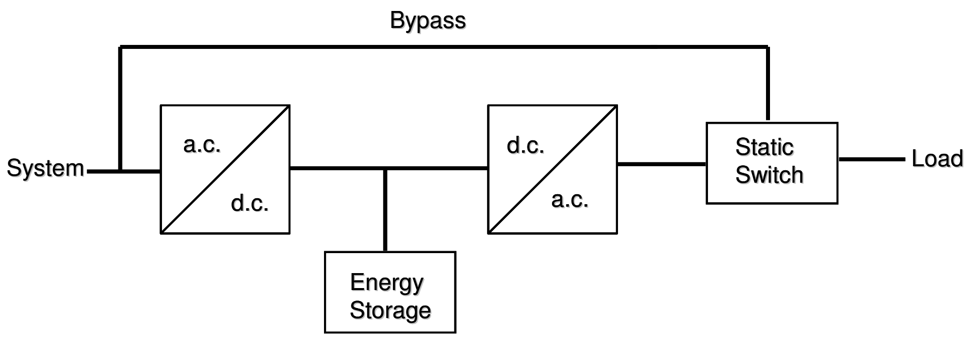



**Figure 2.23:** Typical configuration of a UPS [2]

The main advantage of a UPS is the ease of operation and low cost. A UPS is thus an attractive solution for low-power equipment such as computers. For high-power loads, the costs associated with conversion losses and battery maintenance need careful consideration.

### (g) Energy Storage Devices

Series and shunt compensators need energy storage to mitigate voltage dips. In addition to batteries and flywheels discussed above, a superconducting magnetic energy storage (SMES) device is often mentioned as another form of energy storage [2], [19].

The basic concept of the SMES is to take advantage of the high efficiency of a superconducting coil to store electrical energy in the magnetic field under normal system conditions. In the event of a voltage dip, the stored energy is converted back to electrical form and fed back into the system.

### 2.2.6.3 Process Modifications

Process modifications tend to be the cheapest solution to reduce equipment trips due to voltage dips [1], [3]. A customer often finds out about equipment immunity after the equipment has been installed. The discussion that follows focuses on possible options to improve dip immunity of process equipment.

### (a) Variable Speed a.c. Drives

Variable speed drives (VSDs) that are equipped with an automatic restart, perform a controlled stop sequence during a voltage dip. After voltage recovery, the drive starts automatically after a pre-defined period. Automatic restart can be considered as a feasible option for loads that are not speed-critical such as fans and air-conditioning. A VSD equipped with automatic ‘restart on the fly’, detects when the voltage recovers after a voltage dip and is re-accelerated without first halting the process. This option requires re-synchronisation of the drive output voltage with the voltage across the motor terminals due to residual flux in the motor.

Improving the rectifier or the inverter can also be considered as a possible solution to mitigate voltage dips. Diode rectifiers are commonly used in speed drives due to their low cost [2]. However, it is not possible to control the d.c. bus voltage with a diode rectifier. By using a rectifier based on self-commutating devices (for example, IGBTs – insulated gate bipolar transistors), complete control of the d.c. bus is possible.

One of the commonly used techniques to maintain a constant d.c. voltage at the converter output is to use a boost converter in parallel with the rectifier. Figure 2.24 shows a circuit where a boost converter is employed. In the event of a voltage dip, the boost converter increases its output voltage, providing a stable voltage at the d.c. bus.

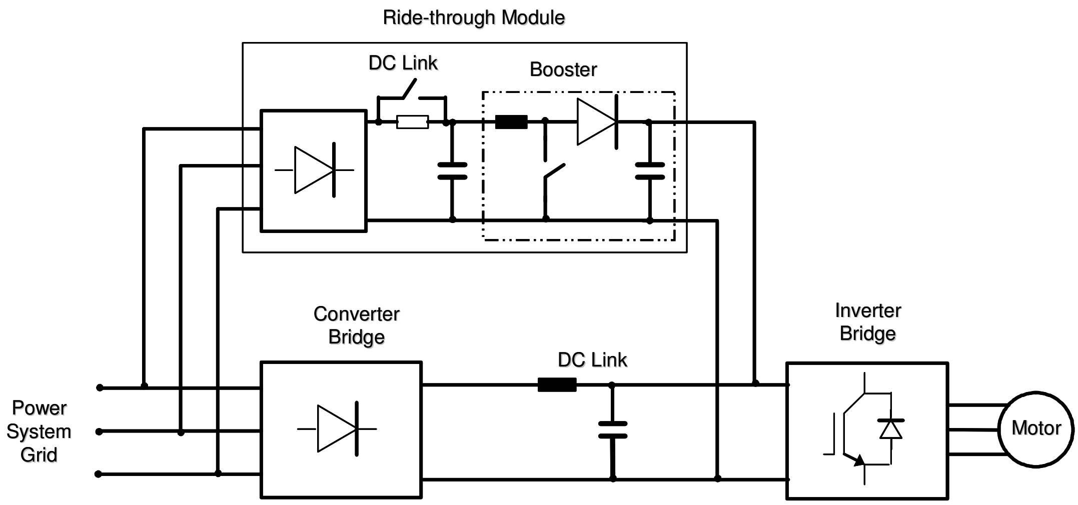



**Figure 2.24:** Parallel boost converter [2]

### (b) Variable Speed d.c. Drives

The control circuitry of a d.c. drive essentially controls the firing angle of a controlled rectifier. A limited improvement in process performance can be achieved by improving the controller. The immediate effect of a voltage dip is a drop in motor speed. The speed controller detects this condition and decreases the firing angle to compensate. Variable speed d.c. drives can be equipped with automatic ‘restart on the fly’.

Uninterruptible power supplies can be employed to increase the ride-through capability of the d.c. drives. A UPS requires synchronisation with the a.c. supply since the timing signals for controlled rectifiers are derived from the a.c. supply.

### (c) Contactors

For installations where a d.c. supply is available, replacement of a.c. contactors with d.c. contactors can be considered. The a.c. contactor coils tend to be inherently more sensitive to voltage dips [2]. The performance of d.c. contactors can be further improved by increasing the size of the d.c. bus capacitors. Another important consideration is the battery back-up for d.c. contactors.

### 2.2.7 DIP SIMULATION TECHNIQUES

Two methods are generally used for the simulation of voltage dips, namely, the method of fault positions and the method of critical distances. Before discussing the two simulation techniques, a brief discussion on factors that determine dip severity is necessary.

#### 2.2.7.1 Factors Affecting Severity of Voltage Dips

Voltage dips are influenced by several factors. Each of these influential factors is briefly discussed.

#### (a) Fault Type

A power system fault generally refers to one of two conditions: insulation failure resulting in a short-circuit condition or failure of conducting path resulting in an open-circuit condition. The former is by far the most common failure condition.

Short-circuited phases are caused by insulation failure between phase conductors or between phase conductor and earth electrode or both. The full range of possible short-circuit conditions is listed in figure 2.25 with illustrations. The three-phase fault is the only balanced or symmetrical short-circuit condition.

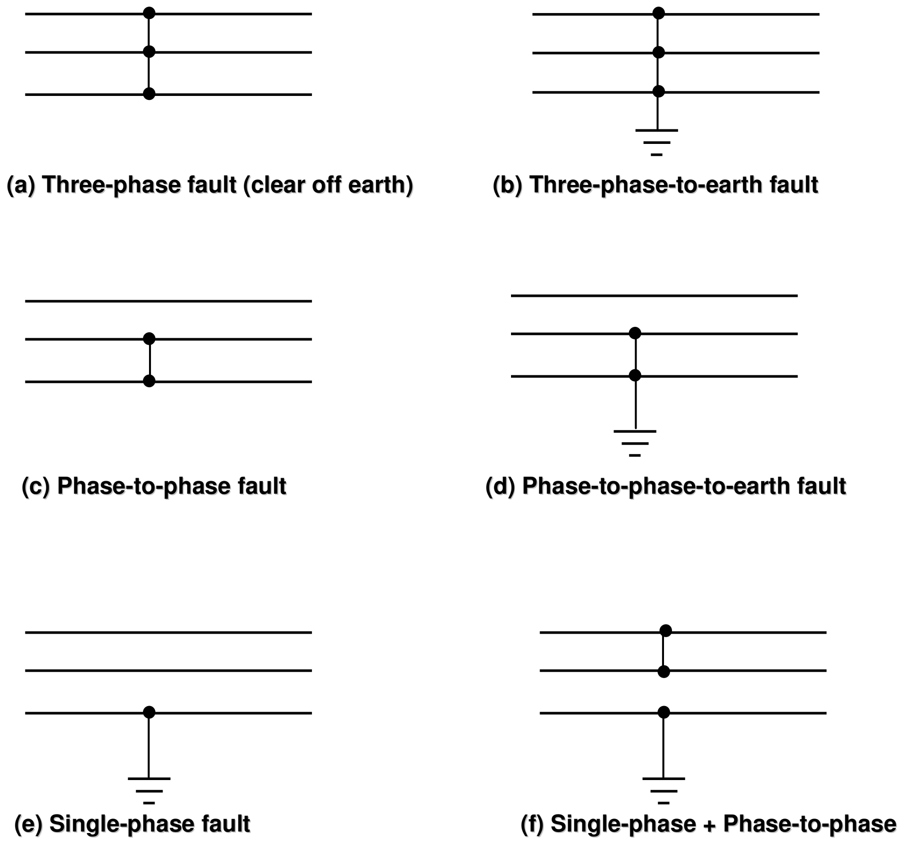



**Figure 2.25:** Short-circuit conditions

Open-circuit conditions arise when one or more phases fail to conduct. The common causes of this type of failure are broken jumpers on overhead lines and joint failures on cables. Various open-circuit conditions are listed in figure 2.26 with illustrations.

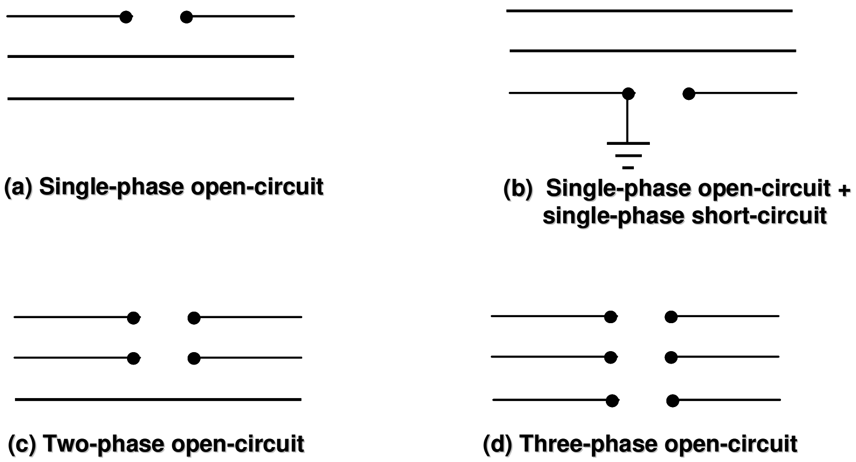



**Figure 2.26:** Open-circuit conditions

The effects of a given fault type on customer equipment may be modified considerably by the simultaneous presence of one or more other fault conditions (for example, in a combination of a short-circuit condition and an open-circuit phase condition). Another factor to take into consideration is the fault impedance. The most severe voltage dips result from faults with zero fault impedance.

### (b) Source Conditions

Source conditions relate to the amount of all connected generation including on-site generation and interconnections with other systems. Supplying a sensitive load from two or more sources reduces the severity of the voltage dip. In the event of a fault in one source, the resultant voltage dip is mitigated to a certain extent by the infeed from the other sources.

### (c) System Configuration

Power system configuration is determined by the items of plant (for example, transformers, cables, overhead lines) being in service at the instant of fault. In meshed networks, the state of normally-open points determines the impedance between the point of observation and the point of fault, which in turn, affects the magnitude of a fault-induced voltage dip. The system configuration may change during the course of a fault, with consequent changes in the profile of the resultant voltage dip (for instance, sequential tripping of circuit breakers at the two ends of a faulted transmission line).

### (d) Fault Position

Faults originating from transmission systems cause dips that can be measured tens of kilometres away, while faults on radial distribution systems may have a more localised effect. Faults that occur close to the substation busbar cause the most severe dips at equipment terminals, typically Z2-class and T-class dips according to the dip window presented in [10].

### (e) Earthing

The general purpose of the earthing system is to provide protection for plant, equipment and personnel against fault conditions. In electrical supply systems, it is therefore common practice to connect the system to ground at suitable points. The tower earthing methods of overhead power lines have a profound influence on dip performance of the system. In addition, faults which involve the flow of earth current may be affected by the presence of transformer neutral earthing impedance.

### (f) Weather Patterns

The occurrence of faults and consequent voltage dips is generally higher during severe weather conditions. Severe weather can take many forms such as wind, snow, rain or ice. Factors such as soil resistivity, vegetation growth and presence of wildlife are largely dependent on rainfall patterns. These factors have been proven to affect fault performance of overhead lines [14].

### (g) System Protection

The type of protection system used may have a significant impact on the duration and profile of the voltage dip. Unit protection schemes on transmission systems can clear the fault typically within 80ms to 150ms [6]. In applications where impedance protection schemes are employed, zone 2 clearance time is delayed by several hundreds of milliseconds.

On MV and LV systems, definite time lag (DTL) overcurrent schemes and inverse definite minimum time (IDMT) overcurrent protection schemes are extensively used. In DTL protection schemes, currents above a threshold value are detected in one or more phases and interrupted after a preset time. The trip time is the same irrespective of the magnitude of fault current. IDMT protection schemes respond faster to more severe fault currents. Both DTL and IDMT protection schemes may take several seconds to clear a fault.

### (h) Loading

Induction and synchronous motors have the largest current demand during and after a short-circuit condition [2]. After a voltage dip, electrical motors re-accelerate until pre-event speed is reached. During re-acceleration, the motor takes a larger current with low power factor, which delays voltage recovery.

### 2.2.7.2 The Method of Fault Positions

The method of fault positions is used to calculate the characteristics of voltage dips (magnitude and duration) at the monitored site for a number of faults spread throughout the supply system. The method of fault positions proceeds as follows:

- ⇨ Determine the area of the power system in which short-circuit faults will be considered.
- ⇨ Select the busbar of interest (examined site). Select a position for a short-circuit fault (busbar or point on a line). Specify short-circuit fault characteristics (for example, fault type, fault impedance).

- ⇨ Calculate dip parameters at the monitored site (magnitude and duration) for the selected fault characteristics. The fault positions are selected, first, close to the monitored site and then further away until the entire area of the power system is covered.
- ⇨ The process is then repeated for different combinations of fault positions and short-circuit fault characteristics to cover all cases.

#### 2.2.7.3 The Method of Critical Distances

The method of critical distances does not calculate the voltage dip characteristics for a given fault position, but the fault position (distance from the monitored site) for a given voltage dip magnitude and duration at the monitored site. The method of critical distances works as follows:

- ⇨ Determine the area of the power system in which short-circuit faults will be considered.
- ⇨ Select a range of dip magnitudes (for example, 0.2pu to 0.8pu in steps of 0.2pu) and a range of dip durations (for example, 200ms to 3s in steps of 200ms).
- ⇨ Select short-circuit fault characteristics for each set of selected dip parameters at the monitored site (for instance, magnitude of less than 0.2pu and duration of less than 200ms). Fault characteristics may include the following:
    - o Type of fault (single-phase, three-phase etc).
    - o Fault impedance at the fault position.
    - o Method of short-circuit fault calculation.
- ⇨ The next step is to select the monitored site and line segments in the power system where short-circuit fault positions are to be calculated, for the given parameters.
- ⇨ Repeat the calculations for different combinations of dip parameters (at the monitored site) and short-circuit characteristics.

#### 2.2.7.4 Dip Influence Zones

The voltage dip influence zone encloses the busbars and line segments where faults cause a voltage dip more severe than a given value at the monitored node.

Voltage dip performance is assessed by performing short-circuit analysis in order to determine dip magnitudes at a particular busbar as a function of short-circuit locations throughout the system. Figure 2.27 is an illustration of the dip influence zone for an industrial customer. An appropriate regulatory approach must be such that the utility limits the number of faults closer to the customer plant *(zone B)* while the customer assumes responsibility for faults further away from the plant *(zone A).*

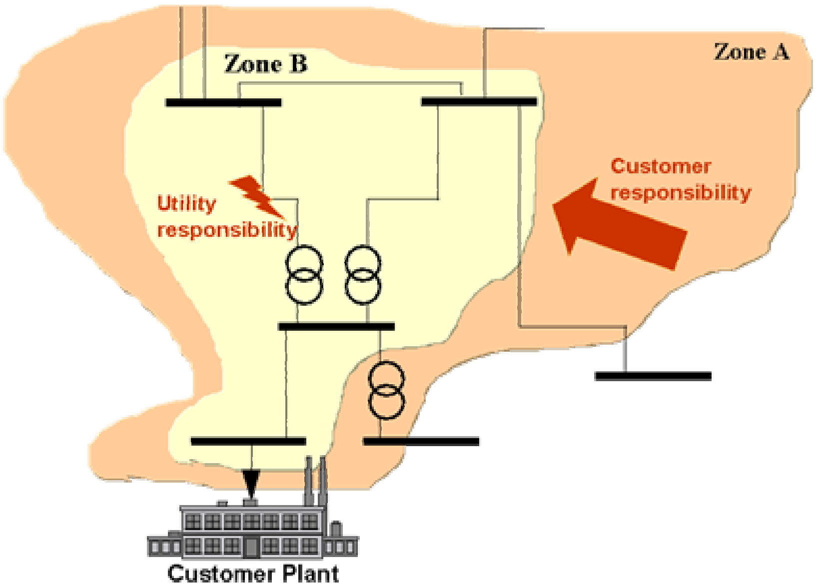



**Figure 2.27:** Voltage dip influence zones [7]

## 2.3 POWER QUALITY MANAGEMENT FRAMEWORK

Power quality management refers to a set of activities aimed at optimising the level to which the electrical product conforms to the requirements of the customer's facility. The acceptable level of power quality requires a balance between power system investment and safe operating margins of customer plant.

Since 1996, the power quality performance of South African utilities has been regulated through application of locally developed standards [8], [10], [20]. The minimum requirements specified in [8] are intended to be applied as quality measures of the electrical product at the point of supply to end customers of the electricity utility. The standard [8] provides NERSA with a means of evaluating and regulating the quality of supply provided by the utilities.

### 2.3.1 NRS 048-2 DIP REQUIREMENTS: THE INITIAL FRAMEWORK

#### 2.3.1.1 Assessment Method

NERSA requires utilities to install suitable measuring equipment at sufficient locations in their networks in order to characterize and report on voltage dip performance [20]. The measurement philosophy seeks to strike a balance between costs and adequacy of the measurement strategy.

NRS 048-2 standard [8] requires that all three phases be monitored. In the case of solidly earthed systems, the phase-to-neutral voltages are to be monitored. In the case of delta-connected systems or systems with impedance earthing, phase-to-phase voltages are to be monitored. Assessed dip values are characterized according to the dip chart shown in figure 2.12 in section 2.2.4.4.

#### 2.3.1.2 Compatibility Levels

The compatibility levels for voltage dips are given in the form of a maximum number of voltage dips per year for each voltage dip type [8]. The voltage dip limits are given for defined network voltage ranges. Table 1.1 shows voltage dip limits to be considered as minimum compatibility standard. Table 1.1 is reproduced here as Table 2.5.

**Table 2.5:** Voltage dip limits per year for each voltage dip type [8]

| Network Voltage Range | Number of Voltage Dips per Year for each Dip Category | | | | |
|---|---|---|---|---|---|
| | S | T | X | Y | Z |
| 6.6kV to ≤ 44kV | 30 | 30 | 100 | 150 | 20 |
| 6.6kV to ≤ 44kV Rural | 69 | 54 | 215 | 314 | 49 |
| > 44kV to ≤ 132kV | 25 | 25 | 80 | 120 | 16 |
| 220kV to ≤ 765kV | 11 | 6 | 45 | 88 | 5 |

A large proportion of voltage dips less than 20ms in duration are generated in customers' plant. It is therefore not a regulatory requirement to report on Y-class dips.

The assessment method for voltage dips allows for the extreme 5% of measured values to be discounted when calculating the assessed level. These assessed values are to be compared with voltage dip limits listed in Table 2.5. In the vent that a customer launches a complaint that annual dip limits have been exceeded, the utility is required to demonstrate compliance with the 95% assessment criteria for its area of supply.

### 2.3.2 SOUTH AFRICAN EXPERIENCE WITH DIP MONITORING

#### 2.3.2.1 The Initial Power Quality Framework

Actual measured utility dip performance has consistently resulted in higher dip numbers than the limits imposed by the initial power quality framework [7]. The availability of monitoring instruments was poor, typically failing during lightning seasons when many of the dips would have occurred [7]. Figure 2.28 shows an example of the actual 95% statistic for X-class dip events in relation to the overall system compatibility level of 80 dip events specified in [8]. Also shown in the figure is the number of instruments and the average dip statistic.

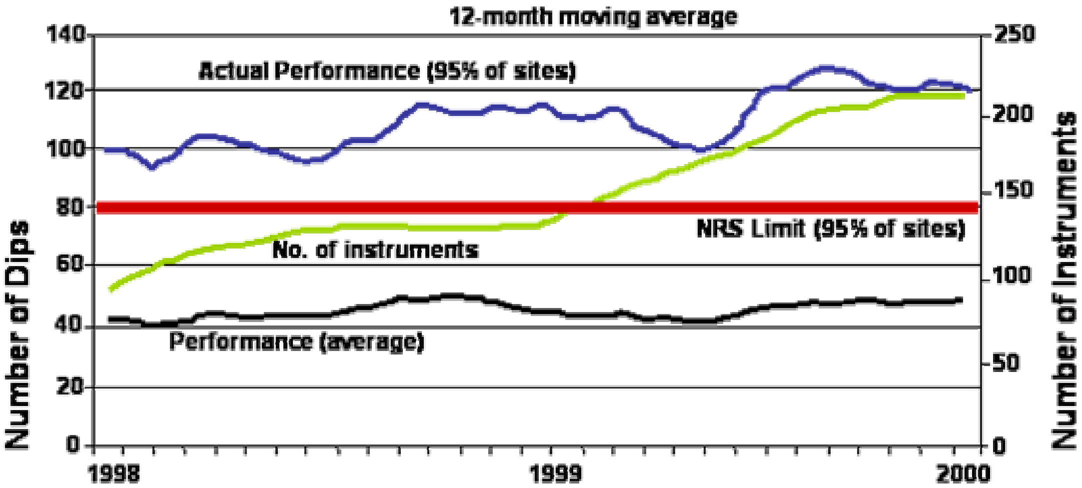



**Figure 2.28:** X-class dip performance vs. dip limits [7]

#### 2.3.2.2 Utility Perspective

The inability to meet limits combined with the impact of seasonal changes, led utilities to the conclusion that the limits specified in NRS 048-2 [8] are unachievable without significant investment in the network. On the other hand, research shows that many of the less severe X-class dips (typically less than 30% in magnitude) do not affect customers, making such investments questionable [7].

#### 2.3.2.3 Customer Perspective

Dissatisfaction exists as a result of the significant difference between actual performance at some sites in the country and the limits in [7]. There are two reasons for the dissatisfaction. Firstly, some sites exceed the dip limits, as illustrated on the right hand side of figure 2.29. Secondly, possibility exists that the utility may allow acceptable dip performance to deteriorate to a level closer to the dip limits prior to initiating corrective action, as illustrated on the left hand side of figure 2.29. At the time of implementing the standard, the dip limits were considered to be less restrictive by the customers. An expectation was present at the time that a revision of voltage dip performance would result in stricter (more restrictive) dip limits. Recent improved statistical data reveals that the compatibility levels need to allow for even more dip events per annum [7]. A survey of power quality costs also revealed that a large percentage of customers are not willing to pay for more improved power quality [7].

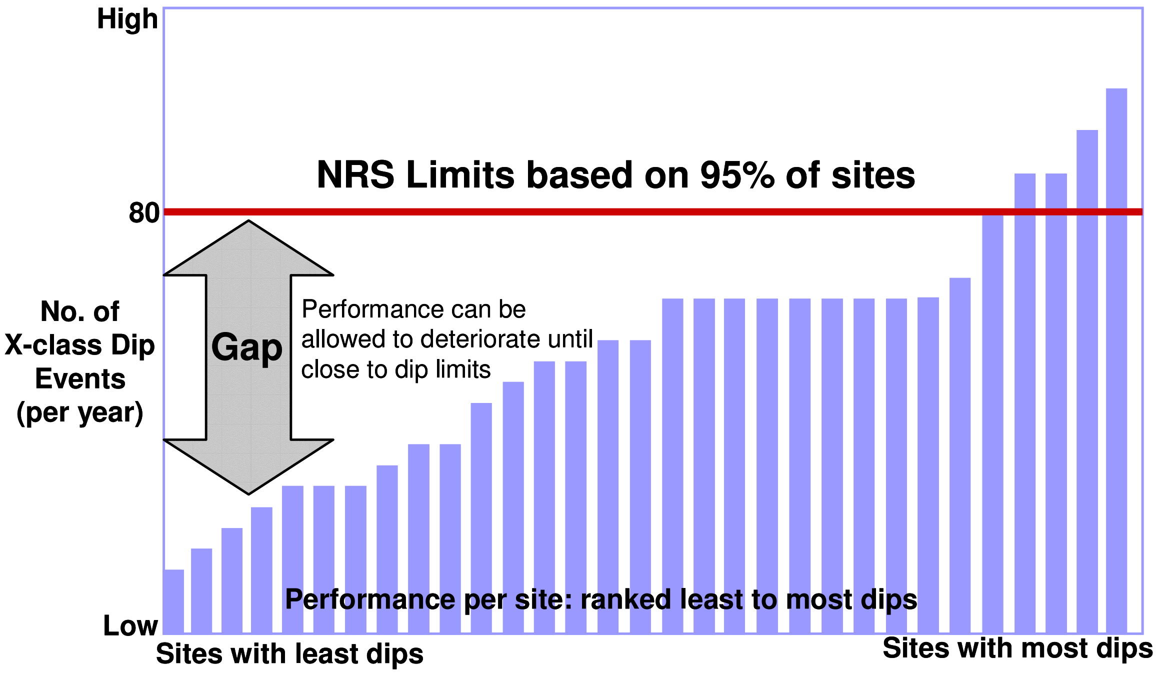



**Figure 2.29:** Illustration of potential problem with dip limits [7]

### 2.3.3 THE NEW POWER QUALITY FRAMEWORK

The revised edition (2003) of the NRS 048-2 standard [10] specifies QOS parameters more comprehensively than was the case in the first edition (1996). Each of the voltage quality parameters is described, and where appropriate, compatibility levels, limits and assessment methods are specified.

#### 2.3.3.1 Assessment Method

The assessment method is the same as in the first edition of the standard, described in section 2.3.1.1. The revised power quality standard [10] requires that all three phases be monitored. For solidly earthed systems, the phase-to-neutral voltages are to be monitored. In the case of delta-connected systems or systems with impedance earthing, phase-to-phase voltages are to be monitored. The assessed dip values are characterized according to the revised dip chart shown in figure 2.12 in section 2.2.4.4.

#### 2.3.3.2 Compatibility Levels

No compliance criteria are specified for voltage dips. The revised power quality standard [10] requires utilities to develop quality management systems for the management of voltage dip performance. This research work develops such an approach.

### 2.3.4 LIMITATIONS OF THE INITIAL POWER QUALITY STANDARD

The original NRS 048-2 dip characterization method [8] was based primarily on theoretical considerations. The standard was adopted with an understanding that it will be revised after five years. Dip measurements on Eskom's networks over a five-year period have highlighted important limitations of the previous standard:

- ⇨ The voltage dip performance requirements specified in [8] were based on limited statistical information (less than 2 years) obtained from about hundred Eskom power quality instruments.
- ⇨ The availability of the monitoring instruments was poor, typically failing during the lightning seasons, when most of the dips would have occurred [7].
- ⇨ The definition of voltage dip limits has a potentially negative effect on some of the customers, as the utility may allow acceptable levels of performance to deteriorate for the sites that achieve better than acceptable performance.
- ⇨ The effects of voltage dip events on customers are dependent on network fault performance and on the sensitivity of process equipment. The definition of a global set of compatibility levels is therefore not practical.
- ⇨ Voltage dips of less than 30% to 40% in magnitude, and duration shorter than 150ms, have a high probability of occurring in South African high voltage networks. These dip events do not have a significant effect on customers' plant.
- ⇨ The previous edition of NRS 048-2 [8] was developed primarily by utilities, although the process included customer forums hosted by NERSA.

In order to manage voltage dips in line with dip limits, Eskom holds regular customer interaction forums to discuss power quality issues. In these interactions, an appreciable amount of time is dedicated to discussions on voltage dips, that is, root causes and action plans to eliminate or at least reduce the probability of re-occurrence.

The Eskom Senior Power Quality Engineer is the key stakeholder in such forums. The following information, pertinent to voltage dips, is presented to the customer:

- ⇨ Date of occurrence, dip class, maximum duration, dip depth and phases involved.
- ⇨ Root cause and circuits on the dips occurred.
- ⇨ Historical monthly dips for each customer supply point.
- ⇨ Statistical dip trends (12 months moving averages) for each customer supply point.

Figure 2.30 shows an example of a dip performance graph for a pulp and paper customer. The graph shows the number of dips (per class) plotted against the month in which the dip events occurred.

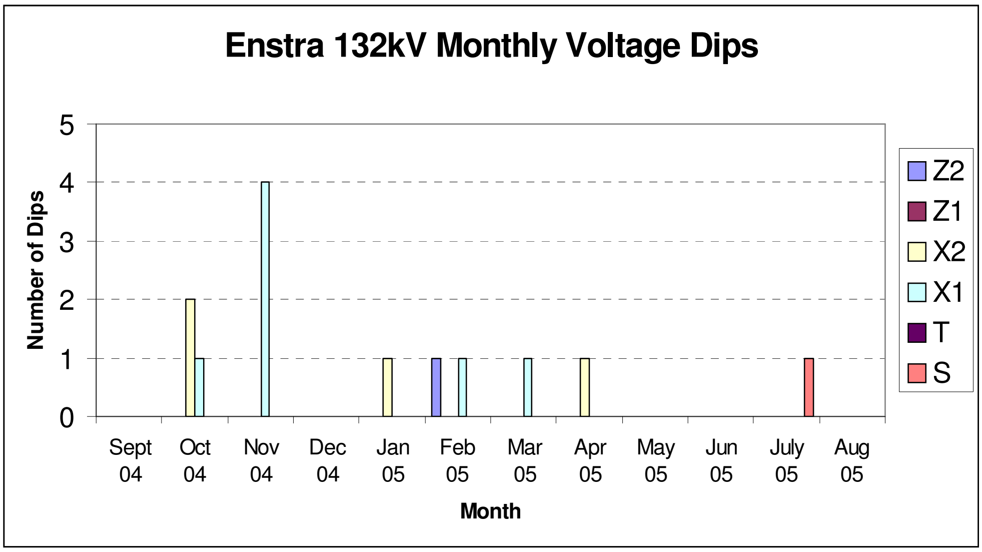



**Figure 2.30:** Example of dip performance graph for a monitored site [21]

The limitations of the current practice in communicating dip performance are highlighted below:

- ⇨ The utility's key objective is to avoid exceeding dip limits for each voltage dip class.
- ⇨ The impact of dips originating from the customer's plant is not assessed. Therefore corrective actions are often initiated on the utility side only.
- ⇨ There is limited effort on the customer side to quantify financial losses due to voltage dips. Availability of production losses due to dips would assist the utility in making investment decisions to improve dip performance.
- ⇨ The worst-performing circuits are not presented. This makes it difficult for the customer to assess critical circuits affecting the industrial plant.
- ⇨ For a given fault on a specific part of the network, the dip impact at the point of supply is not quantified.

### 2.3.5 THE NEW APPROACH

The new regulatory framework was developed in response to the difficulty of managing voltage dip performance based on limits specified in the first edition of the power quality standard [8]. The development of NERSA's power quality directive [9] was based on substantial consultations with utilities, customers, equipment suppliers, standards bodies, academics and consultants. The framework defined in the directive recognises the need for each of the parties in the design and operation of industrial and power system equipment.

The new regulatory framework recognises the dependence of voltage dip performance on geographical location, network topology and environmental influences. This research work develops an alternative approach on power quality interactions between customers and the utility, with specific reference to voltage dips. The research was initiated as a case study to investigate the feasibility of implementing a dip performance management system as opposed to the imposition of annual dip limits. The research study proposes the following:

- ⇨ Comprehensive analysis of dip data considering root causes, circuits where dips originate, dip costs and dip classes. It is expected that this exercise will show how environmental factors (for example, single-phase faults due to industrial pollutants, theft of conductor etc) influence dip performance at the selected site. The purpose of the analysis is to enable the customer and the utility to make informed decisions on initiatives to limit the impact of voltage dips.
- ⇨ Network simulations to calculate dip influence zones. The voltage dip influence zones enable the customer and the utility to quantify the severity of dips at the monitored site as a result of faults on different locations in the supply network. The simulations take into account network topology, conductor sizes, network configuration and tower top geometry.

Table 2.6 highlights key differences between the existing practice in communicating dip performance and the dip communication strategy proposed in this study. Table 2.6 was generated by the author by analysing key differences between the existing dip performance communication strategy and the proposed strategy.

**Table 2.6:** Differences between dip performance communication practices

| | **Existing dip performance communication strategy** | **Proposed dip performance communication strategy** |
|---|---|---|
| Key objective | 1. Monitor dip events to ensure dip limits are not exceeded. | 1. Collaborate with customers to ensure mutual responsibility for dip performance.<br>2. Provide detailed information to enable decisions on QOS improvement projects. |
| Points of discussion | 1. Dip data (class, time of occurrence, phases involved, duration, magnitude).<br>2. Cause of dips.<br>3. Average number of dip events per customer meterpoint (12 months moving average).<br>4. Progress on QOS improvement initiatives identified during previous interactions. | 1. Comprehensive analysis of recorded dip events:<br>i. Ownership of network where dips occurred.<br>ii. Causes of dips.<br>iii. Circuits that affect dip performance of the customer's plant most severely.<br>iv. Types of dips per contributing circuit<br>v. Financial impact of voltage dips on the customer.<br>2. Dip modelling<br>i. Identifying network area in which faults may severely affect dip performance at the examined site.<br>ii. Simulation of electrical faults and resultant dips at the monitored site.<br>iii. Calculating dip sensitivity zones for all fault types.<br>3. Progress on QOS initiatives identified during previous interactions. |
| Basis of interaction | 1. Dip limits per dip class per voltage category | 1. Joint effort to manage dip performance according to known factors (industrial pollution, conductor theft, age of plant). |
| Customer participation | 1. Receiving feedback on progress of the utility's actions to improve dip performance. | 1. Demonstrating how dip immunity levels of plant will be increased for faults on remote networks.<br>2. Tracking production downtime losses as a direct result of dips.<br>3. Sharing feedback on customer's own initiative to improve dip performance.<br>4. Receiving feedback on progress of the utility's actions to improve dip performance. |
| Difficulties | 1. Managing through dip limits and motivating for QOS improvement projects. | 1. Accuracy of dip-related downtime costs. |

## 2.4 CONCLUSION

The objective of this chapter was to review theoretical concepts relating to voltage dips. Dip duration and magnitude are the two most important parameters of a voltage dip.

Voltage dips are caused by short-duration overcurrents flowing through the power system. The principal contributions to overcurrents are motor starting, transformer energizing and power system faults. Electrical motors are three-phase balanced loads, and the associated voltage drops, during start-up, are the same in all phases. The energizing of a large transformer gives rise to voltage dips characterized by a sudden drop in voltage and a slow recovery. Power system faults are the most frequent cause of voltage dips, particularly single-phase short-circuits.

The causes of power system faults can be grouped into various categories. Lightning-induced faults may arise as a result of direct lightning strikes to one of the phase conductors. Bird-initiated faults arise due to bird electrocutions, bird streamers and insulator pollution as a result of bird droppings. Other categories of causes of faults include hardware failures, veld fires, insulator pollution, vegetation-induced faults and extreme weather conditions (ice loading).

Various dip characterization methods have been developed in literature. According to the IEC method, the dip magnitude is given by the maximum r.m.s. excursion from the declared voltage. The dip duration is defined as the instant when the r.m.s. voltage on one phase falls below the dip threshold to the instant when all three phases are again above the dip threshold. The limitation of the IEC method is that a voltage drop in a single phase is characterized as equally severe as a voltage drop in all three phases.

The ABC method distinguishes between seven types of dip events by analysing possible types of short-circuits, the dip propagation through transformers and connection of measuring instruments. The limitation of the ABC method is the assumption that the sequence impedances are equal. The symmetrical dip characterization method distinguishes between dip events with the main voltage drop in one phase and dip events with the main voltage drop in two phases. To characterize the dip event, the symmetrical method introduces two parameters: the positive-negative factor and the characteristic voltage.

The South African dip characterization method has evolved over many years from the ABCD dip window to the STXYZ dip window currently in use. The dip window is a two-dimensional plot of dip magnitude and dip duration as a function of customer equipment dip immunity levels and speed of protection systems.

Different categories of equipment may have significantly different sensitivities to voltage dips. Voltage dips cause tripping of computers and process-control equipment as a result of operation of undervoltage protection. In the presence of a dip, motor contactors can drop out, variable speed drives can trip and directly-fed induction motors can stall.

Solutions to voltage dip problems can be categorized into three: power system grid, system-equipment interface and process improvement solutions. Power system grid solutions include system configuration (splitting of busbars, on-site generation, improving fault-clearing time) and reducing the frequency of short-circuits (servitude maintenance, installing bird guards).

Most of the dip mitigation techniques used at the system-equipment interface are based on the injection of power to compensate for the loss of active power during a dip event. Motor-generator sets, uninterruptible power supplies and ferroresonant transformers are some of many devices that can be installed at the point of common coupling (PCC).

Process improvement solutions are aimed at improving the response of industrial equipment to voltage dips and dip immunity levels of equipment. Variable speed drives can be equipped with automatic restart. For installations where a d.c. supply is available, replacement of a.c. contactors with d.c. contactors can be considered.

Two methods are generally used for modelling of voltage dips, namely, the method of fault positions and the method of critical distances. The method of fault positions is used to calculate the magnitude and duration of voltage dips at the monitored site for a number of faults spread throughout the system. The method of critical distances calculates fault positions (distance from the monitored site) for a given voltage dip magnitude and duration at the monitored site. Dip influence zones are derived from a plot of fault distances (for a set of fault parameters) on the power system.

In the South African context, the initial regulatory framework defined compatibility levels for voltage dips in the form of a maximum number of voltage dips per year for each voltage dip type. South African utilities have experienced difficulty in complying with the dip limits specified by NERSA. Eskom holds regular customer interaction forums with the intention to discuss and solve dip problems and other power quality issues. The primary objective of these interactions is to demonstrate dip performance against dip limits.

The new regulatory framework was developed in response to the difficulty of managing voltage dip performance based on dip limits. This research work was initiated to investigate the feasibility of implementing a dip performance management system as opposed to the application of annual dip limits.

# CHAPTER 3:
# VOLTAGE DIP PERFORMANCE ANALYSIS

## 3.1 INTRODUCTION

A utility power quality monitoring programme generally comprises four distinct levels, namely, installation of instruments, data retrieval, data storage and reporting tools.

This chapter presents Eskom's power quality management system and introduces dip performance analysis case studies for the two industrial plants.

## 3.2 ESKOM'S POWER QUALITY MANAGEMENT PROGRAMME

Power quality measurement was introduced by NERSA as part of license conditions [20]. Eskom has implemented a comprehensive power quality management program that was initiated in the early 1990s [22]. Presently over five hundred sites are being monitored on a continuous basis [22]. The measured data is stored in a central power quality database. The power quality data management system is summarized in figure 3.1. The selection of QOS meter positions is based on the following guidelines provided in [20]. The guidelines are applicable to sites where customers are directly connected.

- ⇨ Sites are classified into categories based on voltage level (for instance, sites greater than 44kV and sites greater than 1kV but below or equal to 44kV).
- ⇨ Special categories exist for rural networks up to 22kV. The term rural network refers to excessively long overhead lines (total line length may reach 400km) supplying mostly residential and farming customers.
- ⇨ Each category is then allocated a minimum sample size of sites that must be monitored. For example, for sites greater than 44kV voltage level, QOS meters must be installed at a minimum of 10% of sites within a distribution network. Distribution networks are grouped according to the transmission source stations.
- ⇨ The utility may decide to install QOS meters as a result of special agreements with the customer or as a result of specific customer complaints.

The retrieval of QOS data can be automated or manual. QOS data is stored in a central database, which interfaces with Oracle database (Oracle is a master database that holds Eskom's asset location and equipment attribute data). Viewing tools are available for reporting and investigation purposes. For reporting purposes, QOS data is correlated with fault management systems (for example, NEPS – Network and Equipment Performance System) to ascertain root causes of events.

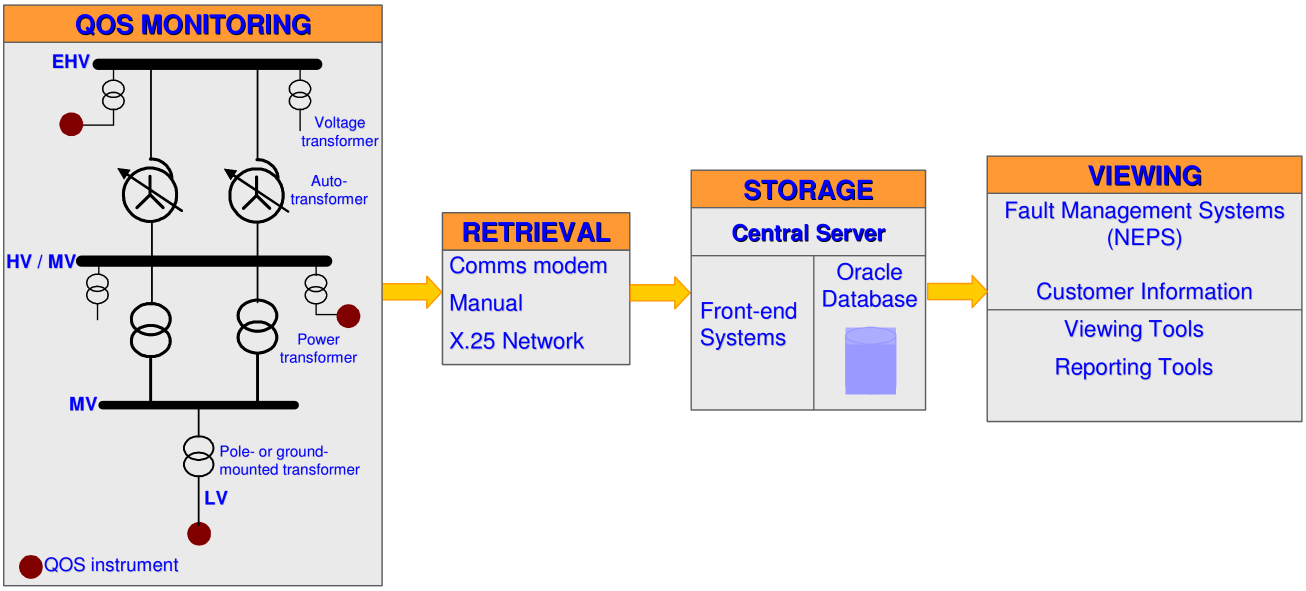



**Figure 3.1:** Architecture of Eskom's power quality management system [22]

A number of front-end systems have been developed for the reporting and viewing of quality of supply data. The Event Viewer tool is of great interest to this study.

Event Viewer allows the user to view graphs, generate reports and extract data associated with quality of supply events, as stored in the QOS database. A pre-defined set of selection criteria allows the user to view dip data for a single meterpoint or multiple meterpoints (*begin date, end date, meterpoint*). Meterpoint refers to the site where a QOS meter is installed. Event Viewer extracts dip data (from the QOS database) for the period defined by *begin date* and *end date*. The Event Viewer tool presents dip data in the form of a list. By selecting *STXYZ Graph* option, Event Viewer generates a scatter plot of dip data superimposed on the voltage dip window as illustrated in figure 3.2. Figure 3.2 was generated by the author to illustrate the viewing function provided by Event Viewer tool. The following data can be read off the graph in figure 3.2:

- 12 X1-class dips, 3 X2-class dips, zero Z1-class dips, 2 Z2-class dips, 39 Y-class dips, 2 S-class dips and 7 T-class dips.
- 38 single-phase dips, 13 phase-phase dips and 14 three-phase dips.

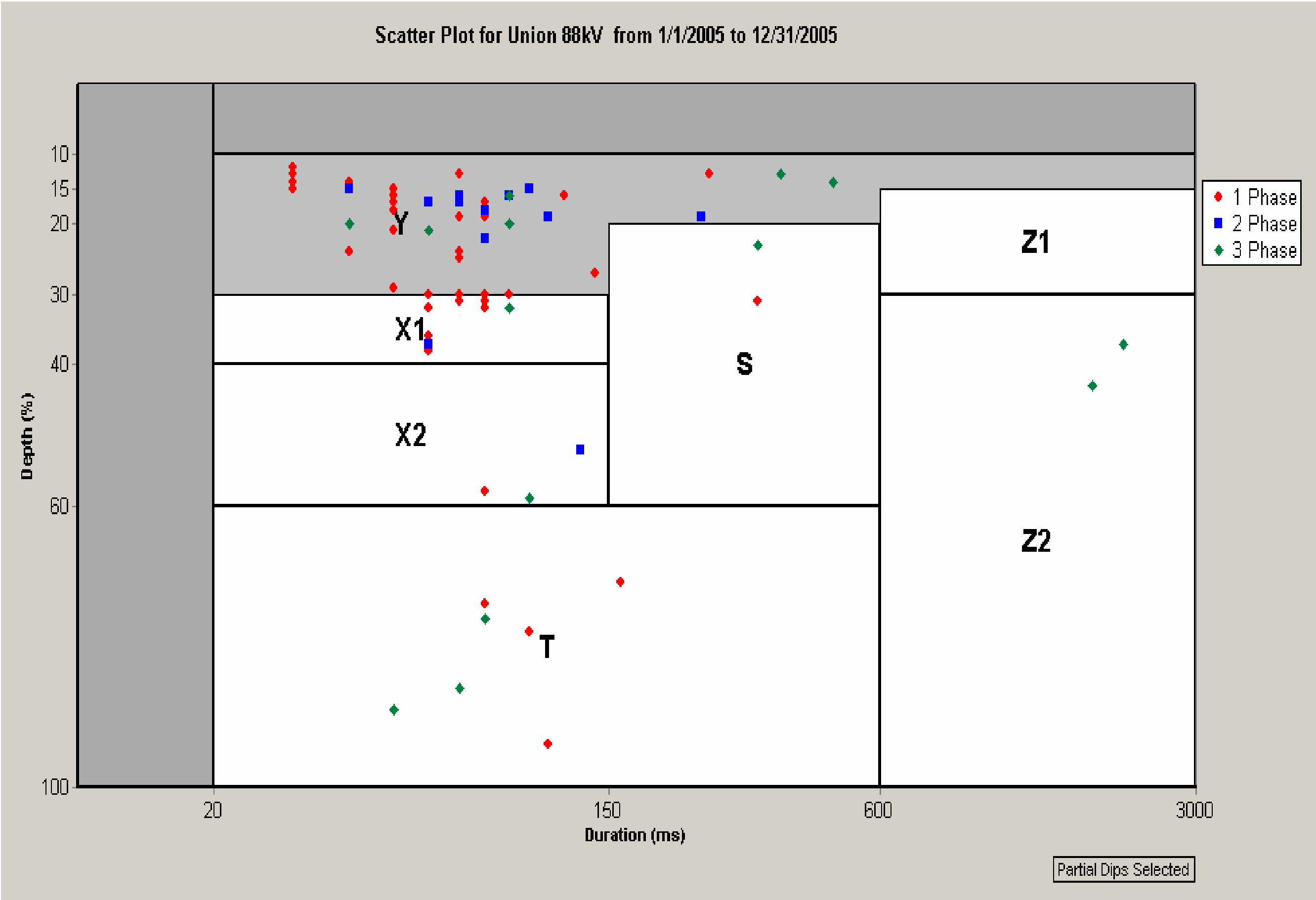



**Figure 3.2:** Event Viewer tool showing STXYZ graph

Profiles for each dip event can be viewed by selecting *Phase 1, Phase 2*, *Phase 3* or *All Phases* tabs in the *Dip Profiles* menu (available in Event Viewer). Figure 3.3 is an example of a dip profile with *All Phases* tab selected. Figure 3.3 was generated by the author to illustrate the viewing of dip data using Event Viewer.

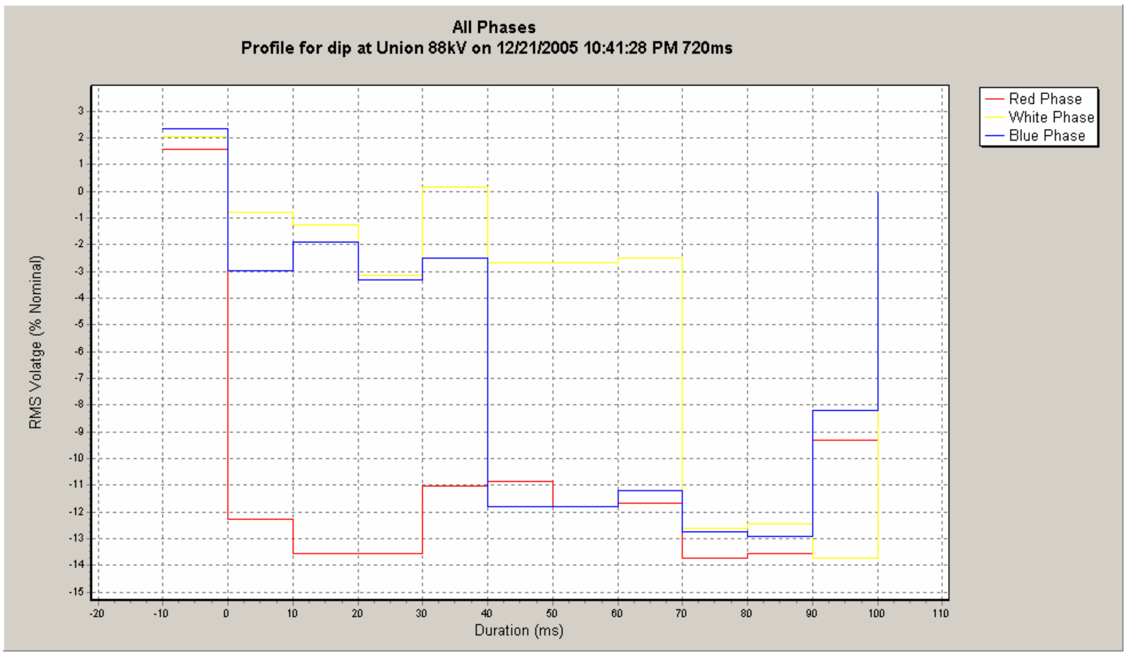



**Figure 3.3:** Profile for a voltage dip

## 3.3 STEEL PLANT CASE STUDY

### 3.3.1 INTRODUCTION

Voltage dip data was extracted from Eskom's QOS database (1st January 2003 to 31st December 2005). Depending on its characteristics, a single voltage dip event may be recorded at multiple sites. Multiple recordings of a single dip event are characterized by identical time stamps at all monitored sites.

Dip events were analysed by considering the ownership of the network, causes of dips, dip classes and costs associated with dip events.

#### 3.3.1.1 Ownership of the Network

Eskom is divided into three main businesses, namely, Distribution, Transmission and Generation. The role of each business unit is explained with reference to figure 3.4 below. Distribution operates electricity networks in the voltage range 380V to 132kV. The interface between Distribution and Transmission is the transmission stations as shown in figure 3.4. Transmission is a business unit within Eskom, that operates electricity networks in the voltage range 220kV to 765kV a.c. and 533kV d.c. Generation operates all power stations owned by Eskom. In the context of this study, reference to customers encompasses electricity redistributors (municipalities), mining, industrial, residential, agricultural electricity users, who are supplied from Eskom's distribution or transmission networks.

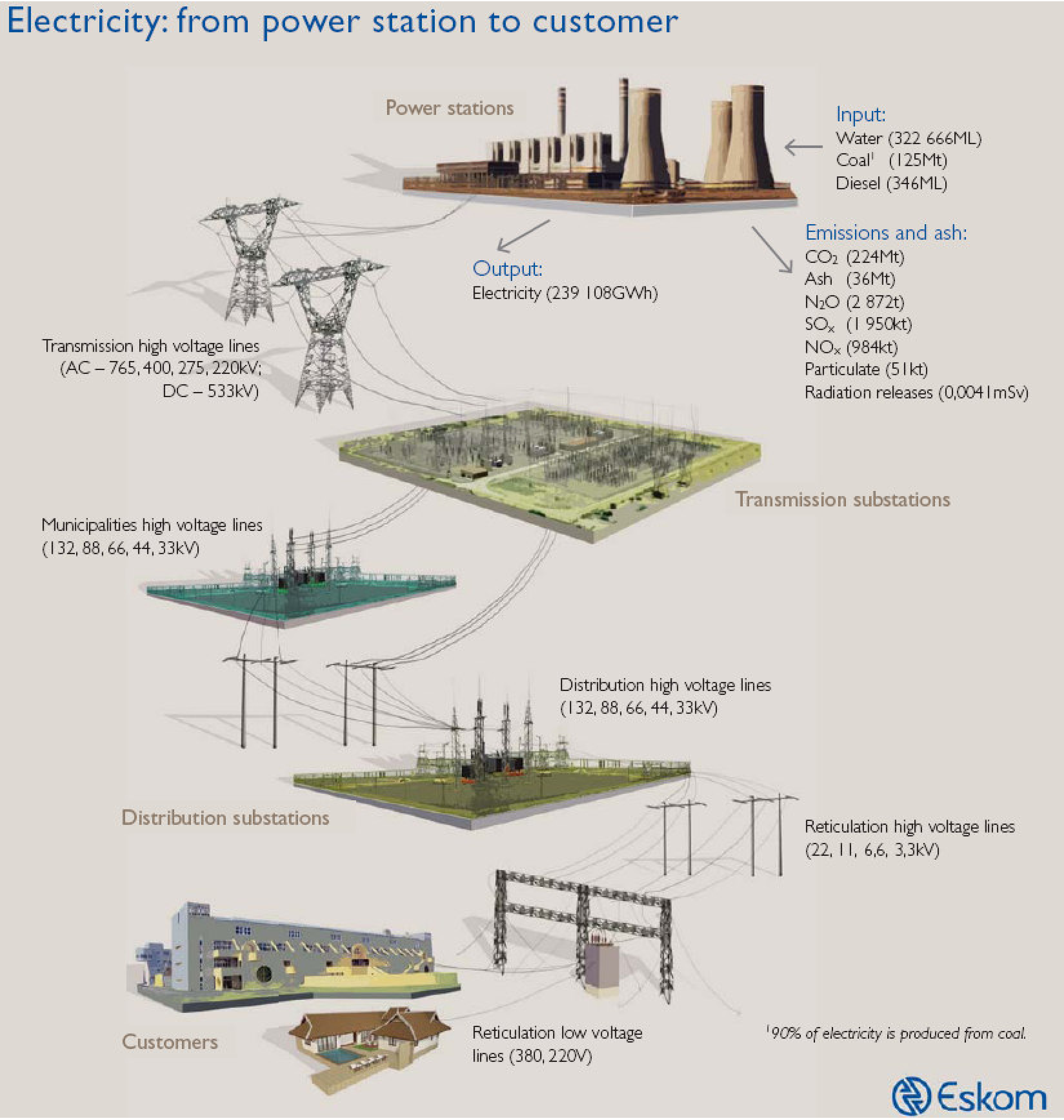



**Figure 3.4:** Eskom's electrical network from power station to customer [23]

#### 3.3.1.2 Causes of Voltage Dips

The causes of the dips are determined through a process called dip-to-trip matching. Dip-to-trip matching involves comparison of the time stamps of voltage dip events (from Event Viewer) against network events associated with circuit breaker trips. Breaker trip information is captured in two fault management systems, namely, NEPS (Network and Equipment Performance System) and TIPPS (Transmission Information Plant Performance System).

#### 3.3.1.3 Dip Classes

The severity of a voltage dip event is characterized by its magnitude and duration. It is generally accepted that customer plant can withstand dips of small magnitude (Y-class dips) since these events occur frequently on the utility network. However, severe dips (Z1-class, Z2-class and T-class) may affect operation of the plant negatively and therefore, are of particular interest to the customer and the utility.

#### 3.3.1.4 Voltage Dip Costs

Customer surveys have gradually gained acceptance as the most effective technique to evaluate the costs of voltage dips to the customer. With this technique, customers are requested to estimate their costs due to dip events of varying duration and magnitude. A disturbance such as a voltage dip can cause customer plant to malfunction or shut down after which a time-dependent restart procedure is needed. Most industrial customers track costs related to voltage dips and interruptions.

### 3.3.2 SUPPLY NETWORK FOR THE STEEL PLANT

Analysis of voltage dip performance for the steel plant is based on the network diagram shown in figure 3.5. The monitored site (steel plant) is supplied from Mill Scaw 88/6.6kV 4 x 20MVA substation, shown using a ‘red fault’ symbol. The distribution network (380V to 132kV) interfaces with transmission network at two nodes: Jupiter 275kV busbar and Eiger 275kV busbar. In figure 3.5, networks of different voltage levels are represented by different colours. Sites where QOS meters are installed, are marked by a ‘red square’ symbol. The meters are installed on the secondary side of the voltage transformers. NERSA requires utilities to install suitable measuring instruments at sufficient locations in their electrical networks to adequately characterize and report on dip performance. The guidelines for the selection of QOS meter locations are discussed in section *3.2*.

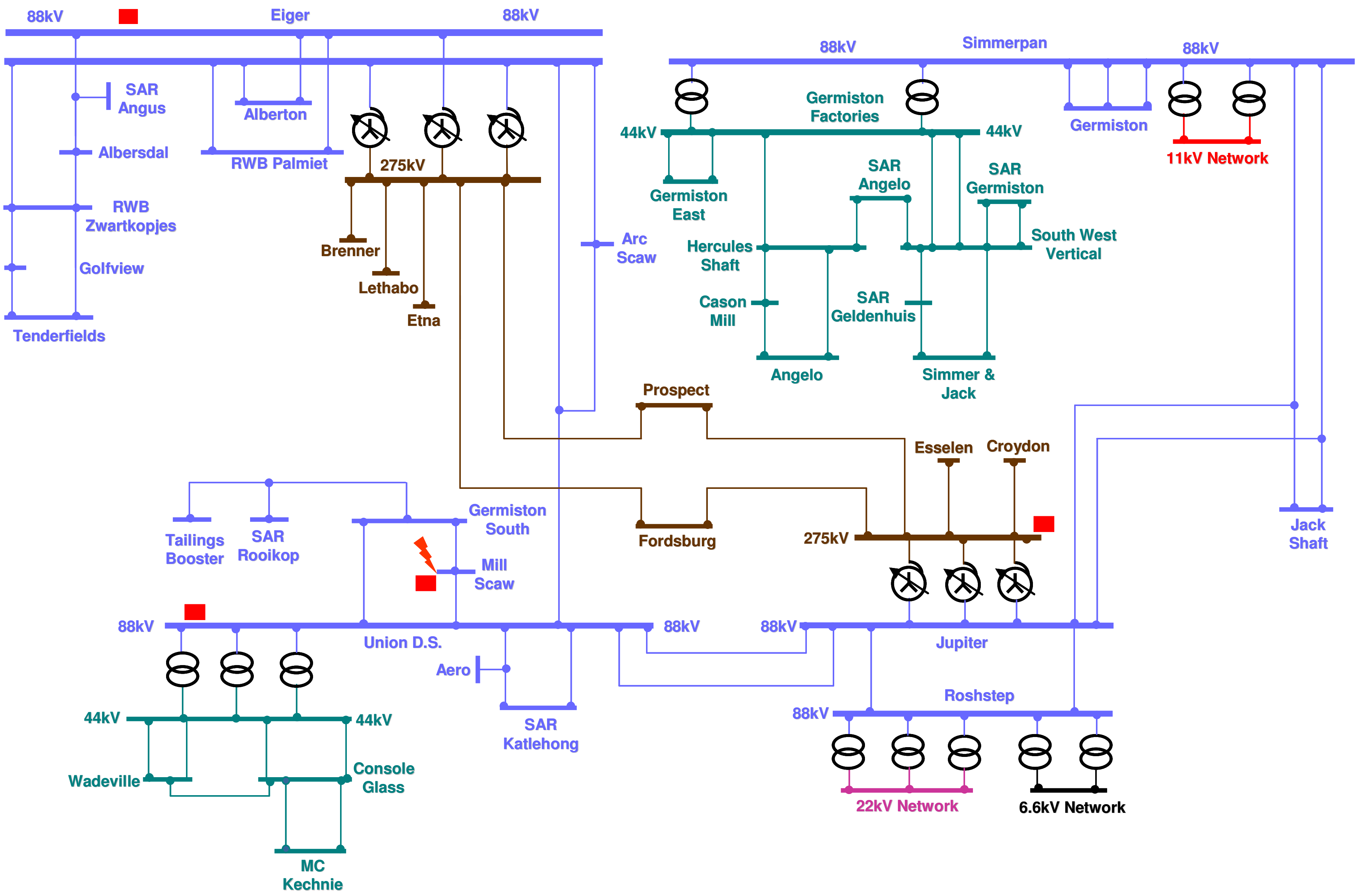



**FIGURE 3.5:** Supply network for the Steel plant

### 3.3.3 RESULTS

This section presents results on the dip performance analysis performed for the network shown in figure 3.5. Dip data for the meter locations (Mill Scaw 88kV, Jupiter 275kV, Eiger 88kV and Union 88kV) was extracted from the QOS database.

#### 3.3.3.1 Ownership of the Network

With reference to figure 3.5, faults causing dips at the monitored site (Mill Scaw) occur on the distribution network (6.6kV to 88kV) or transmission network (275kV) or at the customer's plant (not shown). It is important to compare voltage dip performance on the transmission and distribution networks since these networks are operated by different business units within Eskom. In figure 3.5, the 275kV network is the transmission network, while the rest is the distribution network. Transmission and distribution networks interface at Jupiter and Eiger stations.

A distribution of dip events according to ownership of the network is shown in figure 3.6. The vertical axis represents the number of dip events recorded. The horizontal axis represents dip types, grouped according to the owner of the electrical network where the dips occurred. Customer, distribution and transmission refer to dip events that occurred on the customer's plant, distribution networks and transmission networks, respectively. In the event that the origin of voltage dips cannot be verified accurately, the 'unknown' category is assigned to those dip events. Where there are no bins for specific dip types, it means that there are zero dip events recorded during the analysis window period.

Figure 3.6 was generated by exporting dip data from the QOS database (using Event Viewer) to Excel. From this point, the author used Excel's pivot tables to present the data graphically.

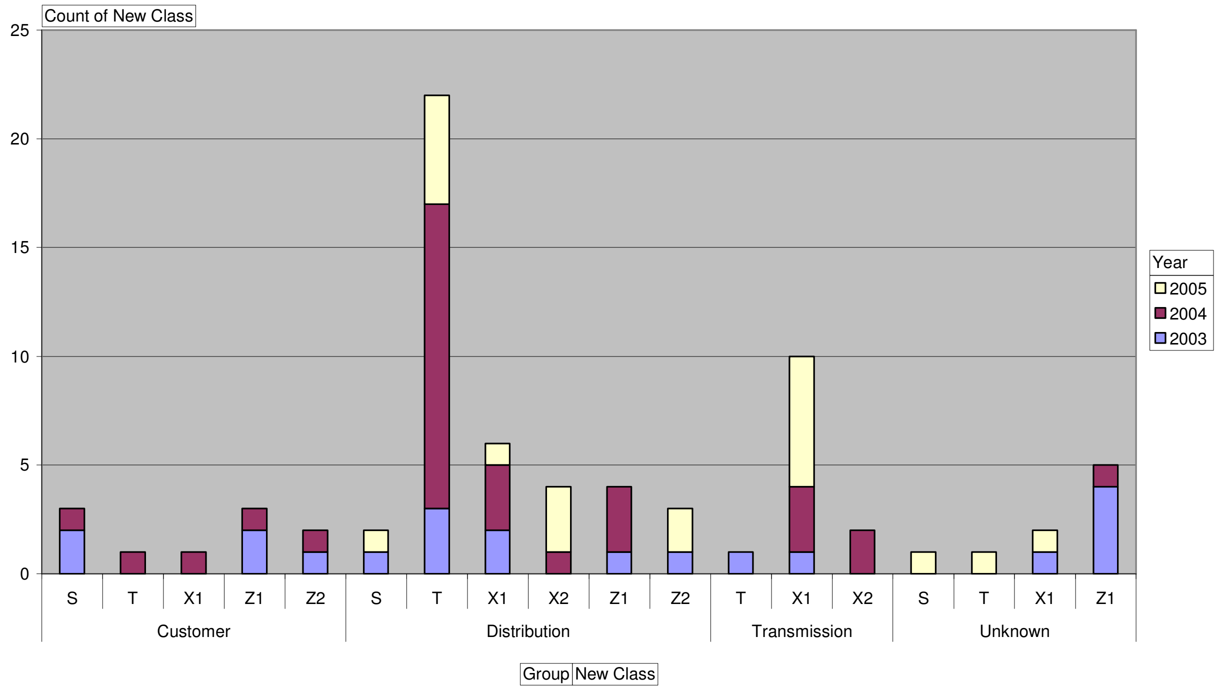



**Figure 3.6:** Distribution of dip events for the steel plant

In figure 3.6, the smallest number of long-duration dip events (T-class, Z1-class and Z2-class) is observed on the transmission networks. This observation is attributed to typical tripping times for protection systems at transmission voltages being less than 150ms. The large number of T-class dips on distribution networks can be attributed to faults clearing via back-up protection, in case of failure of the main protection systems.

### 3.3.3.2 Causes of Voltage Dips

The causes of dip events are determined through a dip-to-trip matching exercise. In this exercise, dip records from the QOS database are correlated with circuit breaker trip events extracted from NEPS. A breaker trip (within the network under investigation) is then matched to a dip event if the time stamps for the two events are the same. The causes of faults that result in voltage dips are verified by field operators who are responsible for fault-finding, operation and maintenance tasks.

Figure 3.7 presents causes of dips arranged in descending order from highest to lowest count. The vertical axis represents the number of dip events recorded. The horizontal axis represents categories of dip causes. Dips caused as a result of inclement weather conditions or lightning are grouped under storm-related category. Conductor-related category includes dips whose origin can be traced to the breaking of conductor (usually at the jumper where two conductors are joined) or vandalism resulting in the breaking of conductor. Customer-related category refers to dip events that occurred within the customer's plant. Human-related category represents dip events that are caused by incidents such as a car driving onto a tower, damage of cables while excavating for road works and other similar incidents.

The graph in figure 3.7 was generated by adding a 'cause' column (in Excel) to the dip data extracted from the QOS database and then producing a plot.

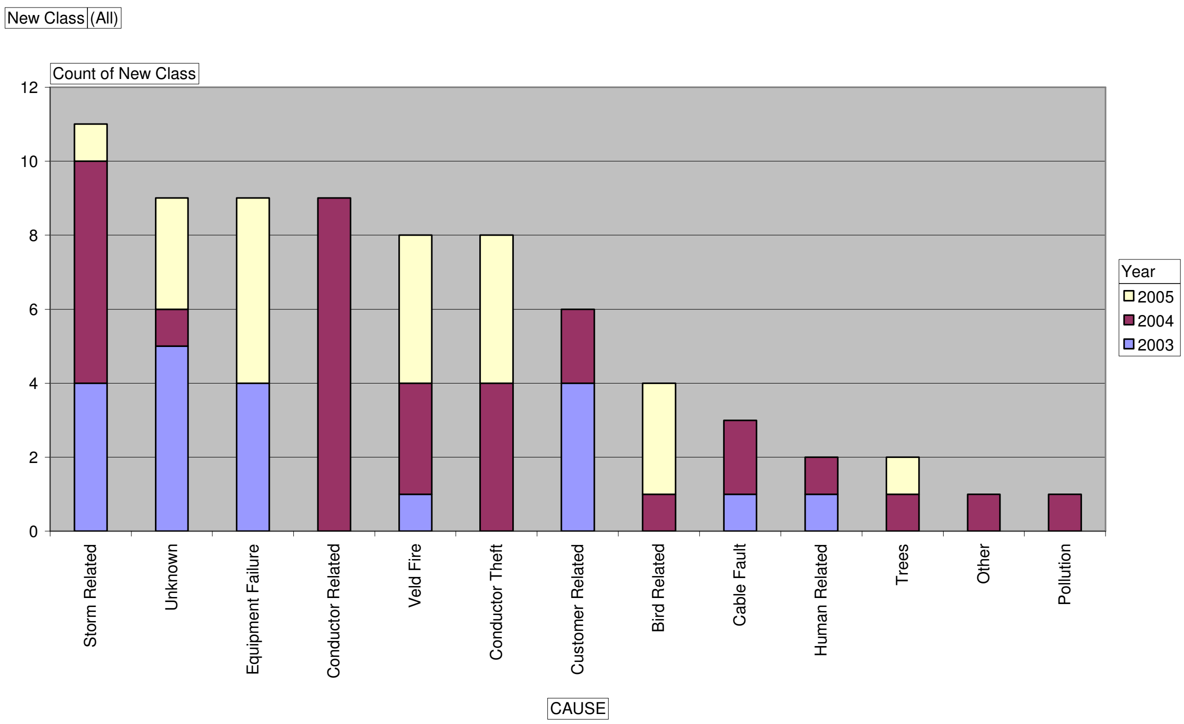



**Figure 3.7:** Causes of voltage dips for the steel plant

In figure 3.7, the first six categories contributed 73% of dip events during the period from 2003 to 2005 (73% is derived from the summation of first 6 categories divided by total dip count). Figure 3.7 enables the customer (steel plant in this instance) to request the utility to further investigate the following issues:

- ⇨ Ability of the network to withstand lightning and other forms of extreme weather conditions.
- ⇨ Reasons why network equipment is failing (could failures be related to age, vandalism etc?).
- ⇨ Actions taken by the utility to limit veld fires and theft of conductor.

The number of dip events with unknown causes is relatively large, which makes it impossible to initiate corrective action. Figure 3.7 informs the utility to review its fault management practices to reduce the number of dip causes in the ‘unknown’ category.

Figure 3.8 shows a breakdown of dip causes per circuit for various categories of dip causes. The graph was generated using Excel’s pivot table functionality. The vertical axis represents the number of dip events. The horizontal axis represents overhead lines and substation equipment where faults resulting in dips, occurred as recorded in the QOS database. With reference to figure 3.8, an 88kV line that joins Germiston South substation and Tailings Booster substation is named Germiston South/Tailings Booster 88kV HV overhead line. The bin labelled South West Vertical TRFR 2AB 44/3.3kV TRFR Bay must be interpreted as follows:

- ⇨ Two faults causing dips at the monitored site occurred at South West Vertical substation.
- ⇨ The two faults occurred on transformer 2AB bay (for example, catastrophic failure of a current transformer).

The circuits shown in figure 3.8 represent segments of the network under analysis (figure 3.5). The data presented is for the period from 2003 to 2005.

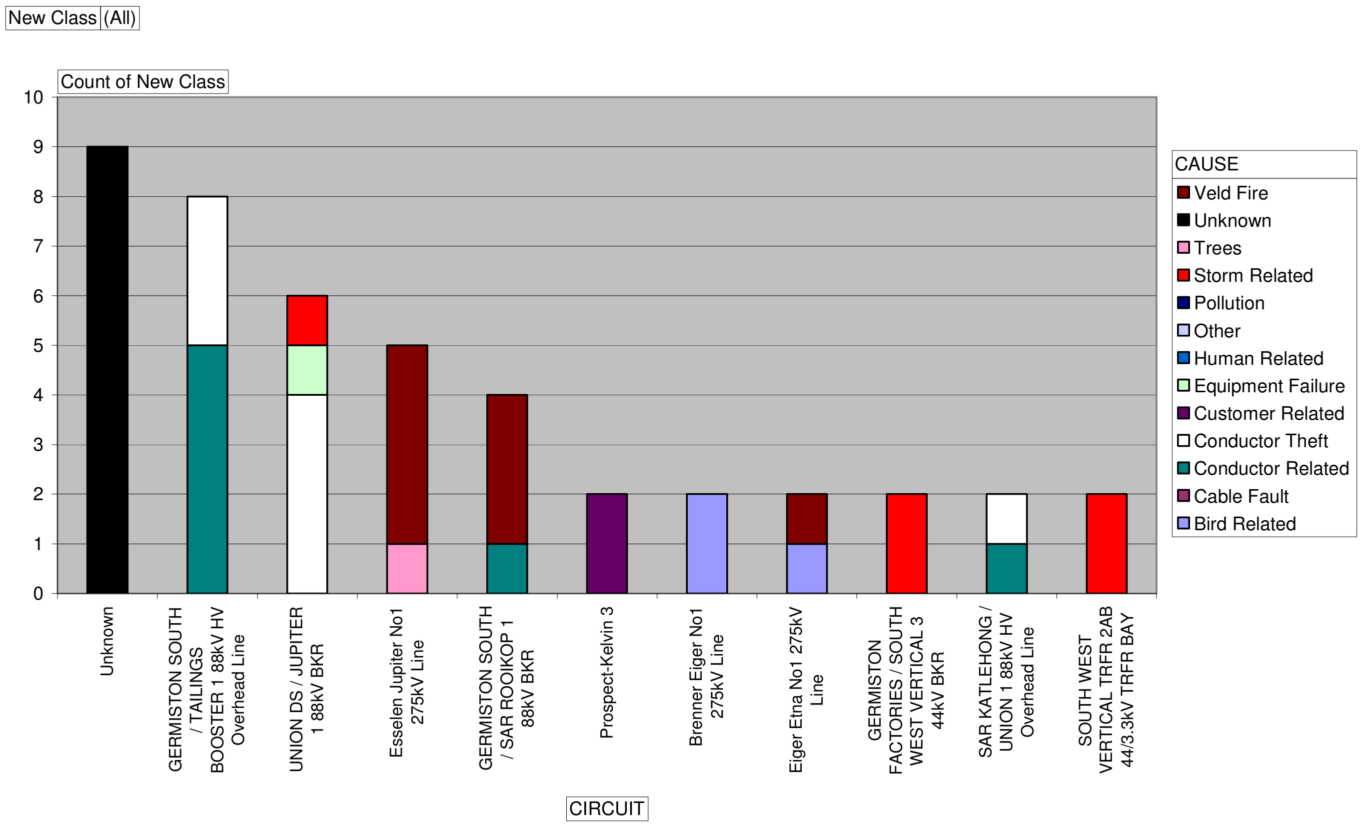



**Figure 3.8:** Breakdown of dip causes per contributing circuit – steel plant

From figure 3.8, it can be deduced that the location of a relatively large number of faults causing dips, is not known. Depending on the severity of dips, the utility may be requested by the customer to review its fault investigation practices. Ignoring the unknown category, the largest number of dips occurred on the Germiston South/Tailings Booster 88kV line as a result of conductor theft and conductor-related incidents. Conductor thieves either cut the conductor live (using tools similar to those used by Eskom's live work teams) or shoot the conductor, causing the breakers to trip on single-phase fault. It is this initial part of the theft operation that causes a voltage dip. Conductor-related incidents occurred mainly on Germiston South/Tailings Booster 88kV lines. According to the investigation conducted in 2004 [24], the root causes of conductor-related incidents were determined to be:

- ⇨ Mechanical failure of shieldwires (stranded steel conductor) due to continuous exposure to corrosive chemical vapours in the vicinity of the line.
- ⇨ Bridging of airgap between live conductor (jumpers) and steel towers due to the jumpers being excessively long and not supported by insulators, on certain towers.

Figure 3.8 answers two important questions:

- ⇨ On which circuits do the dips occur and what are the causes?
- ⇨ How do different circuits rank against each other in terms of dip performance?

The first four circuits (from left to right) contribute 70% of dip events (70% is derived from summation of dip events on the first four circuits and dividing by the total dip count for all circuits). Information presented in figure 3.8 enables the utility to make informed decisions around its maintenance program:

- ⇨ Replacing steel shieldwires on its overhead lines (Germiston South/Tailings Booster line).
- ⇨ Limiting conductor theft incidents on the Germiston South/Tailings Booster and Union DS/Jupiter 88kV lines (for instance, installing sensors to detect open-circuit conditions).

According to figure 3.8, the list of circuits affecting dip performance of the monitored site, excludes Eiger 88kV network. This observation is attributed to the network configuration at the time of performing the analysis. The Union DS network is supplied from Jupiter source only, under normal operating conditions [24] (normal operating condition refers to the absence of major electrical faults where all circuits and transformers are available for energy transfer).

**3.3.3.3 Dip Classes**

Dip data was exported from the database to a spreadsheet environment for processing. The data was presented graphically in figure 3.9 using Excel.

The vertical axis represents the number of dip events for the selected period (2003 to 2005). The horizontal axis represents circuits where dip events occurred, ranked in descending order from left to right.

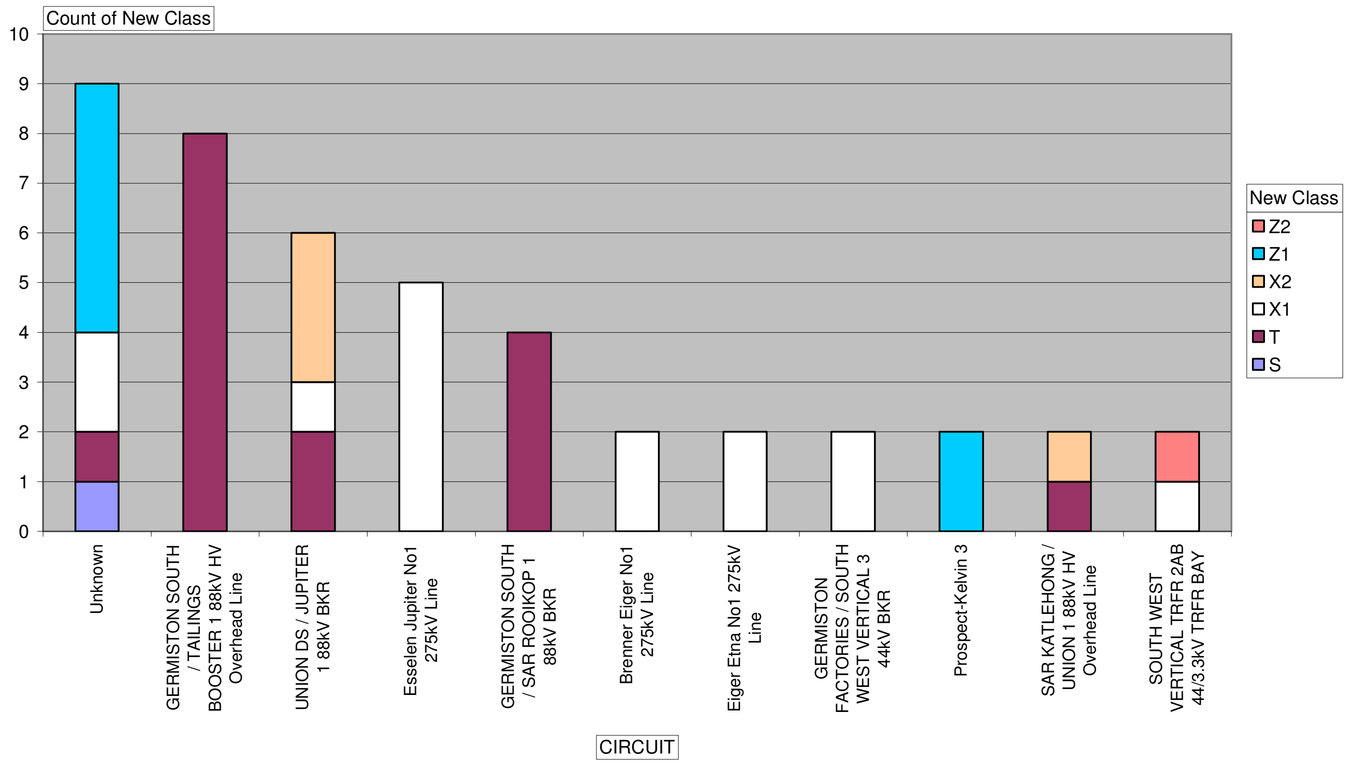



**Figure 3.9:** Dip types versus contributing circuits – steel plant

Long-duration dip events (T-class, Z1-class, Z2-class and S-class dips) occur predominantly on Germiston South/Tailings Booster, Union DS/Jupiter and Germiston South/SAR Rooikop overhead lines. The plant audit conducted by the author on the Union DS 88kV network, revealed that the protection system is outdated and prone to failure while product support has also ceased to exist [25], [26]. A business case for the upgrading of control plant technology at Germiston South, Mill Scaw and Union DS was prepared and submitted to approval authorities [27], [28]. The relay-based protection technology has, over the years, evolved from phase-1 relays (electromagnetic relay technology) to phase-4 relays (digital programmable relay technology). On the other hand, the original phase-1 relays installed at Union DS, Germiston South and Mill Scaw substations, have been in operation for a period exceeding 30 years.

Figure 3.9 is of particular interest to both the utility and the customer for the following reasons:

⇨ Circuits where long-duration dip events occur can be identified. Long-duration dip events are of particular concern to the steel plant customer. With this information, the utility can embark on line audits and detailed line performance investigations to limit the number and the duration of dip events on Germiston South/Tailings Booster, Union DS/Jupiter and Germiston South/SAR Rooikop overhead lines.

⇨ The locations of faults that caused five long-duration dip events (Z1-class under 'unknown' category) are not known. With this information, the customer is able to insist on improvement of fault management practices on the side of the utility.

#### 3.3.3.4 Voltage Dip Costs

To ascertain dip-related costs, customers are requested to estimate their costs due to dip events of varying duration and magnitude. On consultation, the customer was not able to provide reliable dip-related cost data for the plant under study.

## 3.4 THE PAPER PLANT CASE STUDY

### 3.4.1 INTRODUCTION

The dip data was extracted from Eskom's QOS database (1st January 2003 to 31st December 2005). Dip incidents were analysed by considering the ownership of the network, causes of dips, dip classes and costs associated with dip events.

#### 3.4.1.1 Ownership of the Network

It is important to conduct a comparative dip performance study between distribution and transmission networks for two reasons:

1. Transmission and distribution networks are operated and maintained by different business units within Eskom.
2. Faults on the transmission network cause dips over a wider area of the network compared to faults on the distribution networks.

#### 3.4.1.2 Causes of Voltage Dips

The causes of voltage dips are determined using the dip-to-trip matching technique. The dip data resides in the QOS database (viewed via Event Viewer) and the breaker trip information resides in the fault managements systems (NEPS and TIPPS). The two sets of data are correlated using the time stamp to indicate related events.

#### 3.4.1.3 Dip Classes

Long-duration dip events (T-class, Z1-class and Z2-class) are of particular interest to the pulp and paper customer. Therefore the analysis identifies circuits where these long-duration dip events occur.

#### 3.4.1.4 Voltage Dip Costs

To evaluate dip related costs, customers are requested by the utility to estimate plant downtime costs as a direct result of voltage dips.

### 3.4.2 SUPPLY NETWORK FOR THE PAPER PLANT

Voltage dip performance analysis for the paper plant is based on the network diagram shown in figure 3.10. The monitored site (paper plant) is supplied from Enstra substation, demarcated with a 'red fault' symbol. The distribution network (44kV to 132kV) interfaces with the transmission network (275kV) at Nevis station. The transmission network upstream of Nevis was not analysed for the following reasons:

- ⇨ Dip events on the circuits supplying Nevis are relatively infrequent compared to dip events caused by faults on the distribution network.
- ⇨ There is more than one source of supply to Nevis. Should a fault occur on one circuit, three sources are available to maintain supply to the distribution network.

In figure 3.10, networks of different voltage levels are represented by different colours. Sites where QOS meters are installed, are marked by a 'red square' symbol. The QOS meters are installed on the secondary side of the voltage transformers. The selection of meter locations is based on NERSA's guidelines briefly discussed in section 3.2.

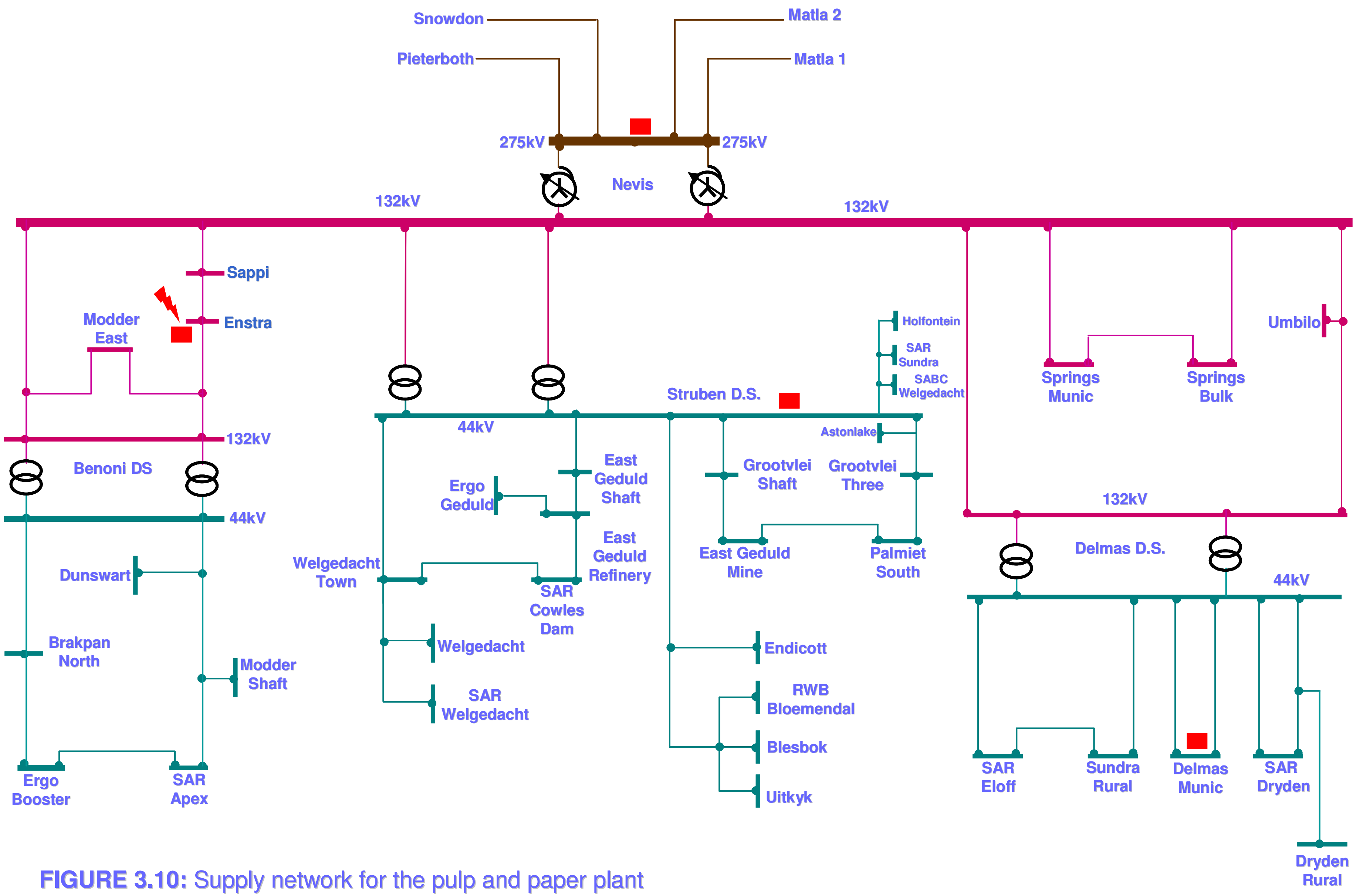



**FIGURE 3.10:** Supply network for the pulp and paper plant

### 3.4.3 RESULTS

This section presents results on the dip performance analysis performed for the network shown in figure 3.10. Dip data for the meter locations (Nevis 275kV, Struben DS 44kV, Delmas Munuc 44kV and Enstra 132kV) was extracted from the QOS database.

#### 3.4.3.1 Ownership of Infrastructure

In the network diagram of figure 3.10, network faults causing dips at the monitored site (Enstra marked with a ‘red fault’ symbol) may occur on the distribution network (44kV to 132kV) or transmission network (275kV) or at the customers’ plant (customer networks not shown).

A distribution of dip events according to ownership of the network is shown in figure 3.11. In figure 3.11, distribution means that dip events originated in the part of the network operated by the Distribution unit of Eskom. The same interpretation is applicable to the transmission network (operated by the Transmission unit of Eskom). ‘Customer’ means that dip events have their origin in the customer’s plant. If the origin of the dip events cannot be ascertained, the ‘unknown’ category is assigned.

The vertical axis represents the number of dip events recorded. The horizontal axis represents dip types, grouped according to the owner of the electrical network where the dips occurred. Where there are no bins for specific dip types, it means that there are zero dip events recorded during the analysis window period.

Figure 3.11 was generated by exporting dip data from the QOS database to a spreadsheet environment (Excel). Excel’s chart wizard was then used to present the data graphically.

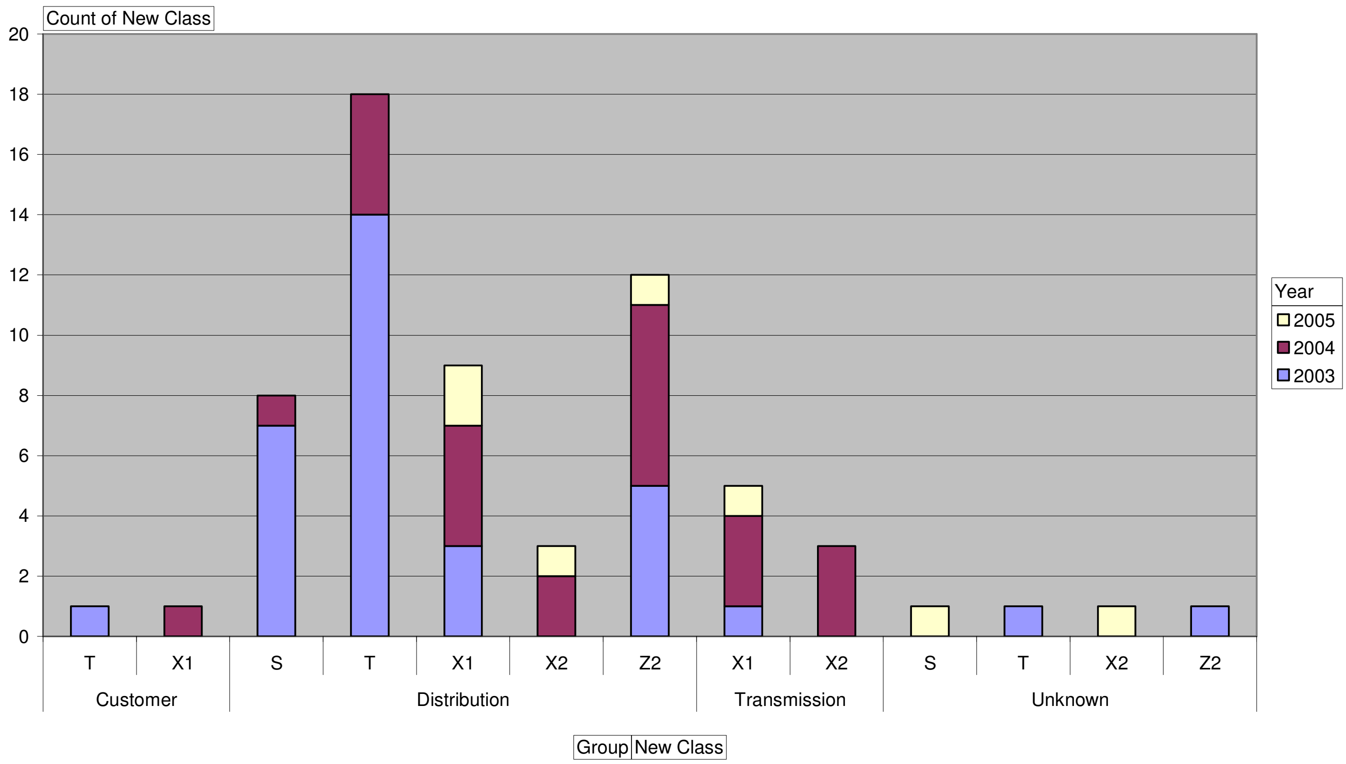



**Figure 3.11:** Distribution of dip events for the paper plant

In figure 3.11, it is apparent that voltage dip events recorded at Enstra originate predominantly from the distribution networks. Faults on the distribution networks resulted in a large number of long-duration events (T-class and Z2-class) at the monitored site. The total number of dip events seems to be progressively decreasing from 2003 to 2005.

Information presented in figure 3.11 enables the utility and its customers to answer the following questions:

- Which Eskom entity operates the networks where dips predominantly originate? In this case, undesirable dip performance seems to be associated with the Distribution unit of Eskom.
- How does dip performance compare from year to year? The utility appears to have developed an effective dip performance improvement strategy. Dip performance has progressively improved from 2003 to 2005, particularly at distribution voltage levels.

#### 3.4.3.2 Causes of Dip Events

The causes of voltage dips are ascertained using two sets of data: QOS database viewed via Event Viewer and NEPS circuit breaker trip data. The two sets of data are correlated using the time stamp to indicate related events.

Figure 3.12 presents the distribution of dip events according to dip cause category, arranged in descending order from left to right. The vertical axis represents the number of dip events recorded over the selected window period. The horizontal axis represents categories of dip causes.

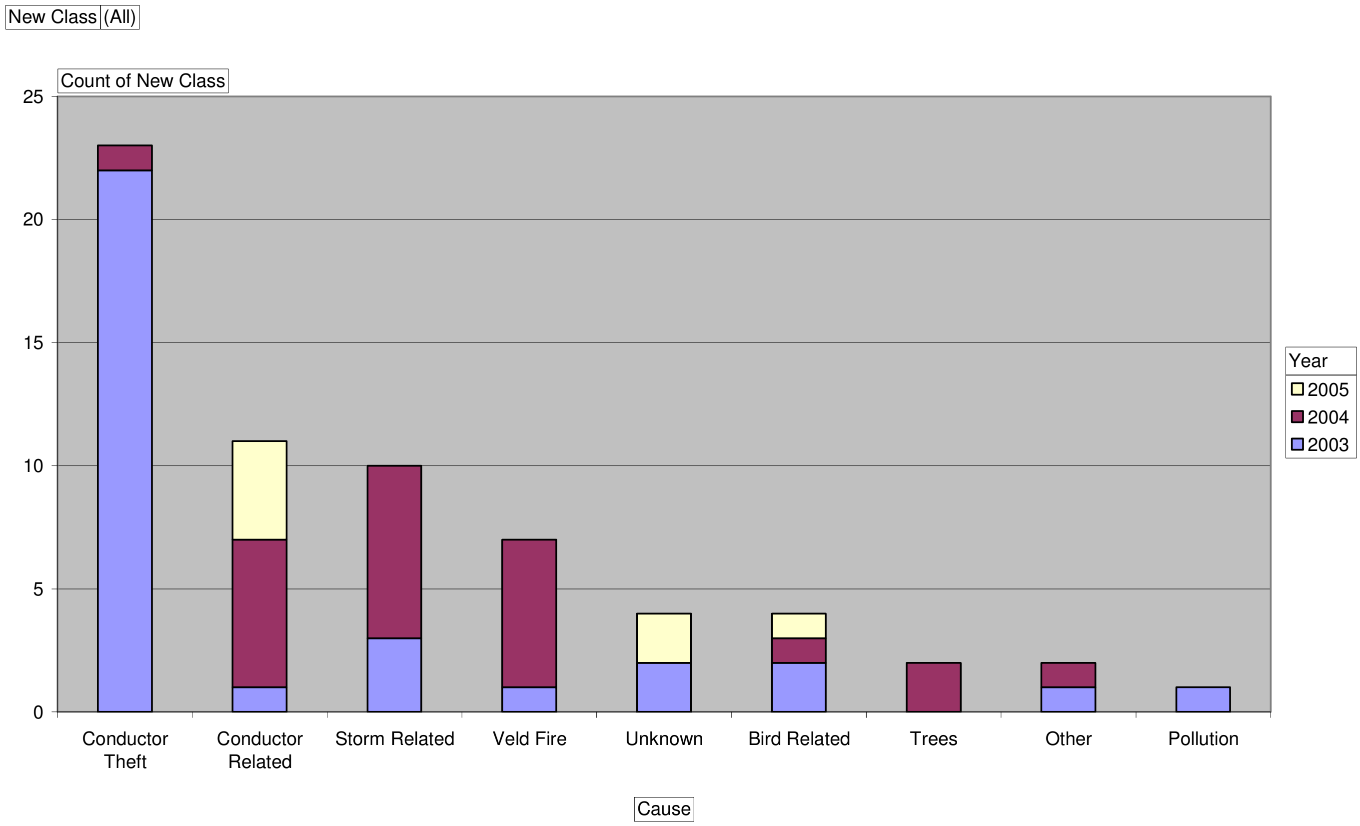



**Figure 3.12:** Causes of voltage dips for paper plant

In figure 3.12, the most important contributing factors to dip performance are conductor theft, conductor-related, storm-related and veld fire incidents. The four dip cause categories are responsible for over 35 dip events between 2003 and 2005 (adding totals for all four categories). More than 20 dip events are attributed to conductor theft incidents. Conductor thieves shoot the conductor or cut it live resulting in a single-phase fault. It is this initial act of the theft operation that causes voltage dips. The large number of conductor theft incidents experienced in 2003 requires further discussion. In [21], Smith discusses efforts taken by the utility (Eskom) to reduce the number of conductor theft incidents on the distribution networks shown in figure 3.10. Figure 3.13 is reproduced here from [21]. The vertical axis represents the number of conductor theft incidents. The horizontal axis represents months per year from January 2002 to May 2005.

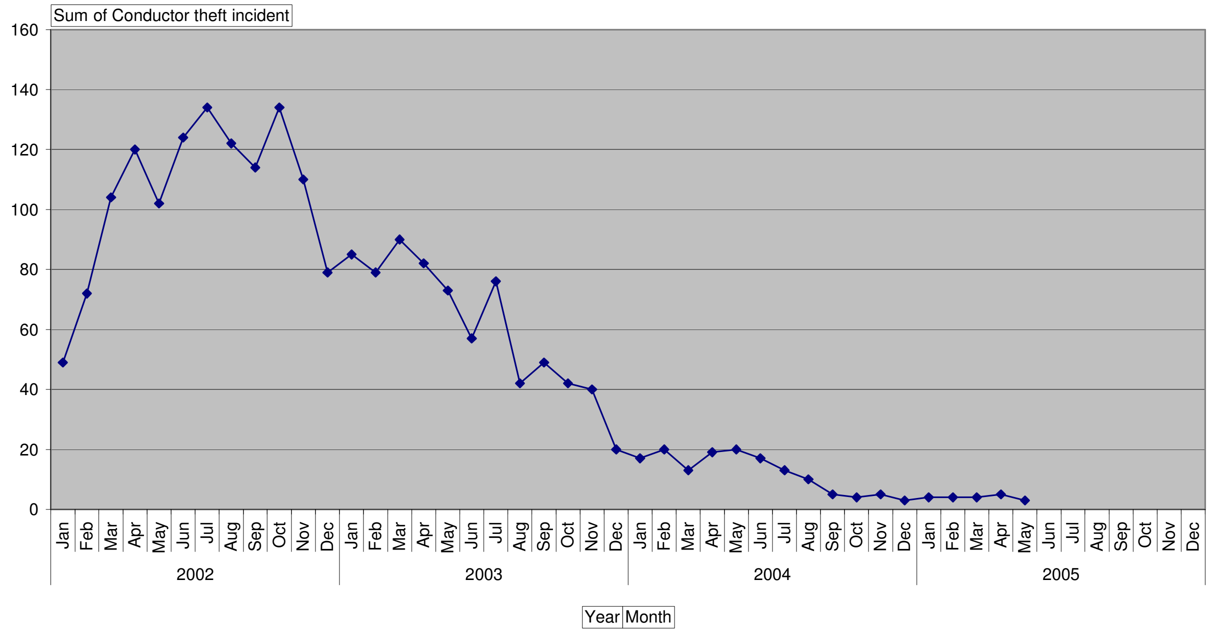



**Figure 3.13:** Decreasing trends in conductor theft incidents [21]

Prior to October 2002, Eskom employed security personnel to physically guard the lines known to be targeted by conductor thieves. From October 2002 to May 2005, Eskom installed electronic sensors on its lines where conductor theft incidents were known to have occurred. The electronic sensors detected open-circuit conditions and sent alarm signals to the network control centre. On receipt of alarm signals, network control centre personnel dispatched armed security guards to the location indicated by the electronic devices installed on the lines. This initiative significantly reduced the number of conductor theft incidents between 2002 and 2005, which explains the improvement in dip performance (2003 to 2005) observed in the figures 3.11 and 3.12.

The identification of key causes of dip events enables the utility and the customer to discuss:

⇨ Progress of activities initiated by the utility to limit the number and the frequency of faults that cause dips.

- ⇨ Maintenance efforts focussing on the most important dip cause categories. In figure 3.12, the major categories are conductor theft, conductor-related, storm-related and veld fire faults.

Figure 3.14 shows a breakdown of dip causes per circuit for various categories of dip causes. The graph was generated using Excel's chart wizard. The vertical axis represents the number of dip events recorded. The horizontal axis represents circuits where faults resulting in dips at the monitored site, occurred during the selected window period. Figure 3.14 is to be interpreted as follows:

- ⇨ The 'unknown' category means that the location of the faults could not be ascertained.
- ⇨ The bin labelled Benoni/Nevis 1 132kV HV overhead line represents dip events caused by faults that occurred on any part of the Benoni/Nevis 132kV line (circuit number 1).
- ⇨ The bin labelled SAPPI/Nevis 1 132kV BKR represents dip events caused by faults that occurred on the SAPPI/Nevis 1 132kV overhead line. The additional information is that the 132kV Nevis 1 circuit breaker (installed at SAPPI substation) is known to have tripped for these faults.
- ⇨ The bin labelled SAPPI/TEE 1 132kV overhead conductor represents faults that occurred on the piece of line between SAPPI substation and Nevis station.

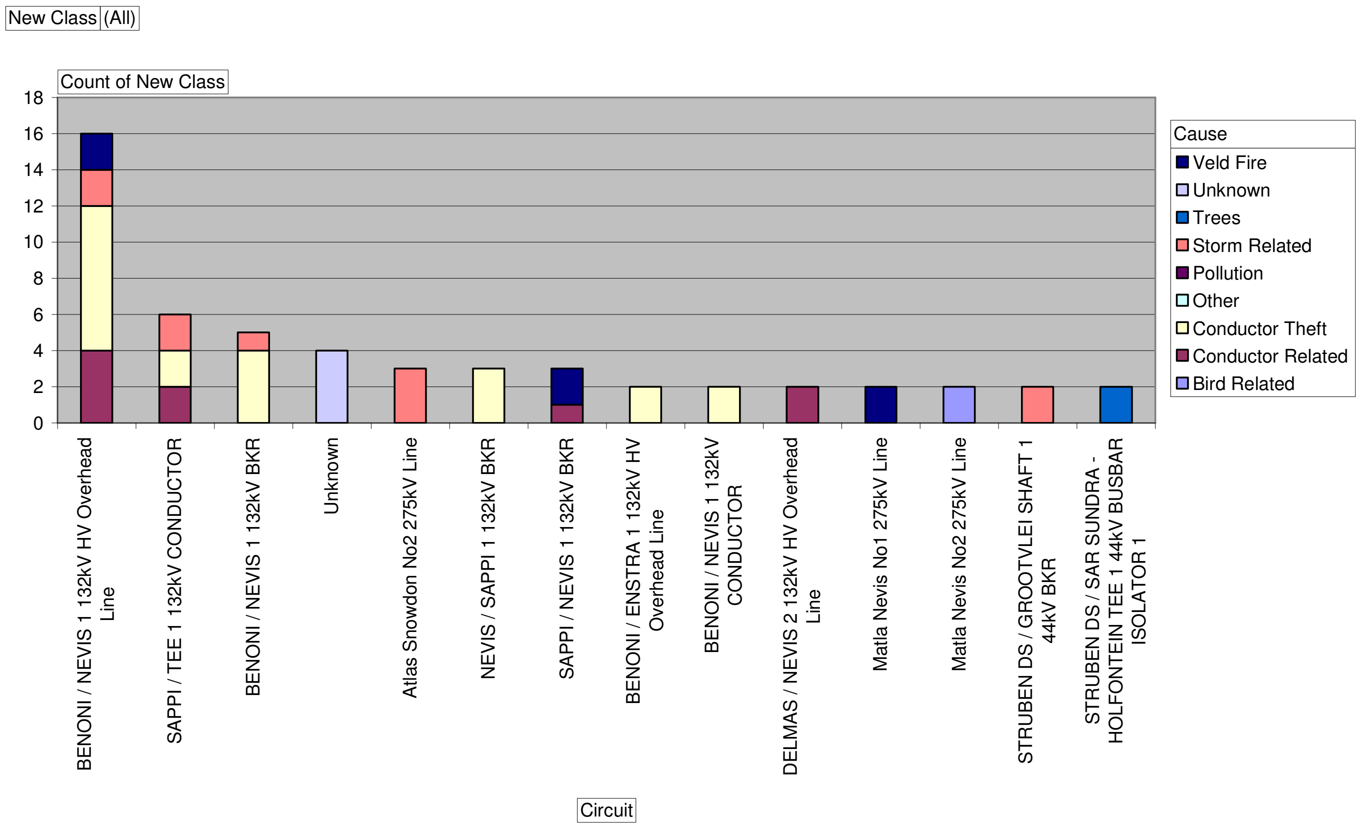



**Figure 3.14:** Breakdown of dip causes per contributing circuit – paper plant

Faults causing dips at the monitored site occurred predominantly on Benoni/Nevis 1 132kV and SAPPI/Tee 1 132kV overhead lines. Conductor theft incidents are the most common dip cause category on the three circuits (total of 14 conductor theft incidents).

Figure 3.14 informs the utility of the circuits where voltage dips occur and related causes. The utility can use this information to prioritize maintenance actions on its overhead lines.

### 3.4.3.3 Dip Classes

The author extracted dip class data directly from the QOS database via Event Viewer and then downloaded it to a spreadsheet environment. The extracted data was presented graphically in figure 3.15 using Excel. The vertical axis represents dip events recorded. The horizontal axis represents bins described by the circuits where dip events occurred. Where there are no bins for certain dip classes, the interpretation is that dips of that specific class did not occur during the analysis period.

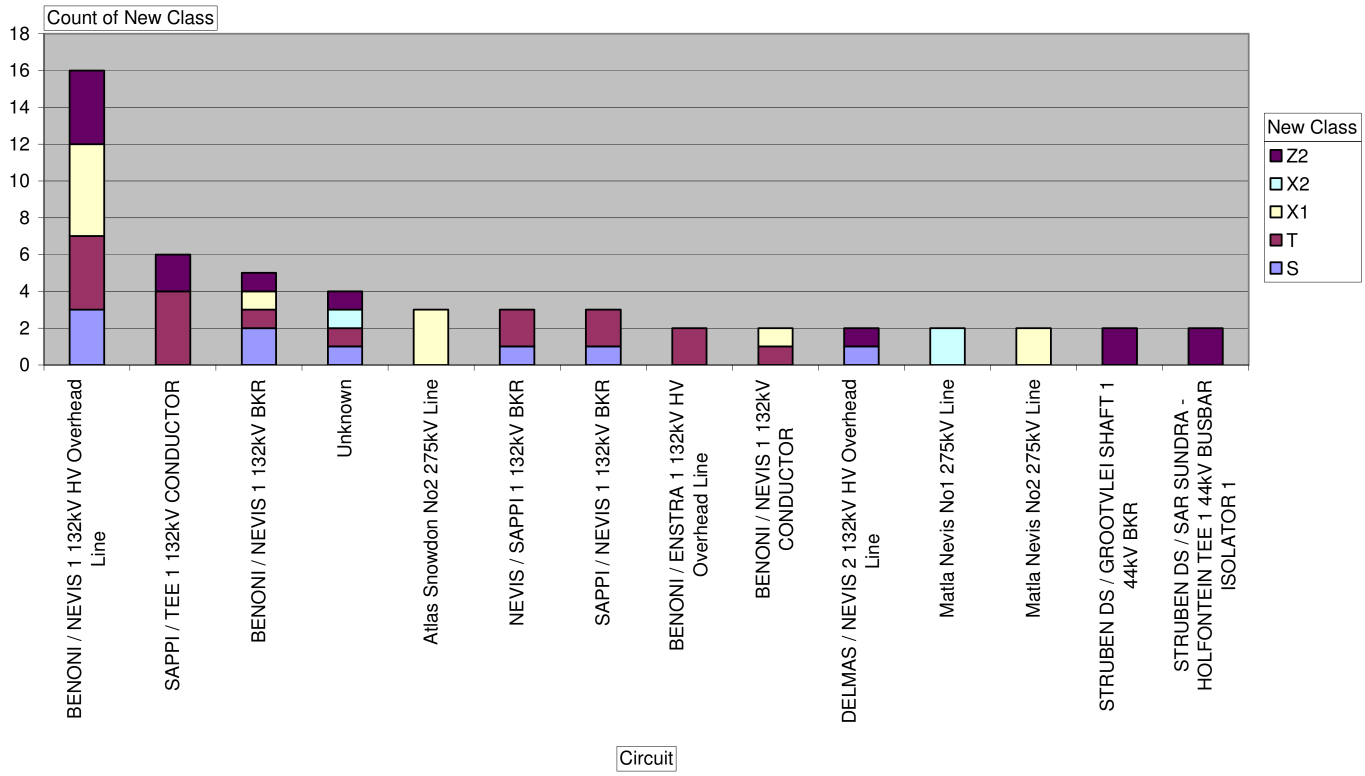



**Figure 3.15:** Dip types versus contributing circuits – paper plant

Long-duration dip events (Z2-class and T-class) occurred predominantly on Benoni/Nevis 1 132kV line and SAPPI/Tee 132kV line. Figure 3.15 enables the utility to identify circuits where long-duration dip events occur.

### 3.4.3.4 Voltage Dip Costs

The tracking of dip-related plant downtime and dips costs is an important tool in quantifying the impact of voltage dips to the customer. Figure 3.16 is an attempt to quantify the financial impact of voltage dips for the paper plant. The vertical axis represents costs as a direct result of voltage dips (downtime costs excluding consequential costs). The horizontal axis represents circuits contributing to dip costs.

Dip costs were obtained from the paper plant customer [29]. The customer records estimated costs associated with each dip event. Dip data was downloaded from the QOS database. The graph of figure 3.16 is produced using Excel. Figure 3.16 is to be interpreted as follows:

⇨ Benoni DS/Nevis 1 132kV BKR represents dip costs as a result of faults that occurred on the Benoni DS/Nevis 1 132kV overhead line. Nevis 1 132kV circuit breaker (installed at Benoni DS) is known to have tripped for these faults.

⇨ Delmas/Nevis 2 132kV HV overhead line represents dip costs as a result of faults (resulting in dips at Enstra) at any part of the second 132kV line between Delmas DS and Nevis transmission station (the convention is to count circuits from left to right on the network diagram – figure 3.10).

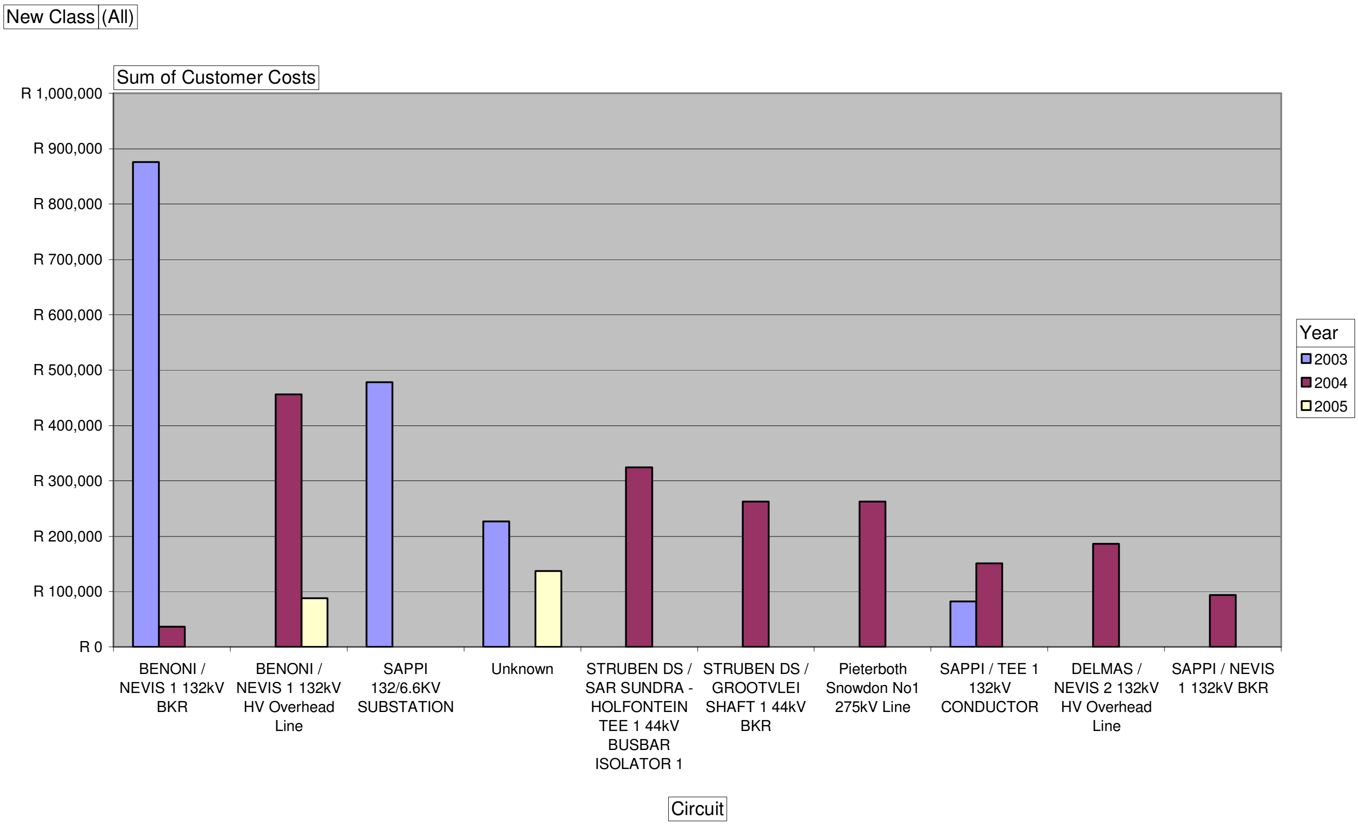



**Figure 3.16:** Circuits contributing to dip costs – paper plant

Figure 3.16 suggests that faults on the Benoni/Nevis 1 132kV overhead line and SAPPI substation resulted in the highest dip-related financial losses to the paper customer. The highest financial loss was experienced in 2003. Figure 3.16 enables the customer to identify circuits contributing to dip-related downtime costs. Based on this information, the utility is able to make informed dip performance investment decisions while on the other hand, the customer may decide to investigate other dip mitigation options.

Figure 3.17 shows costs of voltage dips against dip cause categories. Dip data was obtained from Eskom's QOS database, while dip costs were obtained from the customer. The graph was generated using Excel. The vertical axis represents costs as a direct result of voltage dips. The horizontal axis represents dip cause categories.

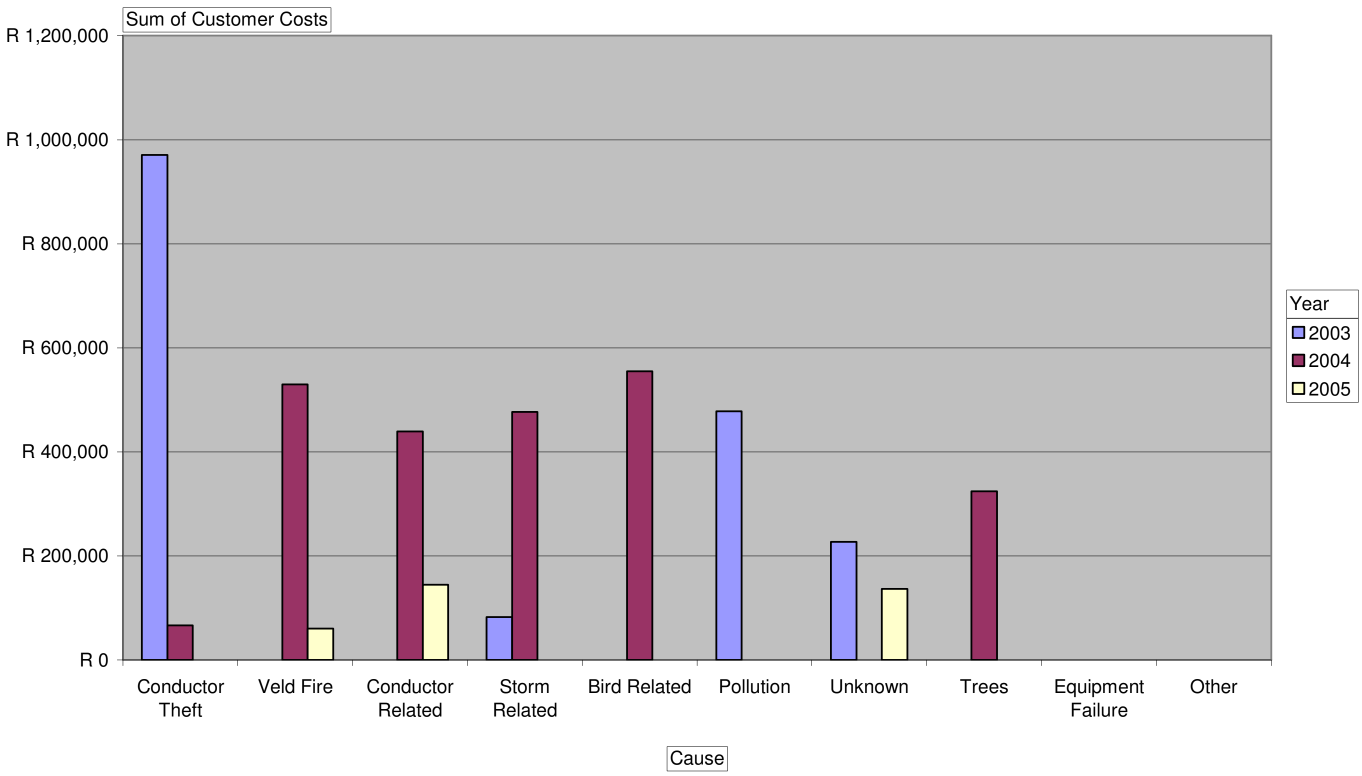



**Figure 3.17:** Causes of dips and the associated costs – paper plant

Figure 3.17 suggests that dips due to conductor theft incidents resulted in the highest financial losses to the customer. The lowest level of dip-related costs is approximately fifty thousand rands, which suggests that all dip cause categories have a remarkable financial impact on the customer.

Figure 3.18 shows a plot of dip costs as a function of dip duration and dip magnitude. The vertical axis represents costs as a direct result of voltage dips. The two horizontal axes represent dip depth (measured as a percentage of declared voltage) and dip duration (in milliseconds). The graph was produced using Excel's chart wizard. The labels in the horizontal axes represent different ranges of dip magnitude and dip duration. For example, T5(150-<600ms) refers to bin T5 defined by the dip duration falling between 150ms and 600ms and D2(30-<40%) represents bin D2 defined by dip magnitude in the range 30% to 40%.

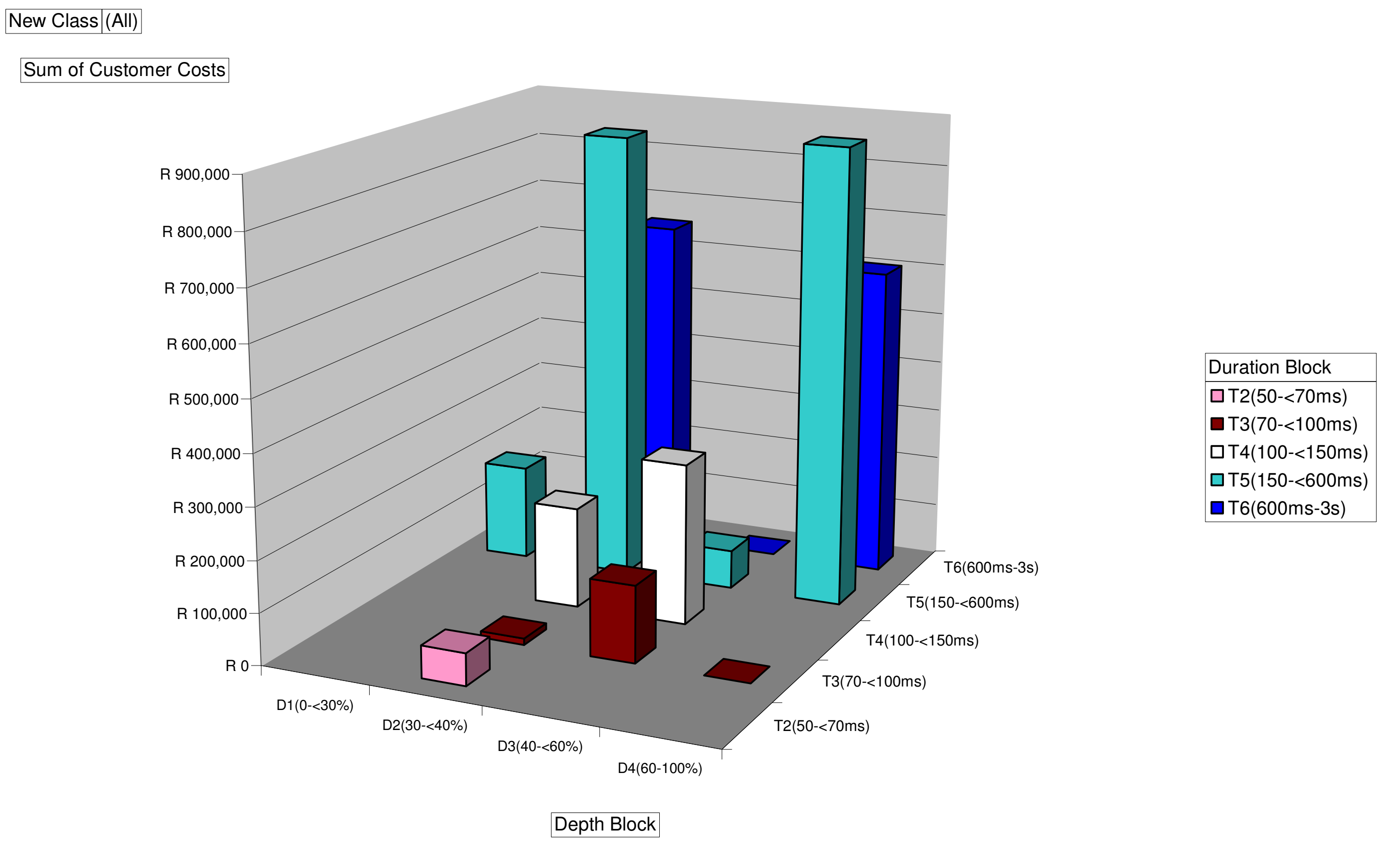



**Figure 3.18:** Dip costs as a function of dip duration and magnitude – paper plant

In figure 3.18, long-duration dips (duration exceeding 150ms) have relatively more severe financial impact on the customer. Dip events of varying magnitudes appear to have financial impact ranging from one extreme of severity to the other.

Figure 3.18 is an additional view of dip performance that the customer and the utility can use to quantify the impact of dips on the customer's plant.

### 3.4.4. CONCLUSION

Power quality monitoring was introduced by NERSA as part of license conditions. Eskom's measured dip data is stored in a central database. Eskom has developed software tools for the viewing and reporting of dip information. For both the steel plant and paper plant, the dip data was analysed by considering the ownership of the network, causes of dips, dip classes and costs associated with dip events.

For the steel plant, a distribution of dip events according to ownership of the network, revealed that a large number of T-class dips occurred on the distribution network. This observation is attributed to faults clearing via back-up protection, in case of failure of the main protection systems. A breakdown of fault causes showed that storm-related faults, equipment failures, conductor-related faults and conductor theft incidents form the greatest contribution to dip performance of the monitored site. The largest number of dips occurred on the Germiston South/Tailings Booster and Union DS/Jupiter 88kV overhead lines. Long-duration dip events (T-class, Z1-class, Z2-class and S-class) occurred predominantly on Germiston South/Tailings Booster, Union DS/Jupiter and Germiston South/SAR Rooikop 88kV lines. The identification of problematic circuits allows the utility to address the causes of electrical faults more decisively.

For the paper plant, faults on the distribution network resulted in long-duration dip events (T-class and Z2-class) at the monitored site (Enstra). A presentation of dip causes shows that conductor theft incidents, conductor-related faults, storm-related faults and veld fires contributed significantly to dip performance of the monitored site. Network faults occurred predominantly on Benoni/Nevis 1 and SAPPI/Tee 1 132kV overhead lines. Long-duration dip events (Z2-class and T-class) also occurred predominantly on the same circuits. Faults on the Benoni/Nevis 1 132kV line (mainly conductor theft) and SAPPI substation resulted in the highest financial losses (exceeding R800,000 in 2003). For the paper plant, dip events of varying magnitude appear to have financial impact ranging from one extreme of severity to the other (from under R50,000 to over R800,000). This observation is attributed to the possibility that the dip costs may have been derived primarily from rough estimates.

For both industrial plants, the analysis of dip performance has successfully identified circuits where dips predominantly occur and ascertained the causes of these dip events. This information (problematic circuits, fault causes, dip types) enables the utility and the customer to jointly formulate plans to respond to poor dip performance.

# CHAPTER 4:
# VOLTAGE DIP SIMULATION

## 4.1 INTRODUCTION

The r.m.s voltage depression caused by a fault propagates through the network and manifests itself as a voltage dip at remote observation points. The effects, in terms of voltage dips, of a fault at a given position can be represented graphically in a single-line diagram of the power system. The resulting single-line diagram is called the dip influence zone.

### 4.1.1 THE SIMULATION TOOL

DIgSILENT PowerFactory was selected as the simulation tool. The choice of DIgSILENT PowerFactory was motivated by ease of availability within the Eskom environment. PowerFactory uses sophisticated multilevel modelling of the power system and can cover the whole range of transient phenomena in electrical power systems [30]. Three different simulation functions are available to study fault levels in a power system, namely:

⇨ A basic steady-state function that uses a symmetrical steady-state network model under balanced network conditions. Only the fundamental components of voltages and currents are taken into consideration.
⇨ A three-phase steady-state function that uses a steady-state network model under both balanced and unbalanced conditions.
⇨ An electromagnetic transient model that uses a dynamic network model for short-term and mid-term transients under both balanced and unbalanced network conditions.

The simulation of voltage dips was performed within the following boundaries:

⇨ Only dip events caused by short-circuits are of interest to this study.
⇨ Protection systems including auto-reclose settings are not simulated. Thus, the expected simulation results are limited to fault distances and magnitudes only.
⇨ Multiple fault conditions are not simulated.

The power system models for the steel plant and paper plant were created in PowerFactory. Lumped parameter models were employed to model underground cables and overhead lines. Sequence impedances, tower top geometries, underground cable data (core size, configuration) and current ratings were obtained from Eskom’s conductor data tables [31].

#### 4.1.2 DIP MACROS AND DIP INFLUENCE ZONES

The following process was adopted in performing dip simulations:

- ⇨ Building a model of the power system that includes busbars of interest and parts of the system that feed these busbars.
- ⇨ Using DIgSILENT PowerFactory macros to define dip influence zones for the two monitored sites. The macros were developed by Schilder [32] and are discussed below.
- ⇨ The simulation results are presented graphically on the power system to give dip influence zones for each plant.

Schilder [32] conducted a research study to develop macros and guidelines for dip performance studies, using DIgSILENT PowerFactory as the simulation tool. In [32] several macros, including the *Area of Sensitivity* macro, were successfully developed and tested. The author of this thesis used results of the research conducted in [32] to calculate dip influence zones for the steel plant and the paper plant, specifically the *Area of Sensitivity* macro. The macro uses the method of critical distances to calculate dip influence zone for a selected monitored busbar.

The *Area of Sensitivity* macros works as follows:

- ⇨ Four input parameters may be specified (shown in figure 4.1 below), namely:
    - o Fault resistance (represented by symbol Zf in the macro).
    - o Voltage dip sensitivity in per unit (represented by symbol Vsens).
    - o Type of fault (0 refers to three-phase fault, 1 refers to single-line-to-ground fault, 2 refers to line-to-line-to-ground fault, 3 refers to line-to-line fault).
    - o Method of short-circuit calculation.
- ⇨ With the input parameters set up, the user then selects lines of interest (multiple lines selected simultaneously). The macro applies specified input parameters at predefined locations on each single selected line, one at a time. For each location on each selected line, the remaining voltage at the monitored site is calculated and compared with Vsens. If the calculated remaining voltage is smaller (less severe) than Vsens, the macro stops doing calculations for this fault location and proceeds to the next location. The point on a line at which the calculation is stopped marks the boundary of the dip influence zone on that line for the given set of input values. The macro calculates voltage values (remaining voltage), first on the lines closest to the monitored site and then proceeds to lines further away from the monitored site.

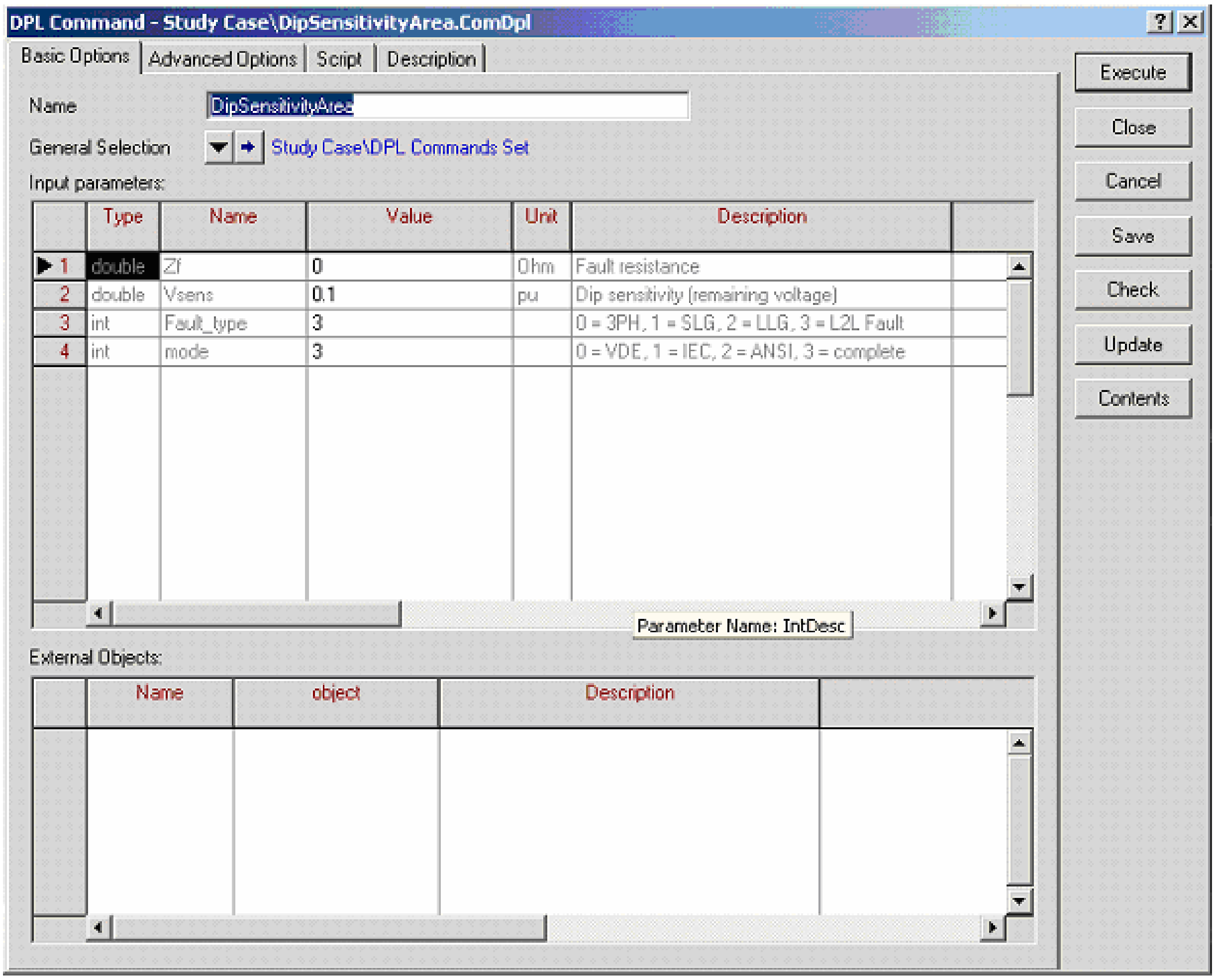



**Figure 4.1:** Input Dialog Box of *Area of Sensitivity Macro* [32]

- ⇨ The output of the macro is a list of lines falling within the dip influence zone defined by the input parameters. The macro gives line distances (relative to the monitored site) for each line in the dip influence zone. The distance on each line is the point at which the zone ends. An example of the output of the *Area of Sensitivity* macro is presented in figure 4.2. The output window shows the monitored site (Enstra in this case) and lines in the dip influence zone defined by the input parameters.
- ⇨ Once a dip influence zone is defined, one or more input parameters may be changed and the process repeated.

```
Number of line(s) in selection:  4
Calculating short-circuits...
Fault type selected: 2-Phase Short-Circuit

Dip sensitivity for monitored site Enstra132:

Results for line Benoni_Bpp/Modder East T_, of length 15.25 km
Fault resistance is 0.00 ohm and dip sensitivity 0.10 pu
Fault distance is 0.00 km, remaining voltage is 0.58 pu

Results for line Benoni_Bpp/Modder East T_Modder East, of length 0.38 km
Fault resistance is 0.00 ohm and dip sensitivity 0.10 pu
Fault distance is 0.00 km, remaining voltage is 0.60 pu

Results for line Benoni_Enstra/Modder East T_Modder East, of length 0.38 km
Fault resistance is 0.00 ohm and dip sensitivity 0.10 pu
Fault distance is 0.00 km, remaining voltage is 0.50 pu

Results for line Benoni_Enstra/Modder East T_, of length 15.29 km
Fault resistance is 0.00 ohm and dip sensitivity 0.10 pu
Fault distance is 0.00 km, remaining voltage is 0.50 pu
```

**Figure 4.2:** Example of output of *Area of Sensitivity* macro

The dip influence zone is obtained by representing the fault distances graphically on the network, for each monitored site. The basic steps to produce dip influence zones are summarised as follows:

(1) Model the appropriate network in a power system simulation tool (PowerFactory).
(2) Use the *Import* function of PowerFactory to import the DPL (DIgSILENT Programming Language) macros, specifically the *Area of Sensitivity* macro developed in [32].
(3) Select the busbar to be monitored. Thereafter, select all circuits where the influence of faults on the monitored busbar is to be determined.
(4) Right-click the mouse while the cursor is on one of the selected objects. Select *Execute DPL* scripts on the right-click menu.
(5) Select the *DipSensitivity* macro.
(6) Provide input data for the macro, that is, fault resistance, dip sensitivity (remaining voltage), fault type and method of fault calculation, as illustrated in figure 4.1.
(7) Press *Execute* button.

(8) The results appear as a list of lines that form part of the dip influence zones. Distances on the lines are shown (boundaries of the exposed area).

(9) Repeat steps (6) to (8) for a selected range of Vsens values as well as for different short-circuit types.

(10) Plot fault distances on the selected lines. For each fault type, dip influence zones are then obtained by joining the points (fault distances). These zones are dependent on the dip sensitivity set at the monitored site.

## 4.2 SIMULATION RESULTS

### 4.2.1 INTRODUCTION TO THE SIMULATION RESULTS

The simulation results discussed in section 4.2.2 and 4.2.3 were generated by the author using the *Area of Sensitivity* macro. To explain how the dip influence zones were plotted consider the output of the macro shown in figure 4.3. Figure 4.3 restates the macro input data as follows:

- ⇨ Fault type is 2-phase short-circuit (phase-to-phase).
- ⇨ Fault resistance is zero.
- ⇨ Dip sensitivity at the monitored site is 0.5pu.

```
Number of line(s) in selection: 48
Calculating short-circuits...
Fault type selected: 2-Phase Short-Circuit

Dip sensitivity for monitored site Mill Scaw88kV:

Results for line Union_Mill Scaw 88kV, of length 0.17 km
Fault resistance is 0.00 ohm and dip sensitivity 0.50 pu
Fault distance is 0.17 km, remaining voltage is 0.50 pu

Results for line Germiston South_Tailings Booster 88kV, of length 1.94 km
Fault resistance is 0.00 ohm and dip sensitivity 0.50 pu
Fault distance is 1.10 km, remaining voltage is 0.50 pu

Results for line Germiston Factories_South West Vertical (1) 44kV, of length 0.51 km
Fault resistance is 0.00 ohm and dip sensitivity 0.50 pu
Fault distance is 0.00 km, remaining voltage is 0.69 pu
```

**Figure 4.3**: Example of macro outputs used to plot dip influence zones

The results are to be interpreted as follows:

- ⇨ The entire Union DS/Mill Scaw 88kV line is part of the dip zone defined by the parameters set above (Zf = 0, Vsens = 0.5, fault type = phase-to-phase). Union DS/Mill Scaw line is 0.17km long and 100% of this line length forms part of the dip zone defined by the input parameters (fault distance is 0.17km). The remaining voltage at the monitored site (Mill Scaw) is 0.5pu.

- ⇨ Germiston South/Tailings Booster 88kV line is 1.94km long and only 1.10km of the line forms part of the dip influence zone under investigation (fault distance is 1.10km). The macro assumes that the reference point (zero point) is the one closest to the monitored site (that is, Germiston South 88kV busbar in the case of Germiston South/Tailings Booster line). To plot the point 1.10km on the 1.94km long Germiston South/Tailings Booster line, the macro output distance was expressed as a fraction of the total line length (1.10km converts to 57% for a 1.94km long line). A complete dip influence zone can then be plotted by joining the points on all lines which form part of the dip influence zone.
- ⇨ Germiston Factories/South West Vertical 1 is 0.51km long and is outside of the dip influence zone defined by the macro input parameters (fault distance is 0.0km). The remaining voltage at the monitored site 0.69pu, which is less severe than the setting of 0.5pu dip sensitivity.

### 4.2.2 STEEL PLANT

#### 4.2.2.1 Phase-to-phase Faults

The network diagram shown in figure 4.4 is part of the network presented in figure 3.5. At the time of performing the analysis, the Union DS network was supplied from Jupiter source only, under normal operating conditions. The dip influence zones are plotted on the network diagram by joining fault distances produced by the *Area of Sensitivity* macro.

Three zones are shown for dip sensitivities of 0.5pu, 0.3pu and 0.1pu. Using figure 4.4 as an example, dip influence zones are to be interpreted as follows:

- ⇨ Phase-to-phase faults occurring on the network enclosed by *Zone A (ph-ph)* will result in voltage dips more severe than 0.5pu, at the monitored site (minimum expected dip depth is 0.5pu).
- ⇨ For circuits that are partially enclosed within *Zone A (ph-ph)* (for example, Jupiter/Simmerpan 44kV lines), the above condition is only applicable up to the critical distances.
- ⇨ Phase-to-phase faults occurring in *Zone B (ph-ph)* will result in voltage dips more severe than 0.3pu at the monitored site (minimum expected dip depth is 0.3pu).
- ⇨ Phase-to-phase faults occurring in *Zone C (ph-ph)* will result in voltage dips more severe than 0.1pu at the monitored site (minimum expected dip depth is 0.1pu).

⇨ Phase-to-phase faults occurring on networks not enclosed by any of the zones will not result in voltage dips at the monitored site. It is assumed that 'voltage dips' less than 0.1pu in magnitude have no effect on customer plant and are therefore ignored.

Phase-to-phase faults on any part of the 88kV network cause dips more severe than 0.3pu at the monitored site. Phase-to-phase faults on Angelo, Cason Mill and Simmerpan 11kV network, do not cause voltage dips at Mill Scaw (remaining voltage still exceeds 0.9pu).

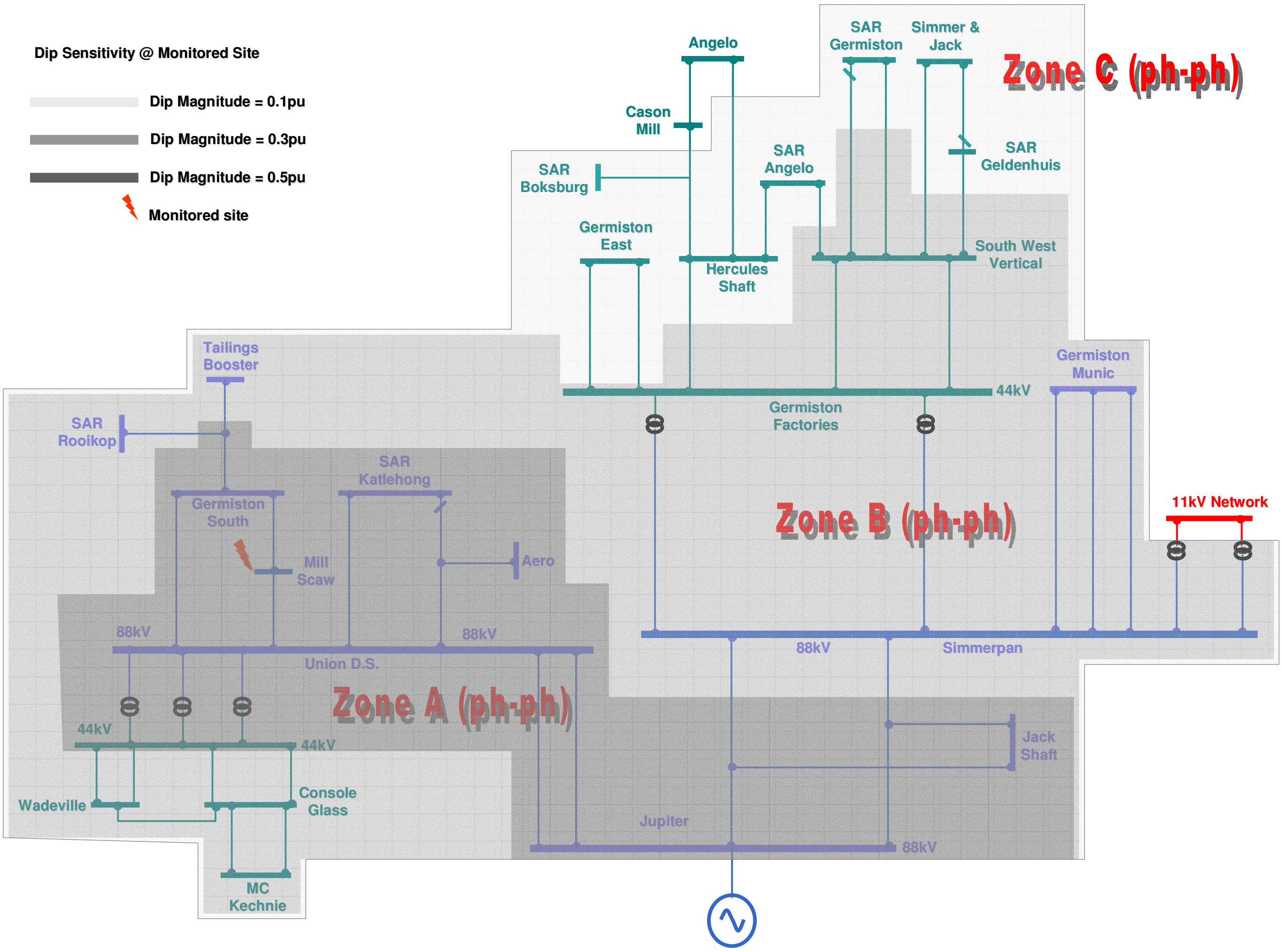



**Figure 4.4:** Dip influence zones for phase-to-phase faults – steel plant

### 4.2.2.2 Single-phase Faults

Four dip influence zones for single-phase faults are shown in figure 4.5. Single-phase faults causing dips with magnitude of at least 0.8pu *(Zone A (1-ph))*, occur in much smaller area compared to the same dip sensitivity for phase-to-phase faults (refer to figure 4.4). The significance of this observation is that single-phase faults occur more frequently than phase-to-phase and three-phase faults on the network.

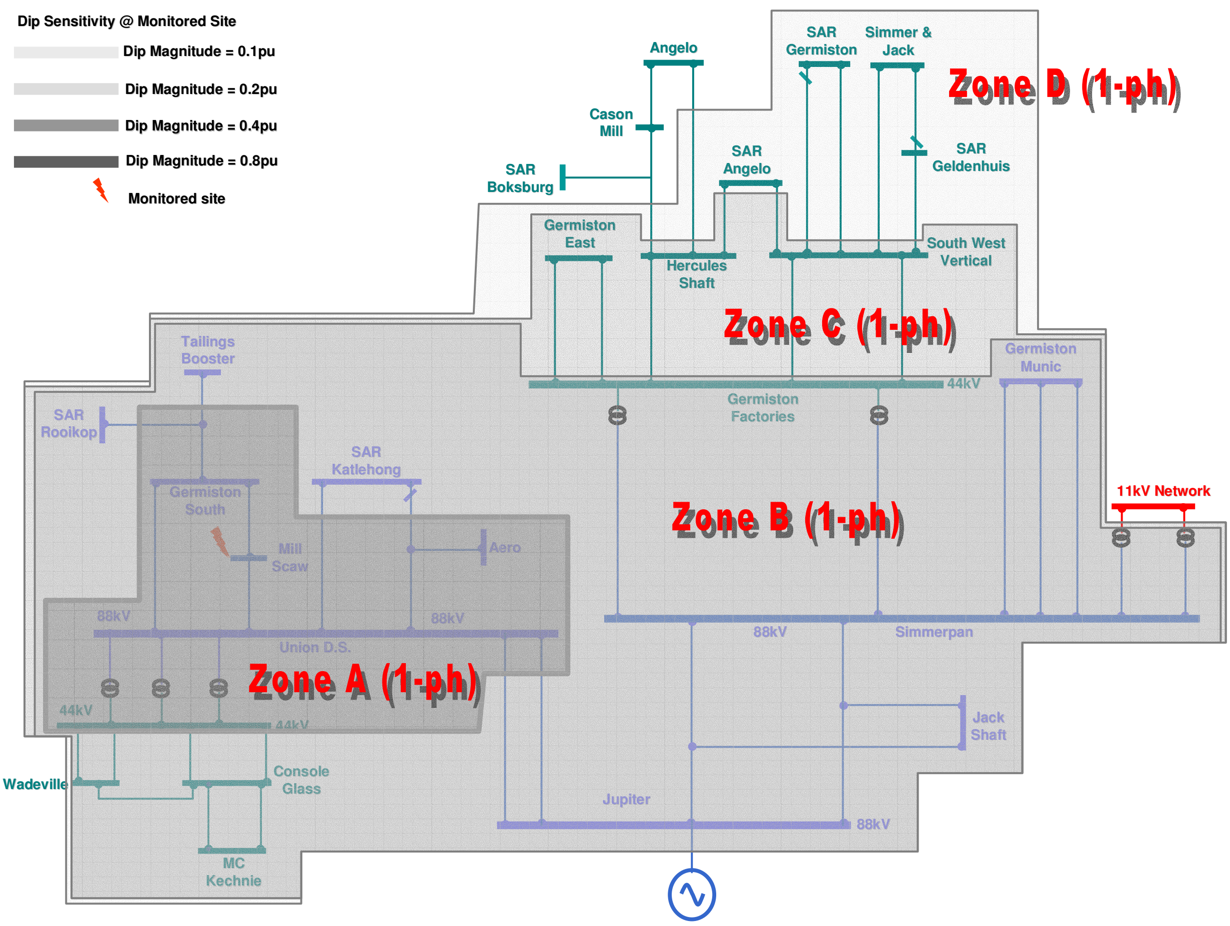



**Figure 4.5:** Dip influence zones for single-phase faults – steel plant

The Simmerpan/Germiston Munic 88kV circuits (oil-filled single-core cables in flat formation) form part of *Zone B (1-ph).* The average performance of these underground cables was calculated to be two faults per kilometre per annum in 2005 [33]. This statistic translates to an average of four dip events with magnitude exceeding 0.4pu per circuit per annum (each cable circuit is 2.15km in length).

### 4.2.2.3 Phase-to-phase-to-ground Faults

The dip influence zones for phase-to-phase-to-ground faults are shown in figure 4.6. Phase-to-phase-to-ground faults on the 88kV network cause dips exceeding 0.7pu (*Zone B (ph-ph-g))* while phase-to-phase faults on the same network area cause dips exceeding 0.3pu *(Zone B (ph-ph))* at the monitored site. It therefore appears that the customer plant is more sensitive to phase-to-phase-to-ground faults compared with phase-to-phase faults.

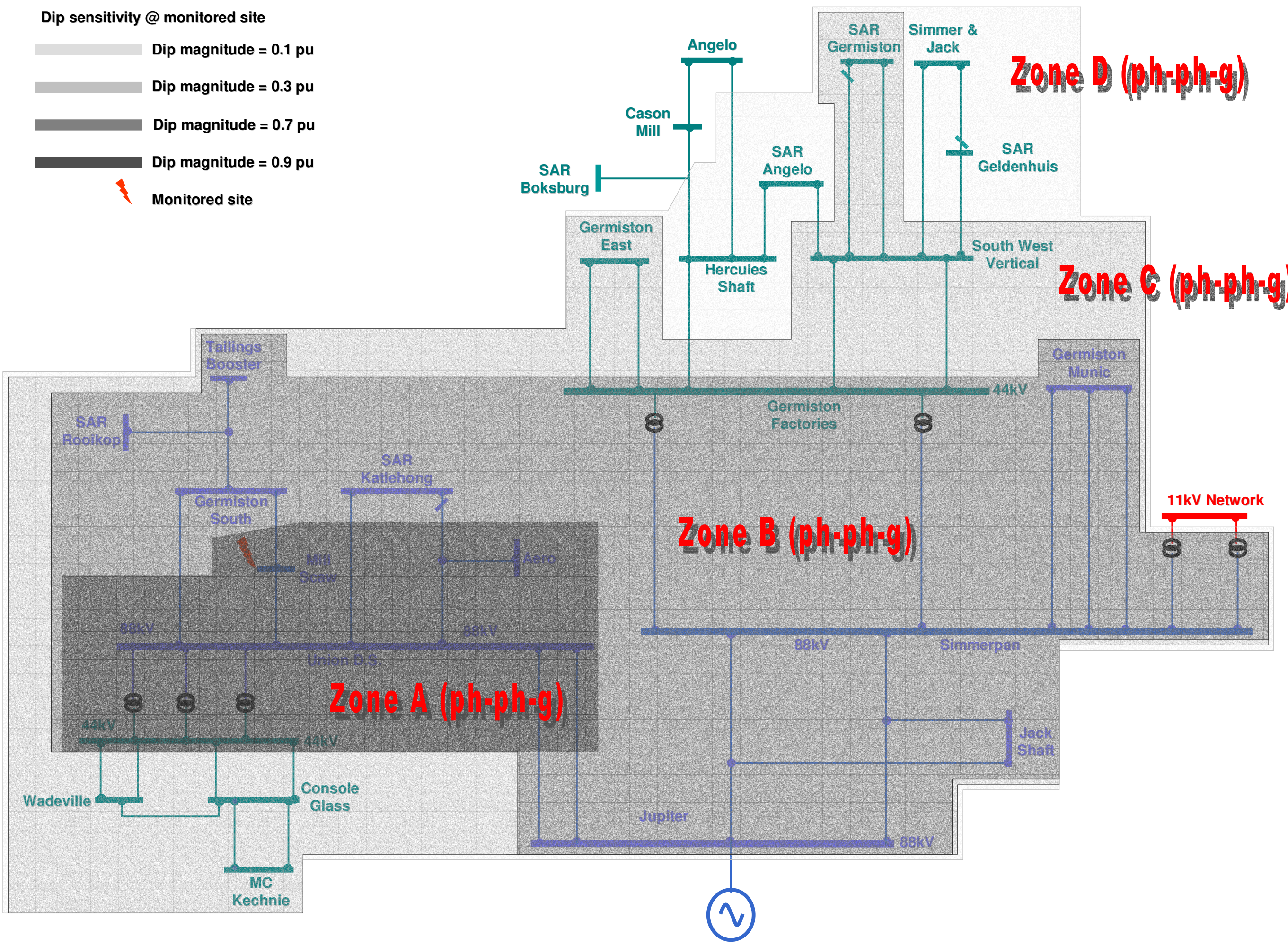



**Figure 4.6:** Dip influence zones for phase-to-phase-to-ground faults – steel plant

### 4.2.2.4. Three-phase Faults

The dip influence zones for three-phase faults are shown in figure 4.7. Three-phase faults on Union DS/Jupiter and Germiston South/Tailings Booster 88kV lines cause dips worse than 0.7pu at the monitored site *(Zone B (3-ph)).* These two lines were identified as the worst-performing circuits in terms of dip performance (figure 3.8 in section 3.3.3.2).

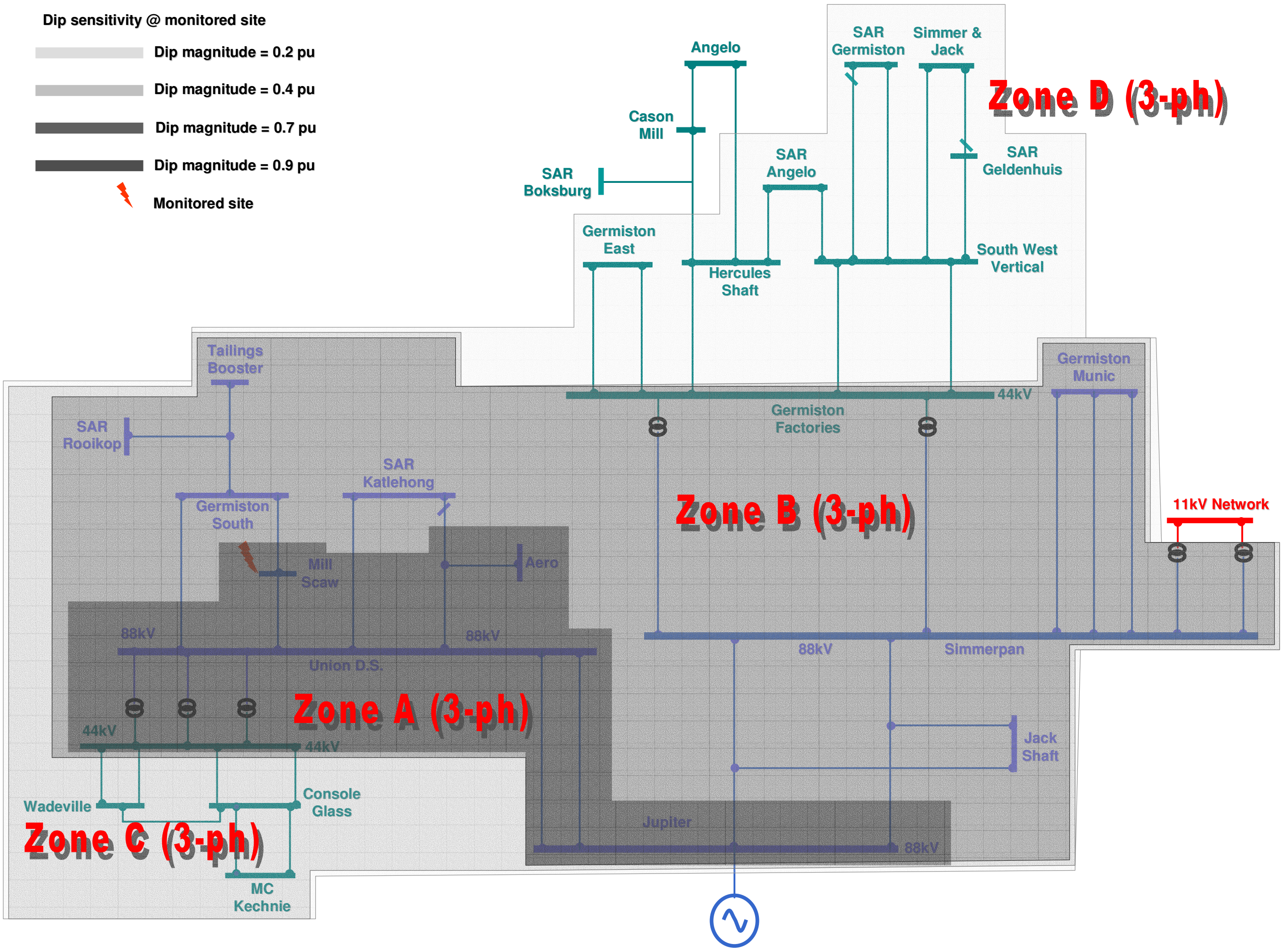



**Figure 4.7:** Dip influence zones for three-phase faults – steel plant

### 4.2.3 THE PAPER PLANT

#### 4.2.3.1 Phase-to-phase Faults

Figure 4.8 shows dip influence zones for phase-to-phase faults. Phase-to-phase faults within *Zone A (ph-ph)* cause dips of at least 0.5pu in magnitude at Enstra substation. *Zone A (ph-ph)* covers part of the 132kV networks. It is therefore expected that maintenance initiatives focussing on the Nevis/Struben lines and Benoni DS/Nevis lines will improve dip performance at the examined site. Phase-to-phase faults on the 44kV network only have a moderate impact on the monitored site (for large area of the 44kV network, dip magnitude is less than 0.3pu).

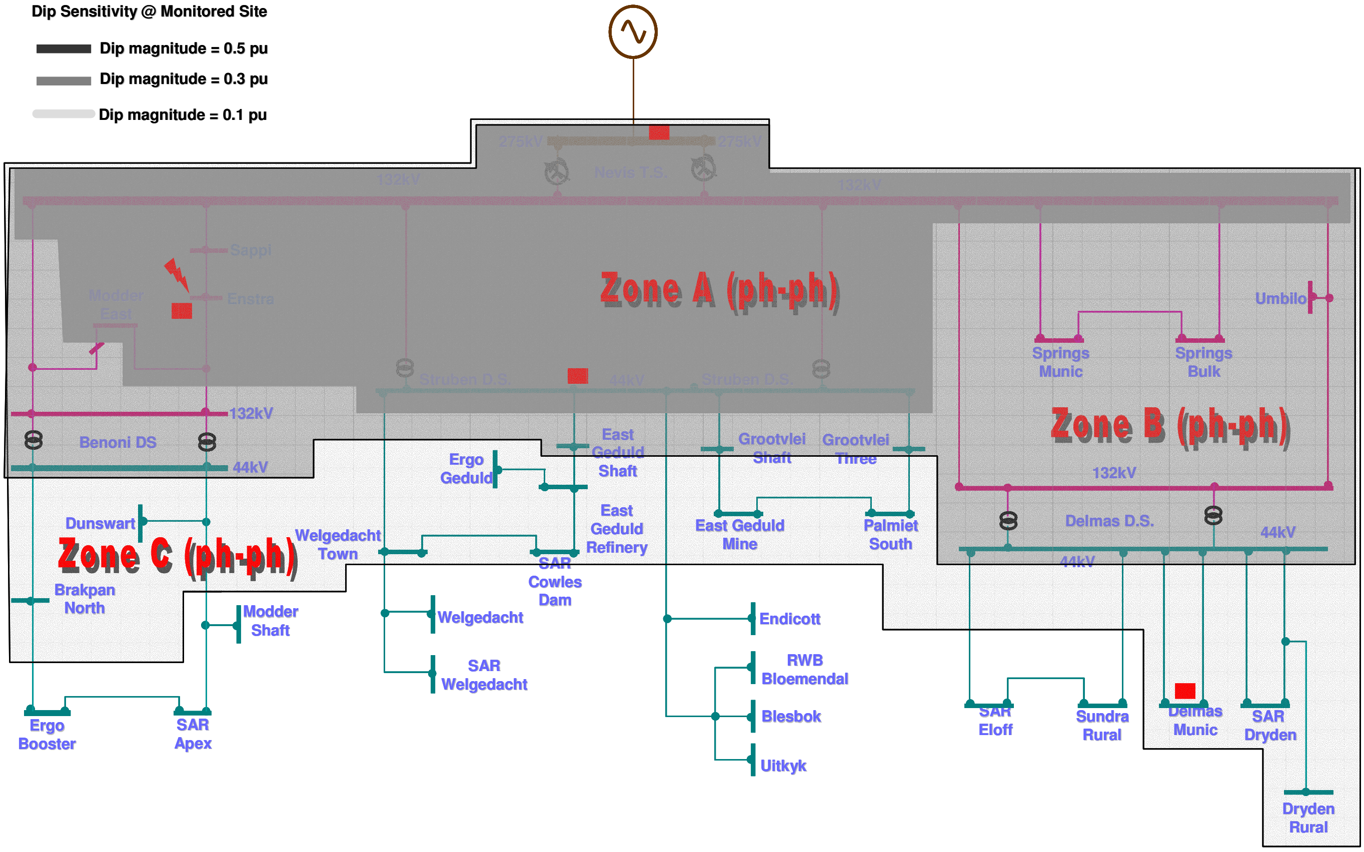



**Figure 4.8:** Dip influence zones for phase-to-phase faults – paper plant

### 4.2.3.2 Single-phase Faults

Voltage dip sensitivity areas for single-phase faults are presented in figure 4.9. SAPPI and Enstra substations are situated in an industrial area. In response to frequent flashover incidents (single-phase faults) as a result of industrial pollutants, maintenance projects were initiated to coat porcelain insulation with hydrophobic silicon rubber coating [24].

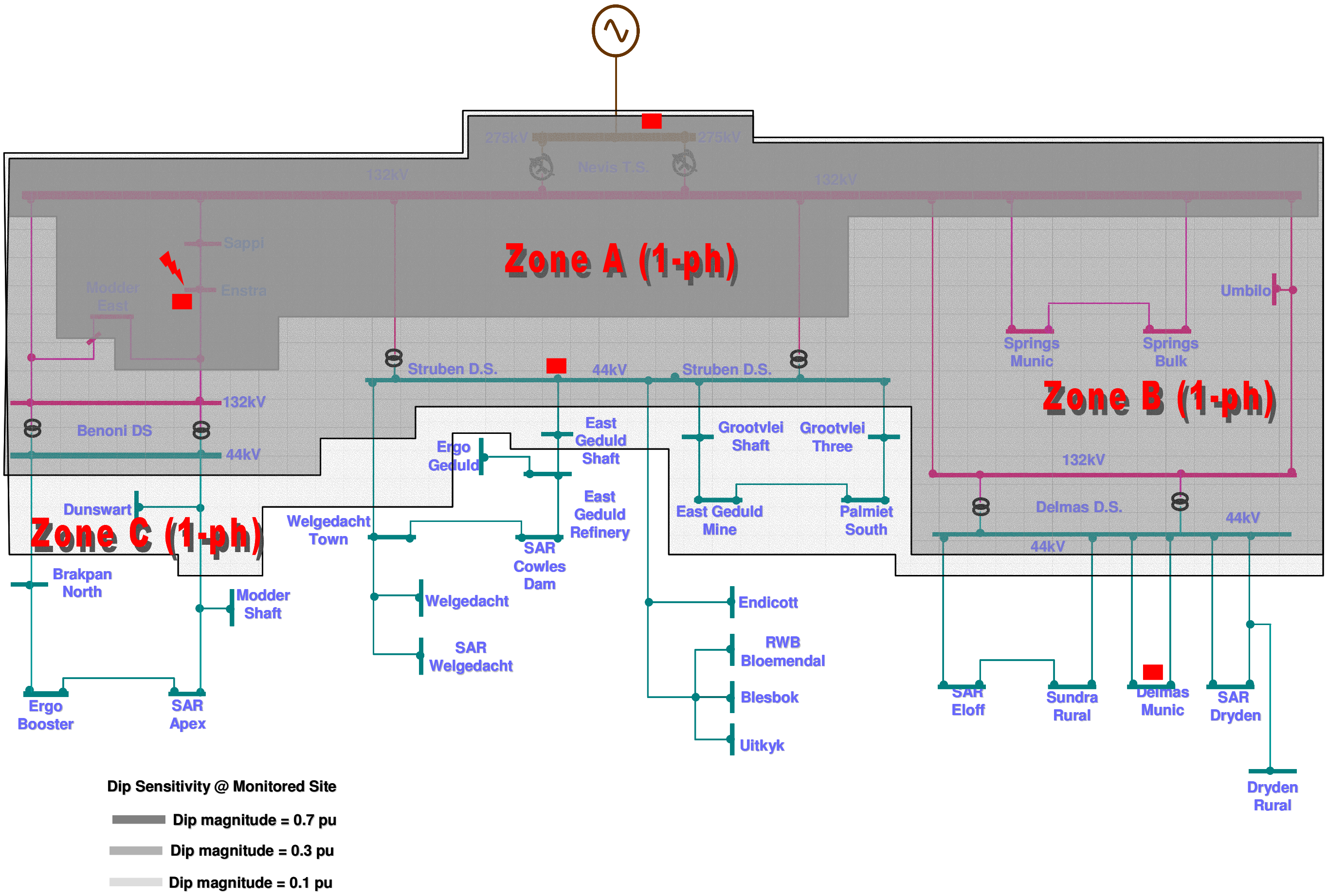



**Figure 4.9:** Dip influence zones for single-phase faults – paper plant

### 4.2.3.3 Phase-to-phase-to-ground Faults

Dip influence zones for phase-to-phase-to-ground faults are depicted in figure 4.10. For the same voltage dip sensitivity at Enstra (for example, dip sensitivity of 0.1pu), phase-to-phase-to-ground faults cover a wider area of the 44kV network compared to phase-to-phase faults for the same dip sensitivity.

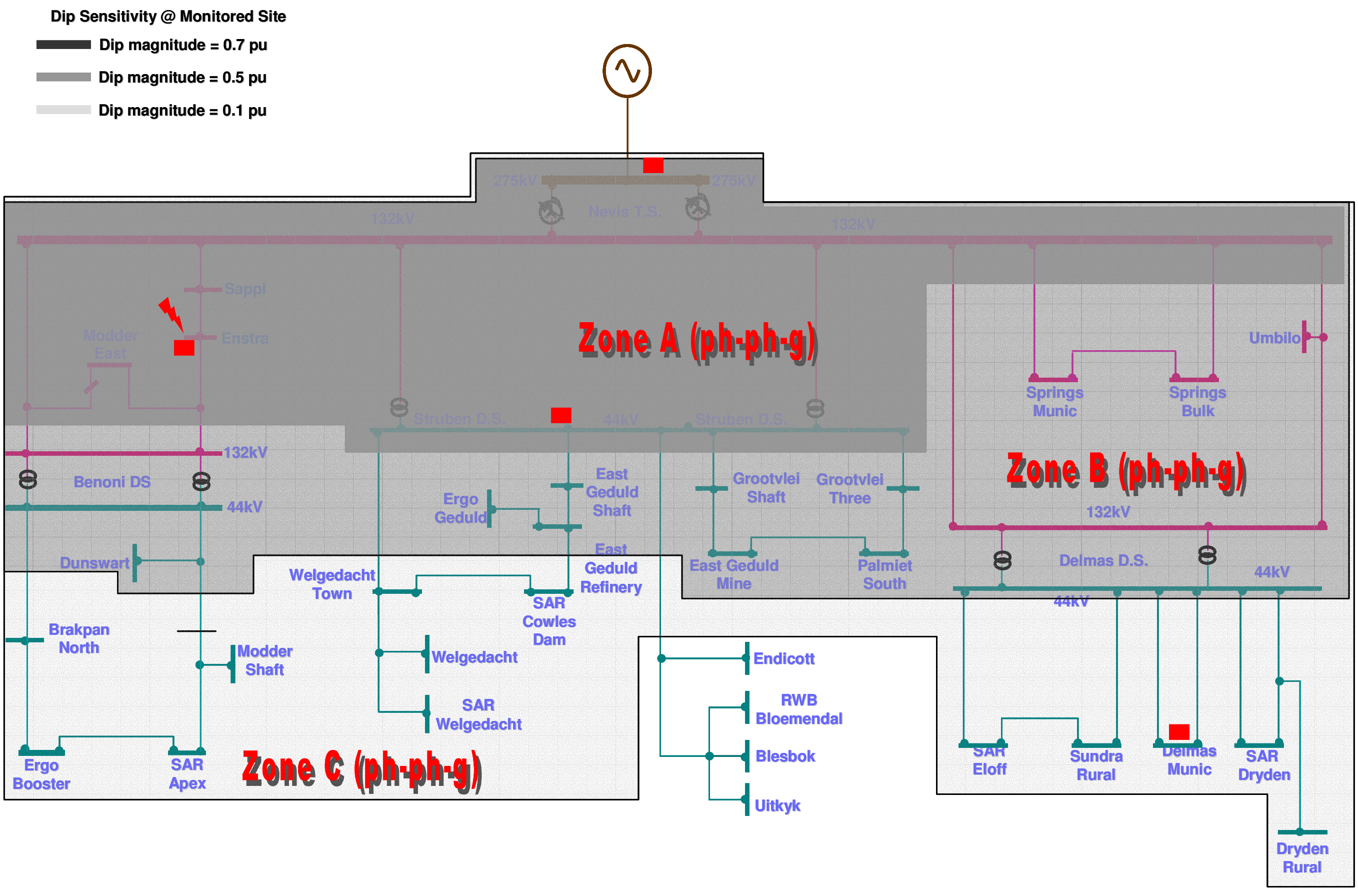



**Figure 4.10:** Dip influence zones for phase-to-phase-to-ground faults – paper plant

### 4.2.3.4 Three-phase Faults

Dip influence zones for three-phase faults are shown in figure 4.11. Failure of substation power plant often results in the most severe dips (three-phase faults) or interruptions. Power plant equipment prone to failure is installed at some of the substations enclosed by *Zone B (3-ph).* The resultant voltage dips at the monitored site will be more severe than 0.5pu. In the network development report compiled by Viljoen *et al* [24], the following catastrophic plant failures are reported to have occurred:

⇨ Weight-operated isolators at Modder East substation failed frequently on mechanical fatigue (isolator technology relying on mechanical weights to open or close; latest technology is based on electrical motor mechanism).

⇨ Contacts for bulk oil circuit breakers at Delmas DS often fail to open for faults in the correct zone of protection (bulk oil circuit breakers represent earliest switching technology based on excessively large volumes of oil for use as dielectric).

⇨ Transformer bushings (Benoni DS 132/44kV transformers) have catastrophically failed (shattering of porcelain bushings) twice during extreme weather (lightning) conditions.

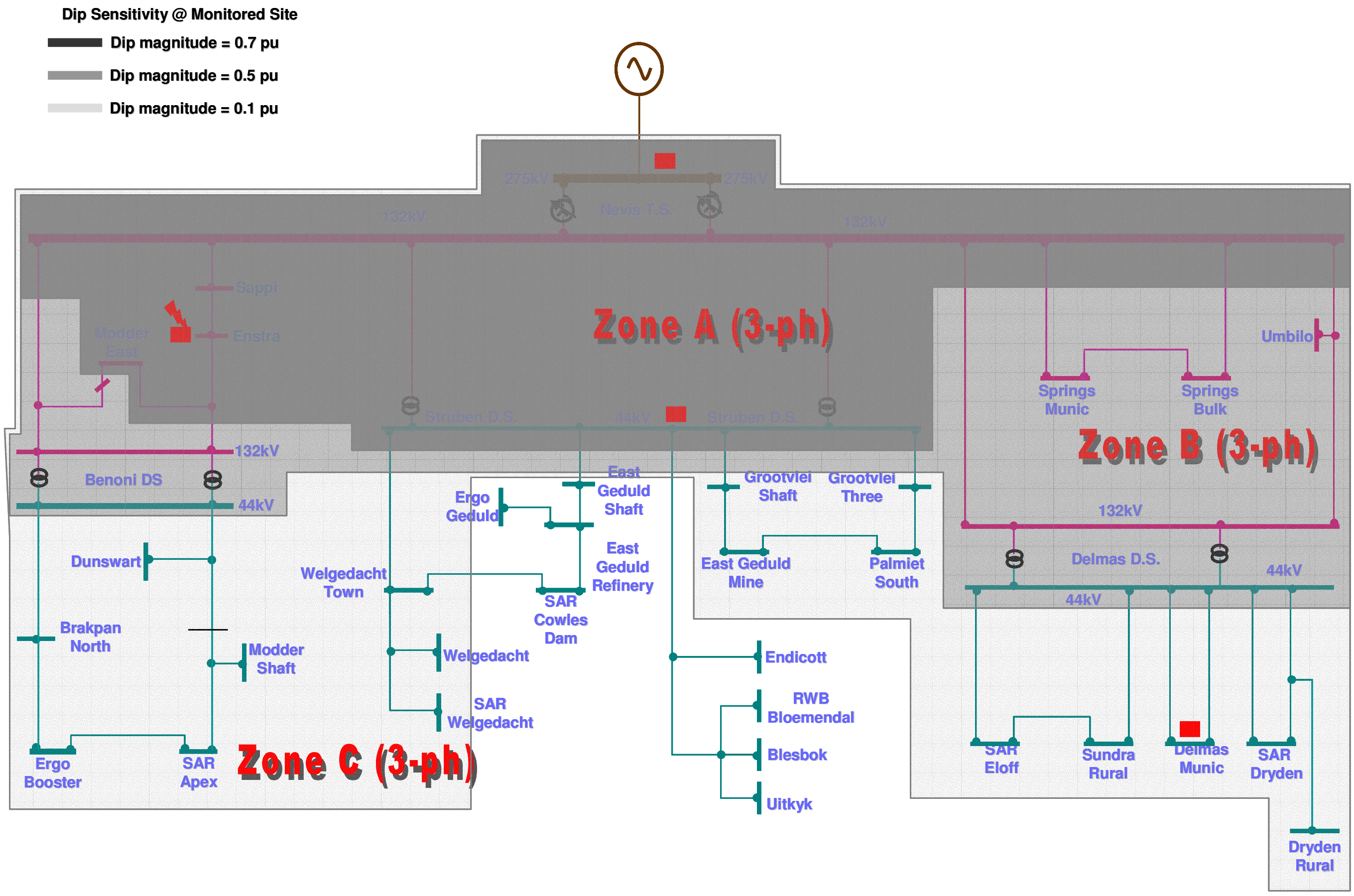



**Figure 4.11:** Dip influence zones for three-phase faults – paper plant

## 4.4 CONCLUSION

The dip influence zones are important graphical tools to assess the severity of dips on the site of interest.

For the steel plant, phase-to-phase faults on any part of the 88kV network cause dips more severe than 0.3pu at the monitored site. *Zone A (ph-ph),* representing a voltage sensitivity of 0.5pu, encloses the Union DS/Jupiter 88kV lines and part of Germiston South/Tailings Booster 88kV line. Germiston South/Tailings Booster and Union DS/Jupiter 88kV lines were identified as the worst-performing circuits in terms of dip performance. *Zone B (1-ph),* representing a voltage sensitivity of 0.4pu, encloses Germiston/Simmerpan 88kV circuits (underground oil-filled single-core cables in flat formation). In the investigation conducted in [33], the average performance of these circuits was calculated to be two faults per circuit per annum in 2005. This performance statistic translates to an average of four dip events more severe than 0.4pu, per circuit per annum (each cable circuit is 2.15km in length).

Phase-to-phase-to-ground faults on the 88kV network cause dips exceeding 0.7pu (*Zone B (ph-ph-g))* while phase-to-phase faults on the same network cause dips exceeding 0.3pu *(Zone B (ph-ph))* at the monitored site. Thus it would appear that the customer plant is more sensitive to phase-to-phase-to-ground faults compared with phase-to-phase faults. Three-phase faults on Union DS/Jupiter and Germiston South/Tailings Booster 88kV lines cause dips worse than 0.7pu at the monitored site *(Zone B (3-ph)).* These two lines were identified as the circuits where the largest number of faults occurred.

For the paper plant, phase-to-phase faults on the 44kV network have a moderate impact on the customer's plant (for a large area of the 44kV network, dip sensitivity is 0.3pu). *Zone A (1-ph),* representing a dip sensitivity of 0.7pu, covers part of the 132kV network. Numerous single-phase faults were experienced on the 132kV network due to industrial pollution (SAPPI and Enstra substations) and conductor theft (Benoni DS/Nevis 1 and SAPPI/TEE 132kV lines). *Zone B (3-ph)* and *Zone B (ph-ph-g),* both with dip sensitivities of 0.5pu, enclose the entire 132kV network. Catastrophic plant failures (three-phase faults) have occurred at certain substations within the 132kV network (Modder East, Delmas DS, Benoni DS) [24]. To improve dip performance at the monitored site, the following strategies may be considered:

⇨ Decreasing the frequency of faults by phasing out obsolete plant technology at Modder East, Delmas DS, Benoni DS and other substations.
⇨ Eliminating or at least decreasing the frequency of faults due to conductor theft, storm-related, conductor-related and veld fire incidents, particularly on the Benoni DS/Nevis 1 and SAPPI/TEE 132kV overhead lines.

# CHAPTER 5:
# COMMUNICATION OF VOLTAGE DIP PERFORMANCE

## 5.1 INTRODUCTION

Regular interactions between Eskom and its industrial customers are necessary to find solutions to power quality problems. In these forums, discussions are centred around dip events recorded since the previous forum. The utility's primary objective is to monitor dip performance so that the dip limits are not exceeded. The limitation of the existing dip performance communication practices are discussed in section 2.3.4.

The proposed strategy is summarized in table 5.1. The key elements of the proposed dip performance communication strategy are briefly discussed below. Table 5.1 was generated in this study.

### 5.2 DIP PERFORMANCE ANALYSIS

Electrical faults can occur on the transmission networks, distribution networks or at the customer's plant. Within Eskom, transmission and distribution networks are operated by independent business units (Transmission and Distribution). It is therefore necessary to analyse dip events according to ownership of the networks where dips occurred.

Dip causes are determined by correlating dip data (time of occurrence) and circuit breaker trip data. Events with identical time stamps (in milliseconds) are considered to be correlated. For ease of analysis, dip causes are classified into a finite number of categories. In the event that the cause of a dip cannot be verified, the dip is assigned to the 'unknown' category. The number of dips in the 'unknown' category must be kept to a minimum, especially in cases where the dips have long durations or large magnitudes or both.

To be able to respond to unsatisfactory dip performance, the location of faults affecting the customer, must be known. When used in conjunction with dip causes and dip types, the identification of critical circuits enables both the utility and customer to formulate appropriate solutions to specific dip performance problems.

A disturbance such as a voltage dip event can cause customer plant to malfunction or shut down after which a time-dependent restart procedure is needed. The evaluation of dip-related financial losses gives the utility the appreciation of the impact of dips on industrial processes.

### 5.3 VOLTAGE DIP SIMULATION

The impact of dips can be quantified by modelling the supply network and simulating faults to compute fault positions for pre-defined dip sensitivities at the monitored site. The end result of the dip simulation exercise is a set of dip influence zones for various fault types. The calculation of dip influence zones is particularly important to both the customer and the utility. The utility can use dip influence zones to direct maintenance and refurbishment initiatives to specific parts of the network to improve dip performance for a specific site. Dip influence zones may also be used as a tool to encourage customers to increase their plant dip immunity levels for faults on remote networks. The additional benefit of defining dip influence zones is that clear responsibilities can be assigned between the customer and the utility, in respect of dip performance. For example, the utility may be required to limit the frequency of faults on networks close to the customer, while the customer may be required to increase plant immunity levels for faults on remote networks.

### 5.4 FEEDBACK FROM CUSTOMERS

The proposed approach (summarized in table 5.1) was adopted in communicating dip performance to industrial customers. The QOS interaction forum of the 10$^{th}$ August 2006 was based on this new approach. This new approach is considered to be the optimal communication strategy for dip performance and has been received with enthusiasm by industrial customers consulted.

*Annexure F* is an incomplete example of the proposed approach to the management of dip performance presented to the pulp and paper customer (dip influence zones were still under development at the time of presentation). The author of this thesis performed the analysis (using Excel, Event Viewer, NEPS and TIPPS) that was presented in [34]. Reference [35] is a complete presentation that was presented to Eskom field personnel in the presence of the steel plant customer.

**Table 5.1:** Elements of the proposed dip performance communication strategy

| **Element** | **Description** |
|---|---|
| Platform to discuss dip performance | 1. Regular customer interaction forums.<br>2. Ad hoc meetings in response to specific customer request. |
| Key objectives of interactions | 1. Collaborate with customers to ensure mutual responsibility of dip performance.<br>2. Provide sufficiently detailed information to enable investment decisions on QOS improvement projects. |
| Points of discussion | 1. Comprehensive analysis of recorded dip events:<br>a. Ownership of network where dips occurred.<br>b. Causes of dips (dip-to-trip matching).<br>c. Circuits that affect dip performance of the customer's plant most severely.<br>d. Types of dips per contributing circuit.<br>e. Financial impact of voltage dips on the customer.<br>2. Dip modelling<br>a. Identifying network areas in which faults may affect dip performance at the examined site.<br>b. Simulating electrical faults and resultant dips at the monitored site.<br>c. Calculating dip sensitivity zones for all fault types.<br>d. Comparison of simulated dip impact (remaining voltage at monitored site) with actual recorded dip events.<br>3. Progress on QOS initiatives identified during previous interactions. |
| Basis of interaction | 1. Joint effort to manage dip performance according to known factors (industrial pollution, conductor theft, age of plant). |
| Customer participation | 1. Demonstrating how dip immunity levels of plant will be increased for faults on remote networks.<br>2. Track production downtime losses as a direct result of dips.<br>3. Share feedback on customer's own initiative to improve dip performance.<br>4. Influencing progress of the utility's initiatives to improve dip performance. |
| Review of dip simulations | 1. Dip influence zones are to be reviewed in the event of major changes in the configuration of the network (new substation connected, network supplied from a different source, major equipment failures). |

# CHAPTER 6:
# CONCLUSIONS

## 6.1 OVERVIEW

This study examined the following key research question: **How can communication of dip performance be optimized, with a view to ensuring mutual technical responsibility of plant, between the utility and the customer?** The scope of the study included dip analysis for the selected industrial plants, network modelling, calculation of dip influence zones and presentation of results to customers concerned. To investigate the key research question the following process, outlined in Section 1.8, was followed:

- ⇨ Conducting a literature review.
- ⇨ Analysing dip performance for industrial plants from both the customer and utility perspective.
- ⇨ Modelling and simulation of networks supplying the industrial plants and calculation of dip influence zones for each plant.
- ⇨ Presentation of results to the industrial customers.

## 6.2 LITERATURE REVIEW

Several definitions of voltage dips exist in literature, differing only in the specification of magnitude and duration thresholds. Industrial processes are sensitive not only to dip magnitude and duration, but also to phase-angle jump and point-on-wave characteristics.

Voltage dips are caused by short-duration overcurrents flowing through the power system. The principal contributions to overcurrents are motor starting, transformer energizing and power system faults. Electrical motors are three-phase balanced loads, and the associated voltage drops, during start-up, are the same in all phases. The energizing of a large transformer gives rise to voltage dips characterized by a sudden drop in voltage and a slow recovery. Power system faults are the most frequent cause of dips, single-phase short-circuits in particular.

The causes of faults can be grouped into a finite number of categories. Lightning-related faults may arise as a consequence of direct lightning strikes, indirect lightning strikes and back-flashover from shield wire or steel tower. Bird-initiated faults arise due to bird electrocutions, bird streamers and insulator pollution as a result of bird droppings. In addition, insulator pollution, hardware failures, veld fires, cane fires and vegetation-induced faults also have a profound influence on the performance of electrical networks.

Various methods of extracting useful information from dip records have been investigated in literature. The IEC dip characterization method defines dip magnitude as the maximum r.m.s. excursion from the declared voltage. The dip duration is defined as the instant when the r.m.s. voltage on one phase falls below the dip threshold to the instant when all three phases are again above the dip threshold. The limitation of the IEC method is that a voltage drop in a single phase is characterized as equally severe as a voltage drop in all three phases.

The ABC method distinguishes between seven types of dip events by analysing possible types of short-circuits, the dip propagation through transformers and connection of measuring instruments. The ABC method assumes that sequence impedances are equal, and this is the limitation of this method. The symmetrical dip characterization method distinguishes between dip events with the main voltage drop in one phase and dip events with the main voltage drop in multiple phases. To characterize the dip event, the symmetrical method defines two parameters: the positive-negative factor and the characteristic voltage.

The South African dip characterization method has evolved over many years from the ABCD dip window to the STXYZ dip window currently in use. The dip window is a two-dimensional plot of dip magnitude and dip duration as a function of customer equipment dip immunity levels and speed of protection systems.

Voltage dip performance is not a standard specification on industrial equipment. Customers are therefore, largely unaware of the potential dip sensitivity problems when designing new plants or extending existing ones. Voltage dips can cause tripping of computers and process-control equipment. Motor contactors can drop out due to lack of voltage required by the magnetic coils to keep the contactors connected. Variable speed drives may trip due to operation of undervoltage protection and overcurrent protection. Voltage dips may cause certain types of lamps to extinguish completely or partially.

Various approaches are available to mitigate voltage dip problems: power system grid, system-equipment interface and process improvement solutions. The frequency and severity of dips may be reduced by reconfiguring the power system grid. Examples of system reconfiguration include splitting of busbars, improving fault clearing time, installing current limiting reactors and others. The frequency of short-circuits can be reduced by installing bird guards, maintaining line servitudes and installing line arresters. Most of the dip mitigation techniques used at the system-equipment interface are based on the injection of power to compensate for the loss of active power during a dip event. Motor-generator sets, static shunt compensators and uninterruptible power supplies are some of many energy storage devices that can be installed at the PCC. Process modification options are concerned with improving the ride-through capability of process equipment. Variable speed drives can be equipped with automatic restart. For installations where a d.c. supply is available, replacement of a.c. contactors with d.c. contactors can be considered.

Two methods are generally used for modelling of voltage dips, namely, the method of fault positions and the method of critical distances. The method of fault positions is used to calculate the magnitude and duration of voltage dips at the monitored site for a number of faults spread throughout the power system. The method of critical distances calculates fault positions (distances from the monitored site) for a given dip sensitivity (magnitude or duration or both) at the monitored site. Voltage dip sensitivity zones are derived from a plot of fault distances (for a set of fault parameters) on the power system.

In the South African context, the initial regulatory framework defined compatibility levels for voltage dips in the form of a maximum number of voltage dips per year for each voltage dip type. South African utilities have experienced difficulty in complying with the dip limits specified by NERSA. Eskom holds regular customer interaction forums with the intention to discuss and solve dip problems and other power quality issues. The primary objective of these interactions is to demonstrate dip performance against dip limits. The new regulatory framework was developed in response to the difficulty of managing voltage dip performance based on limits.

## 6.3 VOLTAGE DIP PERFORMANCE ANALYSIS

It is a regulatory requirement for the utilities to install power quality measuring instruments at sufficient locations in their electrical networks to adequately measure and report performance. Eskom's measured dip data is stored in a central database. For both the steel plant and the paper plant, the dip data was analysed by considering the ownership of the networks, causes of dips, dip classes and costs associated with dip events.

For the steel plant, a presentation of dip events according to ownership of the network, revealed that a large number of T-class dips occurred on the distribution networks. This observation can be attributed to faults clearing via back-up protection, in case of failure of the main protection systems. A breakdown of fault causes showed that storm-related faults, equipment failures, conductor-related faults and conductor theft incidents form the largest contribution to dip performance of the monitored site.

The largest number of electrical faults occurred on the Germiston South/Tailings Booster and Union DS/Jupiter 88kV overhead lines. Long-duration dip events (T-class, Z1-class, Z2-class and S-class) occurred predominantly on Germiston South/Tailings Booster, Union DS/Jupiter and Germiston South/SAR Rooikop 88kV lines. The plant audit conducted by the author on the Union DS 88kV network, revealed that the protection system is outdated and prone to failure while product support has also ceased to exist [25], [26]. The relay-based protection technology has, over the years, evolved from phase-1 relays (electromagnetic relay technology) to phase-4 relays (digital programmable relay technology). On the other hand, the original phase-1 relays installed at Union DS, Germiston South and Mill Scaw substations, have been in operation for a period exceeding 30 years. Consultations with representatives of the steel plant revealed that dip-related costs would only be crude estimates and consequently dip cost analysis was not performed for this plant.

For the pulp and paper plant, long-duration dip events (T-class and Z2-class) experienced at the monitored site, originated from the distribution networks. A distribution of dip causes showed that conductor theft incidents, conductor-related faults, storm-related faults and veld fires contributed significantly to dip performance of the monitored site. Electrical faults occurred predominantly on Benoni/Nevis 1 and SAPPI/Tee 1 132kV overhead lines. Long-duration dip events (Z2-class and T-class) occurred predominantly on Benoni/Nevis 1 132kV line and SAPPI/Tee 132kV line.

Faults on the Benoni/Nevis 1 132kV line (mainly conductor theft) and SAPPI substation resulted in the highest financial losses (exceeding R800,000 in 2003). Possibility exists that the customer may over-estimate dip-related downtime costs in an attempt to accelerate maintenance efforts on the utility side.

## 6.4 VOLTAGE DIP SIMULATION

Voltage dip influence zones are important graphical tools to assess the impact of dips on the examined site.

For the steel plant, phase-to-phase faults on any part of the 88kV network cause dips more severe than 0.3pu at the monitored site. *Zone A (ph-ph),* representing a voltage sensitivity of 0.5pu, encloses the Union DS/Jupiter 88kV lines and part of Germiston South/Tailings Booster 88kV line. Germiston South/Tailings Booster and Union DS/Jupiter 88kV lines were identified as the worst-performing circuits in terms of dip performance. *Zone B (1-ph),* representing a voltage sensitivity of 0.4pu, encloses Germiston/Simmerpan 88kV circuits (underground oil-filled single-core cables in flat formation). In the investigation report conducted in [33], the average performance of these circuits was calculated to be two faults per circuit per annum in 2005. This performance statistic translates to an average of four dip events (minimum depth of 0.4pu) per circuit per annum (each cable circuit is 2.15km in length). Three-phase faults on Union DS/Jupiter and Germiston South/Tailings Booster 88kV lines cause dips worse than 0.7pu at the monitored site *(Zone B (3-ph))*. These two lines were identified as the circuits where the largest number of dips occurred.

For the paper plant, phase-to-phase faults on the 44kV network have a moderate impact on the customer's plant (for a large area of the 44kV network, dip sensitivity is 0.3pu). *Zone A (1-ph),* representing a dip sensitivity of 0.7pu, covers part of the 132kV network. Numerous single-phase faults were experienced on the 132kV network due to industrial pollution (SAPPI and Enstra substations) and conductor theft (Benoni DS/Nevis 1 and SAPPI/TEE 132kV lines). *Zone B (3-ph)* and *Zone B (ph-ph-g),* both with dip sensitivities of 0.5pu, enclose the entire 132kV network. Catastrophic plant failures (three-phase faults) have occurred at certain substations within the 132kV network (Modder East, Delmas DS, Benoni DS) [24].

## 6.5 REVIEW OF STUDY OBJECTIVES

The objectives of the research study were stated as follows:

- ⇨ To quantify voltage dip performance for the selected industrial plants.
- ⇨ To define voltage dip sensitivity zones for the selected plants.
- ⇨ To propose and present to the customers, an alternative approach in communicating dip performance.

A literature review was conducted to develop the conceptual framework for the study. Voltage dip concepts such as phase-angle jump, dip characterization, dip causes, effects of dips and mitigation techniques were reviewed.

A dip analysis study was conducted to extract useful dip information from recorded data. The dip data was analysed in conjunction with circuit breaker trip data available in Eskom's network performance systems. The results of the analysis enable the utility to conduct detailed investigations on the following issues:

- ⇨ Possible solutions to reduce the number of conductor-related faults on the Germiston South/Tailings Booster 88kV line.
- ⇨ Possible solutions to eliminate or at least reduce the number of conductor theft incidents on the Union DS/Jupiter 88kV lines, Germiston South/Tailings Booster 88kV line and Benoni DS/Nevis 132kV lines.
- ⇨ Feasible options to improve the speed of fault-clearing for faults on the Benoni/Nevis 1 132kV line, SAPPI/Tee 132kV line, Germiston South/Tailings Booster 88kV line, Union DS/Jupiter 88kV line and Germiston South/SAR Rooikop 88kV line.
- ⇨ Plans to phase out obsolete plant technology at Modder East substation (weight-operated isolators) and Benoni DS (bulk oil circuit breakers).

The analysis results also make it possible for the customer to critically review financial losses due to voltage dips:

- ⇨ The pulp and paper customer lost in excess of eight hundred thousand rands in 2003. Therefore an opportunity exists to invest in energy storage devices (compensators, ferroresonant transformers etc) or process equipment to improve dip performance of the plant.
- ⇨ Financial losses due to dips are estimated and tracked by the customer. It is not clear how the overall cost estimation is derived. Therefore a need exists to conduct a comprehensive study on the estimation of production losses due to voltage dips.

The dip analysis identified critical circuits, verified causes of faults and made it possible for both the utility and the customer to discuss possible options to improve dip performance.

The models of networks supplying the selected industrial plants were successfully created in DIgSILENT PowerFactory. Different types of faults were then simulated in the power system to evaluate the impact at the monitored sites. The results of the simulations were used to define dip influence zones for each industrial plant. The calculation of dip influence zones allows the utility and its customers to hold discussions on the following issues:

- ⇨ Plans to reduce the frequency of faults on the network closest to the customer's point of supply. *Zone B (3-ph)* for the paper plant, encloses the entire 132kV network. Faults on the 132kV network are expected to cause dips exceeding 0.5pu at the monitored site.
- ⇨ Plans to increase equipment dip immunity levels for faults on remote networks. For the steel plant, single-phase faults on the Simmerpan/Germiston Munic 88kV circuits (underground oil-filled cables) occur frequently and take long to restore. The dip sensitivity for faults on these circuits is 0.4pu, at the monitored site *(Zone A (1-ph)).*

The dip influence zones allow the utility and the customers to quantify the dip impact at the site of interest, as a result of faults at various parts of the supply system.

The alternative approach to dip performance communication was successfully developed. The proposed approach is presented in table 5.1 (section 5.4) and table 2.5 (section 2.3.5). The implication is that a much more comprehensive analysis of dips needs to be conducted by power quality engineers compared to the current practice. The proposed strategy in communicating dip performance was presented and adopted by the customers involved in this study.

## REFERENCES


[1] Martinez-Velasco JA, Bollen MJH, Olguin G, Leborgne RC, Milanovic J, Abi-Samra N, Hatziargyriou N, *"Voltage Dip Evaluation and Prediction Tools",* CIGRE TF C4.1.02, November 2005.

[2] Bollen MJH, *"Understanding Power Quality Problems: Voltage Dips and Interruptions",* IEEE Press, New York, ISBN 0-7803-4713-7, 2000.

[3] Didden M, *"Techno-economic Analysis of Methods to Reduce Damage due to Voltage Dips"*, Ph. D Thesis, Katholieke Universiteit Leuven, ISBN 90-5682-463-5, December 2003.

[4] Zhang LD, Bollen MHJ, *"Characteristics of Voltage Dips (Sags) in Power Systems"*, IEEE Transactions on Power Delivery, Volume 15, No. 2, pp.827 – 832, April 2000.

[5] McGranaghan MF, Mueller DR, Samotyj MJ, *"Voltage Sags in Industrial Power Systems"*, IEEE Transactions on Industry Applications, Volume 29, No. 2, pp.397 – 403, March 1993.

[6] Koch RG, *"Voltage Dips"*, Course Notes: Power Quality and EMC, University of KwaZulu-Natal, May 2005.

[7] Koch RG, Sigwebela I, Geldenhys H, *"A Summary of South African Experience with Power Quality Management"*, CIRED, 2003.

[8] NRS 048-2:1996, *"Electricity Supply – Quality of Supply Standards – Part 2: Minimum Standards*", Rev 0, 1996.

[9] National Energy Regulator of South Africa (NERSA), *"NER Directive on Power Quality: A Regulatory Framework for the Management of Power Quality in South Africa"*, Final Draft, Rev 1.5, March 2002.

[10] NRS 048-2, *"Electricity Supply – Quality of Supply Standards – Part 2: Minimum Standards"*, Rev 2.1, ISBN 0-626-15823, 2004.

[11] Djokić SZ, Milanović JV, Kirschen DS*, "Sensitivity of AC Coil Contactors to Voltage Sags, Short Interruptions and Undervoltage Transients"*, IEEE Transactions on Power Delivery, Volume 19, No. 3, July 2004.

[12] Bollen MHJ, Styvaktakis ME, *"Characterization of Three-phase Unbalanced Dips (as easy as one-two-three)"*, IEEE Power Engineering Society meeting, Volume 2, pp. 899 – 904, ISBN 0-7803-6420-1, July 2000.

[13] Bologna FF, Pillay T, *“Maintenance of Insulators, Conductors and Hardware*”, Chapter 5 in *“The Fundamentals and Practices of Overhead Line Maintenance: 132kV and Above”,* Crown Publications, Johannesburg, ISBN 0-620-30906-7, March 2004.

[14] Vosloo HF, *“The Need for and Contents of a Life Cycle Management Plan for Eskom Transmission Line Servitudes”*, M Sc Thesis in Geography, Rand Afrikaans University, March 2005.

[15] Van Rooyen CS, *“The Management of Wildlife Interactions with Overhead Lines”*, Chapter 11 in *“The Fundamentals and Practices of Overhead Line Maintenance: 132kV and Above”,* Crown Publications, Johannesburg, ISBN 0-620-30906-7, March 2004.

[16] IEC 61000-4-30, *“Electromagnetic Compatibility (EMC) – Part 4-30: Testing and Measurement Techniques – Power Quality Measurement Methods”*, ISBN 978-0-626-194376-6, Edition 1, February 2003.

[17] Bollen MHJ, Zhang LD, *“Different Methods for Classification of Three-phase Voltage Dips due to Faults”*, Electric Power Research Institute (EPRI), Vol. 66, Issue 1, pp.59-69, July 2003.

[18] Coney RG, Johnson PA, *“The Evolution of the A,B,C & D Dip Chart to the S, T, W, X, Y & Z Chart in Depicting Voltage Dips in South Africa”*, First Southern African Power Quality Conference, South Africa, Date unknown**.**

[19] Lamoree J, De Winkel C, Vinett P, *“Description of a Micro-SMES System for Protection of Critical Customer Facilities”*, IEEE Transactions on Power Delivery, Volume 9, No. 2, April 1994.

[20] NRS 048-3, *“Electricity Supply – Quality of Supply Standards – Part 3: Measurement and Reporting Procedures”*, Draft Report, Rev 2.0, January 1997.

[21] Smith J, *“QOS Presentation: Nevis TS Network”,* Power Quality Presentation, QOS Forum, SAPPI (Springs), August 2005.

[22] Ragunanthan R, *“Eskom QOS Database Course”,* QOS Database Course Notes, Eskom Transmission Group, November 2005.

[23] Eskom Annual Report, www.eskom.co.za, 2008.

[24] Viljoen G, de Jager F, Letong R, *“Network Develop Plan: East Rand”,* Network Planning Report, Eskom Distribution North West Region, July 2004.

[25] Nzimande TM, *“Union DS Refurbishment Proposal”,* Plant Refurbishment Investigation Report, Eskom Distribution North West Region, February 2006.

[26] Nzimande TM, *"Mill Scaw Substation Refurbishment Proposal",* Plant Refurbishment Investigation Report, Eskom Distribution North West Region, February 2006.

[27] Nzimande TM, *"Mill Scaw Substation Refurbishment"*, Project Technical Evaluation Committee (PTEC) Presentation, Eskom Distribution North West Region, March 2006.

[28] Nzimande TM, *"Union DS Refurbishment*", Project Technical Evaluation Committee (PTEC) Presentation, Eskom Distribution North West Region, March 2006.

[29] Morreirra I, "Financial Losses due to Voltage Dips for SAPPI Springs", Eskom Power Quality Work Group, February 2006.

[30] DIgSILENT South Africa (Pty) Ltd, *"PowerFactory Manual",* Version 13.0, 2003.

[31] Smit RF, *"Calculation of Conductor Parameters for Overhead Lines",* Network Planning Report, Eskom Distribution Western Region, February 2000.

[32] Schilder M, *"Distribution Power System Simulator Tool Application to Power Quality"*, Eskom Research and Innovation Centre, Research Report, RES/RR/03/21067, November 2003.

[33] Nzimande TM, *"Refurbishment Investigation Report: Germiston Oil-filled Cables",* Plant Refurbishment Report, Eskom Distribution North West Region, October 2005.

[34] Sprunt A, Minaar U, *"QOS Enstra Report"*, Power Quality Presentation, QOS Forum, SAPPI (Springs), August 2005.

[35] Nzimande TM, *"Power Quality Presentation: Mill Scaw Site"*, Power Quality Presentation, Eskom Germiston Technical Service Area, Germiston, October 2006.

[36] CIGRE JWG C04.07, "*Power Quality Indices and Objectives*", CIGRE Joint Working Group, www.cired-s2.org. January 2004.

[37] Park J, *"Voltage Dip Risk Factor for Distribution Networks"*, Master of Science (Eng) Thesis, Rand Afirkaans University, 2004.

[38] Van Schalkwyk ET, *"Reticulation Fault Finder",* Investigation Report, Eskom Distribution North West Region, 2005.

[39] Olguin G, *"Voltage Dip (Sag) Estimation in Power Systems based on Stochastic Assessment and Optimal Monitoring",* Ph D Thesis, Chalmers University of Technology, Gotenborg, Sweden, ISBN 91-7291-594-3, 2005.

[40] SAPPI Annual Report, www.sappi.com, 2008.

# ANNEXURE A:

# STEEL PLANT DIP RECORDS (2003 – 2005)

| Depth Block | Duration Block | DIP_DT | PHASES | New Class | Group | CIRCUIT | CAUSE |
|---|---|---|---|---|---|---|---|
| D1(0-<30%) | T1(0-<50ms) | 2003/01/05 18:31 | R | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2003/01/05 18:31 | RW | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2003/01/09 02:13 | RWB | Z1 | Distribution | SOUTH WEST VERTICAL 44/6.6/3.3KV SUBSTATION | Storm Related |
| D1(0-<30%) | T6(600ms-3s) | 2003/01/09 03:35 | WB | Z1 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T1(0-<50ms) | 2003/01/15 21:55 | W | Y | Unknown | Unknown | Unknown |
| D2(30-<40%) | T1(0-<50ms) | 2003/01/15 21:55 | W | X1 | Unknown | Unknown | Unknown |
| D4(60-100%) | T4(100-<150ms) | 2003/01/17 19:46 | RWB | T | Transmission | Jupiter No4 275kV Shunt Cap Bay | Equipment Failure |
| D2(30-<40%) | T3(70-<100ms) | 2003/02/14 14:37 | B | X1 | Transmission | Esselen No6 275kV - 132kV - 22kV Trfr Bay | Human Related |
| D4(60-100%) | T4(100-<150ms) | 2003/02/14 17:19 | R | T | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV BKR | Veld Fire |
| D2(30-<40%) | T4(100-<150ms) | 2003/03/23 18:22 | RW | X1 | Distribution | SOUTH WEST VERTICAL TRFR 2AB 44/3.3kV TRFR BAY | Storm Related |
| D3(40-<60%) | T6(600ms-3s) | 2003/03/23 18:32 | RWB | Z2 | Distribution | SOUTH WEST VERTICAL TRFR 2AB 44/3.3kV TRFR BAY | Storm Related |
| D1(0-<30%) | T5(150-<600ms) | 2003/03/23 19:00 | B | Y | Unknown | UNION DS TRFR 2 88kV BKR | Protection Failure |
| D3(40-<60%) | T6(600ms-3s) | 2003/03/23 19:20 | RWB | Z2 | Customer | MILL SCAW TRFR 4 88/6.6kV TRFR Bay | Customer Related |
| D4(60-100%) | T3(70-<100ms) | 2003/04/05 21:24 | B | T | Distribution | JACK SHAFT TRFR 1 88/6.6kV TRFR | Equipment Failure |
| D1(0-<30%) | T6(600ms-3s) | 2003/04/18 03:23 | RWB | Z1 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2003/05/02 12:03 | RWB | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2003/05/02 12:03 | RW | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T4(100-<150ms) | 2003/05/02 12:03 | R | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2003/05/02 12:03 | RW | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2003/06/09 14:33 | RWB | Z1 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2003/07/30 08:29 | RWB | Z1 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2003/08/11 11:48 | RWB | Y | Customer | Prospect-Kelvin 3 | Customer Related |
| D1(0-<30%) | T6(600ms-3s) | 2003/08/11 11:48 | RWB | Z1 | Customer | Prospect-Kelvin 3 | Customer Related |
| D1(0-<30%) | T6(600ms-3s) | 2003/08/11 11:48 | RWB | Z1 | Customer | Prospect-Kelvin 3 | Customer Related |
| D2(30-<40%) | T3(70-<100ms) | 2003/08/12 08:39 | RW | X1 | Distribution | SIMMER & JACK / SOUTH WEST VERTICAL 1 44kV HV Overhead Line | Cable Fault |
| D1(0-<30%) | T1(0-<50ms) | 2003/09/19 01:26 | W | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2003/10/06 12:57 | RWB | S | Customer | GERMISTON MUNIC / EKURHULENI METRO - MP1 33KV Bulk Load | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/10/17 05:07 | RWB | Y | Unknown | Unknown | Unknown |
| D3(40-<60%) | T5(150-<600ms) | 2003/10/19 12:40 | RWB | S | Distribution | UNION DS TRFR 2 88/44kV TRFR | Equipment Failure |
| D2(30-<40%) | T5(150-<600ms) | 2003/10/25 11:39 | B | S | Customer | UNION DS / SAR KATLEGONG - AERO TEE 1 88kV BKR | Customer Related |
| D1(0-<30%) | T4(100-<150ms) | 2003/11/14 08:25 | W | Y | Distribution | SOUTH WEST VERTICAL / SIMMER & JACK 1 44kV BKR | Cable Fault |
| D4(60-100%) | T4(100-<150ms) | 2003/11/15 16:26 | RWB | T | Distribution | UNION DS / JUPITER 1 88kV BKR | Storm Related |
| D4(60-100%) | T3(70-<100ms) | 2004/01/03 14:53 | B | T | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV BKR | Conductor Related |
| D1(0-<30%) | T5(150-<600ms) | 2004/01/03 20:51 | RWB | S | Customer | MILL SCAW TRFR 1 88kV TRFR Bay | Customer Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/01/04 22:13 | RWB | Y | Distribution | NORTH RAND D.S. 132/44KV SUBSTATION | Storm Related |
| D3(40-<60%) | T3(70-<100ms) | 2004/01/11 17:55 | RB | X2 | Transmission | Eiger Fordsburg No1 275kV Line | Storm Related |
| D4(60-100%) | T4(100-<150ms) | 2004/01/15 20:09 | R | T | Distribution | UNION DS / SAR KATLEHONG 1 88kV BKR | Storm Related |
| D4(60-100%) | T3(70-<100ms) | 2004/01/19 12:20 | W | T | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV LINE ISOLATOR | Conductor Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/02/03 11:26 | B | Y | Customer | UNION DS / SAR KATLEHONG 1 88kV BKR | Customer Related |
| D4(60-100%) | T4(100-<150ms) | 2004/02/20 06:06 | B | T | Customer | SAR KATLEHONG / UNION 1 88kV HV Overhead Line | Conductor Related |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D2(30-<40%) | T4(100-<150ms) | 2004/02/24 17:08 | RW | X1 | Distribution | SCAW METALS TRFR 1AB 44kV BKR | Pollution |
| D4(60-100%) | T5(150-<600ms) | 2004/02/25 15:46 | R | T | Distribution | GERMISTON SOUTH / MILL SCAW 1 88kV BKR | Conductor Related |
| D2(30-<40%) | T4(100-<150ms) | 2004/02/26 08:52 | RWB | X1 | Customer | GERMISTON SOUTH 88/33KV SUBSTATION | Cable Fault |
| D1(0-<30%) | T2(50-<70ms) | 2004/03/05 23:16 | R | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/03/05 23:16 | RWB | Z1 | Customer | GERMISTON MUNIC TRFR 2 88/33kV TRFR | Cable Fault |
| D1(0-<30%) | T3(70-<100ms) | 2004/03/23 17:47 | WB | Y | Customer | MILL SCAW TRFR 4 88/6.6kV TRFR Bay | Customer Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/04/05 23:26 | W | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/04/20 05:11 | RWB | Z1 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2004/05/25 16:38 | W | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/06/08 08:37 | RWB | Z1 | Distribution | MILL SCAW TRFR 2 88kV BKR | Human Related |
| D2(30-<40%) | T2(50-<70ms) | 2004/06/17 13:47 | RW | X1 | Transmission | Eiger Etna No1 275kV Line | Veld Fire |
| D1(0-<30%) | T1(0-<50ms) | 2004/06/22 03:13 | R | Y | Distribution | UNION DS / JUPITER 1 88kV BKR | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/06/22 04:26 | R | Y | Distribution | UNION DS / JUPITER 1 88kV BKR | Storm Related |
| D1(0-<30%) | T1(0-<50ms) | 2004/06/28 13:36 | B | Y | Unknown | Unknown | Unknown |
| D4(60-100%) | T4(100-<150ms) | 2004/07/26 16:40 | W | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Related |
| D4(60-100%) | T4(100-<150ms) | 2004/07/26 16:40 | W | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Related |
| D2(30-<40%) | T1(0-<50ms) | 2004/08/08 20:31 | W | X1 | Transmission | Eiger Etna No1 275kV Line | Bird Related |
| D2(30-<40%) | T6(600ms-3s) | 2004/08/09 10:18 | RWB | Z2 | Customer | UNION DS / CONSOL GLASS 2 44kV BKR | Customer Related |
| D4(60-100%) | T4(100-<150ms) | 2004/08/09 16:39 | RW | T | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV BKR | Veld Fire |
| D4(60-100%) | T4(100-<150ms) | 2004/08/09 16:39 | RW | T | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV BKR | Veld Fire |
| D4(60-100%) | T4(100-<150ms) | 2004/08/14 20:03 | W | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T4(100-<150ms) | 2004/08/14 20:03 | W | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T4(100-<150ms) | 2004/08/14 20:05 | W | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Theft |
| D2(30-<40%) | T4(100-<150ms) | 2004/08/31 13:43 | R | X1 | Transmission | Esselen Jupiter No1 275kV Line | Trees |
| D1(0-<30%) | T2(50-<70ms) | 2004/09/01 13:48 | W | Y | Distribution | UNION DS TRFR 1 88kV BKR | Protection Failure |
| D3(40-<60%) | T3(70-<100ms) | 2004/09/16 10:36 | B | X2 | Distribution | SAR KATLEHONG / UNION 1 88kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T4(100-<150ms) | 2004/09/25 13:36 | B | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Related |
| D4(60-100%) | T4(100-<150ms) | 2004/09/25 13:39 | B | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Related |
| D4(60-100%) | T4(100-<150ms) | 2004/09/25 13:44 | B | T | Distribution | GERMISTON SOUTH / TAILINGS BOOSTER 1 88kV HV Overhead Line | Conductor Related |
| D3(40-<60%) | T3(70-<100ms) | 2004/10/06 22:21 | W | X2 | Transmission | Fordsburg Jupiter No1 275kV Line | Other |
| D1(0-<30%) | T4(100-<150ms) | 2004/10/12 17:09 | RWB | Y | Distribution | UNION DS / MILL SCAW 1 88kV BKR | Storm Related |
| D1(0-<30%) | T5(150-<600ms) | 2004/10/25 17:17 | B | Y | Distribution | UNION DS / SAR KATLEGONG - AERO TEE 1 88kV BKR | Storm Related |
| D1(0-<30%) | T1(0-<50ms) | 2004/10/25 17:17 | B | Y | Distribution | UNION DS / SAR KATLEGONG - AERO TEE 1 88kV BKR | Storm Related |
| D1(0-<30%) | T6(600ms-3s) | 2004/10/25 17:17 | WB | Z1 | Distribution | GERMISTON FACTORIES / HERCULES SHAFT 1 44kV HV Overhead Line | Storm Related |
| D2(30-<40%) | T3(70-<100ms) | 2004/10/28 00:44 | R | X1 | Distribution | GERMISTON FACTORIES / SOUTH WEST VERTICAL 3 44kV BKR | Storm Related |
| D2(30-<40%) | T3(70-<100ms) | 2004/10/28 00:46 | R | X1 | Distribution | GERMISTON FACTORIES / SOUTH WEST VERTICAL 3 44kV BKR | Storm Related |
| D1(0-<30%) | T6(600ms-3s) | 2004/11/08 17:16 | RB | Z1 | Distribution | HERCULES SHAFT / CASON MILL 1 44kV BKR | Storm Related |
| D1(0-<30%) | T1(0-<50ms) | 2004/12/01 05:10 | WB | Y | Distribution | MILL SCAW TRFR 2 88/6.6kV TRFR Bay | Human Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/12/19 16:08 | R | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T1(0-<50ms) | 2005/01/03 22:57 | B | Y | Unknown | Unknown | Unknown |
| D4(60-100%) | T2(50-<70ms) | 2005/01/06 09:35 | RWB | T | Distribution | ROSHSTEP TRFR 3 88/6.6kV Two Winding Transformer | Equipment Failure |
| D2(30-<40%) | T2(50-<70ms) | 2005/01/08 21:57 | WB | X1 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T1(0-<50ms) | 2005/01/15 04:55 | W | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T4(100-<150ms) | 2005/01/29 08:25 | B | Y | Distribution | GERMISTON SOUTH / MILL SCAW 1 88kV BKR | Conductor Theft |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D3(40-<60%) | T6(600ms-3s) | 2005/02/06 11:15 | RWB | Z2 | Distribution | UNION DS / GERMISTON SOUTH 1 88kV BKR | Bird Related |
| D1(0-<30%) | T1(0-<50ms) | 2005/02/17 09:27 | B | Y | Distribution | UNION DS / MILL SCAW 1 88kV BKR | Protection Failure |
| D1(0-<30%) | T3(70-<100ms) | 2005/02/24 21:48 | W | Y | Distribution | UNION DS / JUPITER 2 88kV BKR | Trees |
| D1(0-<30%) | T3(70-<100ms) | 2005/02/27 20:56 | B | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2005/03/13 09:56 | W | Y | Distribution | MILL SCAW / UNION DS 88KV LINE | Equipment Failure |
| D1(0-<30%) | T1(0-<50ms) | 2005/03/13 09:56 | W | Y | Distribution | MILL SCAW / UNION DS 88KV LINE | Equipment Failure |
| D4(60-100%) | T3(70-<100ms) | 2005/03/14 21:48 | RWB | T | Distribution | ROSHSTEP TRFR 2 88/22kV Two Winding Transformer | Storm Related |
| D3(40-<60%) | T4(100-<150ms) | 2005/03/15 14:54 | WB | X2 | Distribution | UNION DS / JUPITER 1 88kV BKR | Conductor Theft |
| D3(40-<60%) | T4(100-<150ms) | 2005/03/15 14:54 | RWB | X2 | Distribution | UNION DS / JUPITER 1 88kV BKR | Conductor Theft |
| D3(40-<60%) | T3(70-<100ms) | 2005/03/15 14:54 | B | X2 | Distribution | UNION DS / JUPITER 1 88kV BKR | Conductor Theft |
| D4(60-100%) | T3(70-<100ms) | 2005/03/15 14:54 | RWB | T | Distribution | UNION DS / JUPITER 1 88kV BKR | Conductor Theft |
| D1(0-<30%) | T3(70-<100ms) | 2005/03/15 14:55 | B | Y | Distribution | UNION DS / GERMISTON SOUTH 1 88kV BKR | Bird Related |
| D4(60-100%) | T4(100-<150ms) | 2005/04/10 09:04 | W | T | Distribution | UNION DS / JUPITER 2 88kV BKR | Trees |
| D1(0-<30%) | T3(70-<100ms) | 2005/04/28 21:04 | W | Y | Distribution | MILL SCAW TRFR 2 88kV BKR | Equipment Failure |
| D1(0-<30%) | T3(70-<100ms) | 2005/05/12 14:49 | R | Y | Distribution | UNION DS TRFR 1 88kV BKR | Equipment Failure |
| D2(30-<40%) | T3(70-<100ms) | 2005/05/16 23:01 | R | X1 | Transmission | Brenner Eiger No1 275kV Line | Bird Related |
| D1(0-<30%) | T2(50-<70ms) | 2005/05/17 21:07 | R | Y | Unknown | Unknown | Unknown |
| D2(30-<40%) | T5(150-<600ms) | 2005/05/27 02:26 | W | S | Distribution | UNION DS 88/44KV SUBSTATION | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2005/05/31 12:59 | RWB | S | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2005/06/16 16:37 | RW | Y | Distribution | UNION DS / EIGER 88KV LINE | Veld Fire |
| D1(0-<30%) | T4(100-<150ms) | 2005/06/16 16:37 | WB | Y | Distribution | UNION DS / EIGER 88KV LINE | Veld Fire |
| D1(0-<30%) | T1(0-<50ms) | 2005/06/16 16:37 | WB | Y | Distribution | UNION DS / EIGER 88KV LINE | Veld Fire |
| D1(0-<30%) | T3(70-<100ms) | 2005/06/16 16:37 | RWB | Y | Distribution | UNION DS / EIGER 88KV LINE | Veld Fire |
| D2(30-<40%) | T2(50-<70ms) | 2005/06/20 03:22 | R | X1 | Transmission | Brenner Eiger No1 275kV Line | Bird Related |
| D1(0-<30%) | T5(150-<600ms) | 2005/07/21 08:28 | RW | Y | Unknown | Unknown | Unknown |
| D2(30-<40%) | T3(70-<100ms) | 2005/07/25 15:58 | B | X1 | Transmission | Esselen Jupiter No1 275kV Line | Veld Fire |
| D2(30-<40%) | T3(70-<100ms) | 2005/07/25 15:58 | B | X1 | Transmission | Esselen Jupiter No1 275kV Line | Veld Fire |
| D2(30-<40%) | T3(70-<100ms) | 2005/08/11 11:36 | RWB | X1 | Distribution | UNION DS / JUPITER 1 88kV BKR | Equipment Failure |
| D2(30-<40%) | T3(70-<100ms) | 2005/08/14 11:15 | B | X1 | Transmission | Esselen Jupiter No1 275kV Line | Veld Fire |
| D2(30-<40%) | T3(70-<100ms) | 2005/08/14 11:15 | B | X1 | Transmission | Esselen Jupiter No1 275kV Line | Veld Fire |
| D1(0-<30%) | T2(50-<70ms) | 2005/08/17 10:14 | B | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T4(100-<150ms) | 2005/09/03 16:51 | W | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T4(100-<150ms) | 2005/09/22 11:37 | RW | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T2(50-<70ms) | 2005/09/26 04:30 | RWB | Y | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV BKR | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2005/09/26 04:35 | RB | Y | Distribution | GERMISTON SOUTH / SAR ROOIKOP 1 88kV BKR | Storm Related |
| D2(30-<40%) | T6(600ms-3s) | 2005/09/28 05:17 | RWB | Z2 | Distribution | UNION DS TRFR 2 44kV BKR | Equipment Failure |
| D4(60-100%) | T5(150-<600ms) | 2005/10/03 16:28 | R | T | Distribution | UNION DS / MILL SCAW 1 88kV BKR | Equipment Failure |
| D1(0-<30%) | T2(50-<70ms) | 2005/10/16 09:26 | B | Y | Distribution | GERMISTON SOUTH / MILL SCAW 1 88kV BKR | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2005/10/16 09:30 | B | Y | Distribution | GERMISTON SOUTH / MILL SCAW 1 88kV BKR | Storm Related |
| D1(0-<30%) | T2(50-<70ms) | 2005/11/04 18:01 | WB | Y | Unknown | Unknown | Unknown |
| D4(60-100%) | T4(100-<150ms) | 2005/11/25 17:52 | B | T | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2005/12/21 22:41 | RWB | Y | Unknown | Unknown | Unknown |

# ANNEXURE B:

# PULP & PAPER PLANT DIP RECORDS (2003 – 2005)

| Depth Block | Duration Block | DIP_DT | PHASES | New Class | Group | Circuit | Cause |
|---|---|---|---|---|---|---|---|
| D2(30-<40%) | T5(150-<600ms) | 2003/01/06 01:15 | WB | S | Distribution | BENONI / NEVIS 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T3(70-<100ms) | 2003/01/06 01:15 | WB | Y | Distribution | BENONI / NEVIS 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T5(150-<600ms) | 2003/01/06 05:23 | W | Y | Distribution | BENONI / NEVIS 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T4(100-<150ms) | 2003/01/17 20:00 | RWB | Y | Transmission | Nevis Pieterboth No1 275kV Line | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2003/01/20 00:09 | W | Y | Distribution | DELMAS DS / NEVIS 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T6(600ms-3s) | 2003/01/20 00:09 | R | Y | Distribution | DELMAS DS / NEVIS 1 132kV BKR | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/01/20 14:10 | RWB | T | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Storm Related |
| D4(60-100%) | T5(150-<600ms) | 2003/01/21 17:01 | RWB | T | Distribution | BENONI / NEVIS 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T4(100-<150ms) | 2003/02/16 14:39 | W | Y | Transmission | Nevis Snowdon No2 275kV Line | Storm Related |
| D1(0-<30%) | T2(50-<70ms) | 2003/03/12 09:53 | W | Y | Transmission | Atlas Highveld No3 275kV Line | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2003/03/14 20:38 | WB | Y | Transmission | Nevis Snowdon No2 275kV Line | Storm Related |
| D2(30-<40%) | T5(150-<600ms) | 2003/03/14 22:49 | RWB | S | Distribution | BENONI / NEVIS 1 132kV BKR | Conductor Theft |
| D4(60-100%) | T6(600ms-3s) | 2003/03/14 22:49 | RWB | Z2 | Distribution | BENONI / NEVIS 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T2(50-<70ms) | 2003/03/19 18:03 | RWB | Y | Transmission | Atlas Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T2(50-<70ms) | 2003/03/22 03:11 | W | Y | Transmission | Atlas Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T2(50-<70ms) | 2003/03/25 02:11 | W | Y | Transmission | Atlas Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T2(50-<70ms) | 2003/03/27 01:18 | W | Y | Transmission | Atlas Snowdon No1 275kV Line | Bird Related |
| D4(60-100%) | T6(600ms-3s) | 2003/04/07 16:42 | RWB | Z2 | Distribution | SAPPI / TEE 1 132kV CONDUCTOR | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/04/07 16:42 | RWB | T | Distribution | SAPPI / TEE 1 132kV CONDUCTOR | Conductor Theft |
| D4(60-100%) | T6(600ms-3s) | 2003/04/07 19:22 | RWB | Z2 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2003/04/08 05:34 | WB | Y | Transmission | Duvha Vulcan No1 400kV Line | Bird Related |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/11 02:47 | RWB | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T2(50-<70ms) | 2003/04/14 14:30 | W | Y | Transmission | Atlas Everest No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T6(600ms-3s) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T6(600ms-3s) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T6(600ms-3s) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:32 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/18 03:33 | RWB | Y | Transmission | Benburg Esselen No1 275kV Fdr Bay | Equipment Failure |
| D1(0-<30%) | T5(150-<600ms) | 2003/04/22 20:52 | RWB | S | Distribution | SAPPI / NEVIS 1 132kV BKR | Conductor Related |
| D1(0-<30%) | T6(600ms-3s) | 2003/05/08 14:22 | W | Y | Distribution | STRUBEN DS / GROOTVLEI SHAFT 1 44kV BKR | Veld Fire |
| D2(30-<40%) | T5(150-<600ms) | 2003/05/13 23:31 | RWB | S | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T6(600ms-3s) | 2003/05/13 23:31 | RWB | Z2 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D2(30-<40%) | T4(100-<150ms) | 2003/05/29 02:26 | RWB | X1 | Transmission | Matla Nevis No2 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2003/05/30 01:07 | W | Y | Transmission | Pieterboth Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2003/05/30 20:13 | WB | Y | Distribution | Nevis Snowdon No2 275kV Line | Bird Related |
| D4(60-100%) | T6(600ms-3s) | 2003/06/05 15:54 | RWB | Z2 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Veld Fire |
| D4(60-100%) | T5(150-<600ms) | 2003/06/14 06:31 | RWB | T | Distribution | Sappi- Enstra 132kV line | Bird Related |
| D4(60-100%) | T5(150-<600ms) | 2003/06/23 21:17 | RWB | T | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/06/24 21:35 | RWB | T | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D1(0-<30%) | T5(150-<600ms) | 2003/06/24 21:35 | RWB | S | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D2(30-<40%) | T3(70-<100ms) | 2003/06/24 21:35 | RWB | X1 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/06/25 18:14 | RWB | T | Customer | ENSTRA / METER PANEL 1 6.6kV BKR | Other |
| D4(60-100%) | T5(150-<600ms) | 2003/07/01 23:23 | RWB | T | Distribution | BENONI / ENSTRA 1 132kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/07/01 23:23 | RWB | T | Distribution | BENONI / ENSTRA 1 132kV HV Overhead Line | Conductor Theft |
| D1(0-<30%) | T1(0-<50ms) | 2003/07/05 19:14 | RB | Y | Distribution | BENONI / NEVIS 1 132kV CONDUCTOR | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/07/05 22:07 | RWB | T | Distribution | BENONI / NEVIS 1 132kV CONDUCTOR | Conductor Theft |
| D1(0-<30%) | T4(100-<150ms) | 2003/07/05 22:07 | WB | Y | Distribution | BENONI / NEVIS 1 132kV CONDUCTOR | Conductor Theft |
| D2(30-<40%) | T4(100-<150ms) | 2003/07/05 22:07 | RWB | X1 | Distribution | BENONI / NEVIS 1 132kV CONDUCTOR | Conductor Theft |
| D2(30-<40%) | T5(150-<600ms) | 2003/07/13 22:11 | RWB | S | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/07/13 22:12 | RWB | T | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Theft |
| D1(0-<30%) | T4(100-<150ms) | 2003/07/14 13:33 | WB | Y | Customer | Unknown | Unknown |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D1(0-<30%) | T6(600ms-3s) | 2003/07/23 21:27 | RWB | Y | Distribution | SAR SUNDRA / STRUBEN 1 44kV HV Overhead Line (TSA - GERMISTON) | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/08/05 18:30 | RWB | T | Distribution | NEVIS / SAPPI 1 132kV BKR | Conductor Theft |
| D4(60-100%) | T5(150-<600ms) | 2003/08/05 18:30 | RWB | T | Distribution | NEVIS / SAPPI 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T5(150-<600ms) | 2003/08/05 18:30 | RWB | S | Distribution | NEVIS / SAPPI 1 132kV BKR | Conductor Theft |
| D1(0-<30%) | T4(100-<150ms) | 2003/08/06 06:19 | R | Y | Distribution | SAR SUNDRA / STRUBEN 1 44kV HV Overhead Line (TSA - GERMISTON) | Conductor Theft |
| D1(0-<30%) | T3(70-<100ms) | 2003/09/09 22:22 | WB | Y | Transmission | Matla Atlas No1 400kV Line | Veld Fire |
| D4(60-100%) | T5(150-<600ms) | 2003/09/24 05:57 | RWB | T | Distribution | SAPPI 132/6.6KV SUBSTATION | Pollution |
| D4(60-100%) | T5(150-<600ms) | 2003/10/11 23:45 | RWB | T | Unknown | Unknown | Unknown |
| D4(60-100%) | T5(150-<600ms) | 2003/10/19 04:04 | RWB | T | Distribution | SAPPI / TEE 1 132kV CONDUCTOR | Storm Related |
| D4(60-100%) | T6(600ms-3s) | 2003/10/19 04:05 | RWB | Z2 | Distribution | SAPPI / TEE 1 132kV CONDUCTOR | Storm Related |
| D2(30-<40%) | T3(70-<100ms) | 2003/11/18 19:22 | RB | X1 | Distribution | MODDER EAST / TEE 2 132kV CONDUCTOR | Conductor Theft |
| D1(0-<30%) | T1(0-<50ms) | 2003/11/22 16:46 | RWB | Y | Transmission | Eiger Prospect No1 275kV Line | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2003/12/22 20:25 | WB | Y | Distribution | STRUBEN / WELGEDACHT TOWN 1 44kV HV Overhead Line | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/01/03 07:37 | RB | Y | Transmission | Esselen Kruispunt - Matla No1 275kV Line | Storm Related |
| D1(0-<30%) | T5(150-<600ms) | 2004/01/03 12:13 | RW | S | Distribution | DELMAS / NEVIS 2 132kV HV Overhead Line | Conductor Related |
| D2(30-<40%) | T6(600ms-3s) | 2004/01/03 12:13 | RWB | Z2 | Distribution | DELMAS / NEVIS 2 132kV HV Overhead Line | Conductor Related |
| D1(0-<30%) | T4(100-<150ms) | 2004/01/03 12:13 | RWB | Y | Distribution | DELMAS / NEVIS 2 132kV HV Overhead Line | Conductor Related |
| D1(0-<30%) | T2(50-<70ms) | 2004/01/11 18:06 | WB | Y | Distribution | STRUBEN / WELGEDACHT TOWN 1 44kV HV Overhead Line | Conductor Related |
| D2(30-<40%) | T6(600ms-3s) | 2004/01/16 17:54 | RWB | Z2 | Distribution | STRUBEN DS / GROOTVLEI SHAFT 1 44kV BKR | Storm Related |
| D2(30-<40%) | T6(600ms-3s) | 2004/01/16 17:54 | RWB | Z2 | Distribution | STRUBEN DS / GROOTVLEI SHAFT 1 44kV BKR | Storm Related |
| D2(30-<40%) | T4(100-<150ms) | 2004/01/28 18:22 | WB | X1 | Customer | Benoni-Farramere 132kV cable | Other |
| D1(0-<30%) | T3(70-<100ms) | 2004/02/07 15:01 | RWB | Y | Distribution | WELGEDACHT TOWN / STRUBEN DS 1 44kV BKR | Storm Related |
| D2(30-<40%) | T4(100-<150ms) | 2004/02/09 22:46 | RB | X1 | Distribution | Town-Morehill 132kV cable | Conductor Theft |
| D3(40-<60%) | T4(100-<150ms) | 2004/02/13 19:46 | RWB | X2 | Transmission | Pieterboth Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/02/19 16:50 | RWB | Y | Transmission | Camden 400kV Transfer BB Coupler B | Conductor Theft |
| D1(0-<30%) | T3(70-<100ms) | 2004/03/01 18:01 | RWB | Y | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D1(0-<30%) | T1(0-<50ms) | 2004/03/01 19:37 | B | Y | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D2(30-<40%) | T6(600ms-3s) | 2004/03/07 13:45 | RWB | Z2 | Distribution | STRUBEN DS / SAR SUNDRA - HOLFONTEIN TEE 1 44kV BUSBAR ISOLATOR 1 | Trees |
| D3(40-<60%) | T6(600ms-3s) | 2004/03/07 13:45 | RWB | Z2 | Distribution | STRUBEN DS / SAR SUNDRA - HOLFONTEIN TEE 1 44kV BUSBAR ISOLATOR 1 | Trees |
| D2(30-<40%) | T4(100-<150ms) | 2004/03/10 19:20 | WB | X1 | Distribution | BENONI / NEVIS 1 132kV BKR | Storm Related |
| D1(0-<30%) | T2(50-<70ms) | 2004/04/29 01:34 | RW | Y | Transmission | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2004/05/01 17:19 | RW | Y | Transmission | Nevis Snowdon No2 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/05/09 00:58 | RW | Y | Transmission | Nevis Snowdon No2 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/05/17 02:32 | RW | Y | Transmission | Nevis Snowdon No2 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/05/17 03:08 | RB | Y | Transmission | Matla Nevis No1 275kV Line | Bird Related |
| D4(60-100%) | T5(150-<600ms) | 2004/06/06 13:26 | RWB | T | Distribution | SAPPI / TEE 1 132kV CONDUCTOR | Conductor Related |
| D4(60-100%) | T3(70-<100ms) | 2004/06/06 13:26 | RWB | T | Distribution | SAPPI / TEE 1 132kV CONDUCTOR | Conductor Related |
| D3(40-<60%) | T3(70-<100ms) | 2004/06/11 13:44 | RW | X2 | Distribution | MODDER EAST / TEE 1 132kV CONDUCTOR | Veld Fire |
| D4(60-100%) | T5(150-<600ms) | 2004/06/12 13:09 | RWB | T | Distribution | SAPPI / NEVIS 1 132kV BKR | Veld Fire |
| D4(60-100%) | T3(70-<100ms) | 2004/06/12 13:09 | RWB | T | Distribution | SAPPI / NEVIS 1 132kV BKR | Veld Fire |
| D1(0-<30%) | T6(600ms-3s) | 2004/06/19 17:11 | RB | Y | Unknown | Unknown | Unknown |
| D3(40-<60%) | T3(70-<100ms) | 2004/06/27 06:39 | RB | X2 | Distribution | BENONI / ENSTRA 1 132kV BKR | Conductor Related |
| D4(60-100%) | T6(600ms-3s) | 2004/07/24 13:16 | RWB | Z2 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Veld Fire |
| D1(0-<30%) | T5(150-<600ms) | 2004/08/13 00:49 | B | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/08/13 00:49 | RB | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/08/13 00:49 | B | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/09/22 09:41 | B | Y | Unknown | Unknown | Unknown |
| D3(40-<60%) | T4(100-<150ms) | 2004/10/07 13:39 | RWB | X2 | Transmission | Matla Nevis No1 275kV Line | Veld Fire |
| D3(40-<60%) | T4(100-<150ms) | 2004/10/07 13:40 | RWB | X2 | Transmission | Matla Nevis No1 275kV Line | Veld Fire |
| D2(30-<40%) | T4(100-<150ms) | 2004/10/25 17:44 | WB | X1 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Storm Related |
| D1(0-<30%) | T5(150-<600ms) | 2004/10/27 18:22 | R | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2004/10/27 18:30 | RB | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2004/10/27 18:30 | R | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T6(600ms-3s) | 2004/10/27 18:31 | RWB | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T2(50-<70ms) | 2004/11/05 16:52 | B | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T5(150-<600ms) | 2004/11/05 16:52 | B | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T2(50-<70ms) | 2004/11/06 13:49 | WB | Y | Transmission | Atlas Snowdon No1 275kV Line | Storm Related |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D1(0-<30%) | T2(50-<70ms) | 2004/11/15 19:31 | WB | Y | Transmission | Atlas Snowdon No1 275kV Line | Storm Related |
| D2(30-<40%) | T2(50-<70ms) | 2004/11/15 19:56 | RWB | X1 | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D2(30-<40%) | T3(70-<100ms) | 2004/11/15 19:56 | RWB | X1 | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D2(30-<40%) | T2(50-<70ms) | 2004/11/15 20:11 | RWB | X1 | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D2(30-<40%) | T4(100-<150ms) | 2004/11/18 19:14 | WB | X1 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Related |
| D1(0-<30%) | T2(50-<70ms) | 2004/11/28 18:50 | RB | Y | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2004/11/28 19:40 | RB | Y | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D1(0-<30%) | T1(0-<50ms) | 2005/01/03 20:02 | RB | Y | Transmission | Atlas Snowdon No2 275kV Line | Storm Related |
| D1(0-<30%) | T3(70-<100ms) | 2005/01/08 20:24 | RW | Y | Transmission | Nevis Snowdon No2 275kV Line | Storm Related |
| D3(40-<60%) | T3(70-<100ms) | 2005/01/08 20:25 | RWB | X2 | Distribution | NIGEL TERMINAL / SAR NIGEL 1 88kV BKR | Conductor Related |
| D1(0-<30%) | T1(0-<50ms) | 2005/01/27 22:52 | B | Y | Transmission | Atlas Snowdon No1 275kV Line | Storm Related |
| D2(30-<40%) | T6(600ms-3s) | 2005/02/08 18:30 | WB | Z2 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Related |
| D2(30-<40%) | T4(100-<150ms) | 2005/02/08 19:00 | WB | X1 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Related |
| D1(0-<30%) | T5(150-<600ms) | 2005/02/11 17:50 | B | Y | Distribution | Nevis - Struben No1 & 2 132kV Line Trip and L/O | Storm Related |
| D1(0-<30%) | T1(0-<50ms) | 2005/02/18 05:45 | RW | Y | Transmission | Matla Komati No1 275kV Line | Veld Fire |
| D1(0-<30%) | T2(50-<70ms) | 2005/02/25 16:30 | RB | Y | Unknown | Unknown | Unknown |
| D2(30-<40%) | T4(100-<150ms) | 2005/03/02 17:08 | WB | X1 | Distribution | BENONI / NEVIS 1 132kV HV Overhead Line | Conductor Related |
| D3(40-<60%) | T3(70-<100ms) | 2005/04/14 18:46 | RB | X2 | Unknown | Unknown | Unknown |
| D1(0-<30%) | T4(100-<150ms) | 2005/06/02 12:46 | RB | Y | Transmission | Nevis Pieterboth No1 275kV Line | Veld Fire |
| D1(0-<30%) | T4(100-<150ms) | 2005/06/02 12:46 | RB | Y | Transmission | Nevis Pieterboth No1 275kV Line | Veld Fire |
| D1(0-<30%) | T4(100-<150ms) | 2005/06/07 05:44 | WB | Y | Transmission | Matla Nevis No2 275kV Line | Bird Related |
| D1(0-<30%) | T2(50-<70ms) | 2005/06/12 13:33 | W | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2005/06/29 04:32 | RW | Y | Transmission | Pieterboth Snowdon No1 275kV Line | Conductor Theft |
| D1(0-<30%) | T3(70-<100ms) | 2005/06/29 05:48 | RW | Y | Transmission | Pieterboth Snowdon No1 275kV Line | Conductor Theft |
| D1(0-<30%) | T1(0-<50ms) | 2005/07/03 05:09 | RW | Y | Transmission | Matla Glockner No2 400kV Fdr Bay | Other |
| D3(40-<60%) | T5(150-<600ms) | 2005/07/21 08:28 | RWB | S | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2005/08/14 15:25 | B | Y | Transmission | Nevis Snowdon No2 275kV Line | Veld Fire |
| D1(0-<30%) | T3(70-<100ms) | 2005/08/20 05:58 | RW | Y | Transmission | Pieterboth Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2005/08/20 07:14 | RW | Y | Transmission | Pieterboth Snowdon No1 275kV Line | Bird Related |
| D1(0-<30%) | T3(70-<100ms) | 2005/09/13 12:37 | RB | Y | Transmission | Matla Nevis No2 275kV Line | Veld Fire |
| D1(0-<30%) | T5(150-<600ms) | 2005/09/27 03:15 | R | Y | Distribution | ENSTRA / SAPPI 1 132KV BKR | Bird Related |
| D1(0-<30%) | T6(600ms-3s) | 2005/11/19 03:14 | RB | Y | Unknown | Unknown | Unknown |
| D1(0-<30%) | T3(70-<100ms) | 2005/11/19 03:24 | RB | Y | Transmission | Nevis Snowdon No2 275kV Line | Bird Related |
| D2(30-<40%) | T4(100-<150ms) | 2005/11/27 13:07 | WB | X1 | Transmission | Matla Nevis No2 275kV Line | Bird Related |
| | | | | | | | |

# ANNEXURE C:

# STEEL PLANT NETWORK SIMULATION DATA

| Description | Total Line Length (km) | r' (Ω/km) | x' (Ω/km) | r0 (Ω/km) | x0 (Ω/km) |
|---|---|---|---|---|---|
| Simmerpan / Germiston Factories 1 88kV | 3.05 | 0.0384 | 0.1400 | 0.1520 | 0.1370 |
| Simmerpan / Germiston Factories 2 88kV | 3.05 | 0.0384 | 0.1400 | 0.1520 | 0.1370 |
| Germiston Factories / Germiston 1 East 44kV | 0.27 | 0.0388 | 0.1108 | 0.1003 | 0.0562 |
| Germiston Factories / Germiston 2 East 44kV | 0.27 | 0.0388 | 0.1108 | 0.1003 | 0.0562 |
| Germiston Factories / South West Vertical 1 44kV | 0.51 | 0.0388 | 0.1108 | 0.1003 | 0.0562 |
| Germiston Factories / South West Vertical 2 44kV | 0.51 | 0.0388 | 0.1108 | 0.1003 | 0.0562 |
| South West Vertical / SAR Germiston 1 44kV | 1.46 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| South West Vertical / SAR Germiston 2 44kV | 1.46 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| South West Vertical / Simmer & Jack 44kV | 6.81 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| South West Vertical / SAR Geldenhuis 44kV | 6.81 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| Simmer & Jack / SAR Geldenhuis 44kV | 0.45 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| South West Vertical / SAR Angelo 44kV | 4.15 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Hercules Shaft / SAR Angelo 44kV | 2.56 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Hercules Shaft / SAR Boksburg Tee 44kV | 4.96 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Hercules Shaft / Angelo 44kV | 3.96 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Hercules Shaft / Cason Mill - SAR Boksburg 44kV | 0.09 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Angelo / Cason Mill 44kV | 2.07 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| SAR Boksburg Tee / Cason Mill 44kV | 2.44 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Germiston Factories / Hercules Shaft 44kV | 10.88 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Simmerpan / Germiston Munic 1 88kV | 2.15 | 0.0384 | 0.1400 | 0.1520 | 0.1370 |
| Simmerpan / Germiston Munic 2 88kV | 2.15 | 0.0384 | 0.1400 | 0.1520 | 0.1370 |
| Simmerpan / Germiston Munic 3 88kV | 2.15 | 0.0384 | 0.1400 | 0.1520 | 0.1370 |
| Tailings Booster / SAR Rooikop Tee 88kV | 0.44 | 0.0388 | 0.1108 | 0.1003 | 0.0562 |
| Germiston South / Tailings Booster - SAR Rooikop Tee 88kV | 1.94 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Germiston South / SAR Rooikop Tee 88kV | 0.05 | 0.1471 | 0.3717 | 0.4414 | 1.4791 |
| Union DS / Germiston South 88kV | 2.04 | 0.0721 | 0.5990 | 0.3568 | 1.5147 |
| Germiston South / Mill Scaw 88kV | 2.05 | 0.0721 | 0.5990 | 0.3568 | 1.5147 |
| Union DS / Mill Scaw 88kV | 0.17 | 0.0697 | 0.3485 | 0.3717 | 1.4636 |
| Union DS / SAR Katlehong 88kV | 3.7 | 0.2013 | 0.3795 | 0.5034 | 1.4868 |
| SAR Katlehong / Aero Tee 88kV | 1.35 | 0.2013 | 0.3795 | 0.5034 | 1.4868 |
| Aero Tee / Union DS 88kV | 0.23 | 0.2013 | 0.3795 | 0.5034 | 1.4868 |
| SAR Katlehong / Union DS - Aero Tee 88kV | 0.1 | 0.0697 | 0.3485 | 0.3717 | 1.4636 |
| Union DS / Wadeville 1 44kV | 3.91 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| Union DS / Wadeville 2 44kV | 3.91 | 0.1010 | 0.0820 | 0.3400 | 0.1070 |
| Union DS / Console Glass 1 44kV | 1.35 | 0.1588 | 0.4414 | 0.4066 | 1.5140 |
| Union DS / Console Glass 2 44kV | 3.98 | 0.1588 | 0.4414 | 0.4066 | 1.5140 |
| Console Glass / Wadeville 44kV | 1.64 | 0.1588 | 0.4414 | 0.4066 | 1.5140 |
| Console Glass / MC Kechnie 1 44kV | 1.97 | 0.1588 | 0.4414 | 0.4066 | 1.5140 |
| Console Glass / MC Kechnie 2 44kV | 1.97 | 0.1588 | 0.4414 | 0.4066 | 1.5140 |
| Simmerpan / Jack Shaft Tee 1 88kV | 1.73 | 0.0303 | 0.2360 | 0.3116 | 1.0761 |
| Simmerpan / Jack Shaft Tee 2 88kV | 1.91 | 0.0303 | 0.2360 | 0.3116 | 1.0761 |
| Simmerpan / Jupiter - Jack Shaft 1 88kV | 0.14 | 0.1471 | 0.3717 | 0.4414 | 1.0761 |
| Simmerpan / Jupiter - Jack Shaft 2 88kV | 0.09 | 0.1471 | 0.3717 | 0.4414 | 1.0761 |

| | | | | | |
|---|---|---|---|---|---|
| Jupiter / Jack Shaft Tee 1 88kV | 2.41 | 0.0303 | 0.2360 | 0.3116 | 1.0761 |
| Jupiter / Jack Shaft Tee 2 88kV | 2.24 | 0.0303 | 0.2360 | 0.3116 | 1.0761 |
| Jupiter / Union 1 88kV | 11.12 | 0.0387 | 0.2943 | 0.3407 | 1.4017 |
| Jupiter / Union 2 88kV | 11.12 | 0.0387 | 0.2943 | 0.3407 | 1.4017 |

| **Description** | **MVA** | **HV Side** | **MV Side** | **% Impedance** | **Volts / Tap** | **Min Position** | **Max Position** | **Neutral Tap** |
|---|---|---|---|---|---|---|---|---|
| Simmerpan 88/11kV Trf 1 | 88 | 11 | 30 | 11.2 | 1.25 | 1 | 17 | 5 |
| Simmerpan 88/11kV Trf 2 | 88 | 11 | 30 | 11.2 | 1.25 | 1 | 17 | 5 |
| Germiston Factories Trf 1 | 88 | 44 | 80 | 3 | 1.25 | 1 | 17 | 5 |
| Union DS 88/11 Trf 1 | 45 | 88 | 44 | 8.2 | 1.25 | 1 | 17 | 5 |
| Union DS 88/11 Trf 2 | 45 | 88 | 44 | 8.2 | 1.25 | 1 | 17 | 5 |
| Union DS 88/11 Trf 3 | 45 | 88 | 44 | 8.2 | 1.25 | 1 | 17 | 5 |

| **Description** | **MW** | **MVAr** |
|---|---|---|
| SAR Geldenhuis 44kV | 1.3 | 0.6 |
| Simmer & Jack 2.2kV | 0.4 | 0.4 |
| Simmer & Jack 6.6kV | 0.5 | 0.2 |
| Cason Mill 3.3kV | 5.5 | 4.6 |
| Angelo 3.3kV | 3 | 0.8 |
| SAR Angelo 44kV | 1 | 0.4 |
| Hercules Shaft 3.3kV | 10.7 | 4 |
| Hercules Shaft 6.6kV | 5.1 | 3.3 |
| South West Vertical 3.3kV | 0.7 | 0.4 |
| South West Vertical 6.6kV | 0.5 | 0.7 |
| SAR Rooikop 44kV | 0.4 | 0.3 |
| Tailings Booster 6.6kV | 1.1 | 0.7 |
| Germiston Munic 33kV | 44.8 | 0 |
| Mill Scaw 88kV | 35.9 | 8.5 |
| Germiston South 88kV | 135.9 | 28.4 |
| SAR Katlehong 88kV | 1.8 | 0.6 |
| Aero 88kV | 7.6 | 2 |
| Jack Shaft 88kV | 0.1 | 0 |
| Union DS | 47 | 7 |

# ANNEXURE D:

# PULP & PLANT NETWORK SIMULATION DATA

| Circuit | Total Line Length (km) | r' (Ω/km) | x' (Ω/km) | r0 (Ω/km) | x0 (Ω/km) |
|---|---|---|---|---|---|
| Nevis / Modder East Tee 132kV | 14.42 | 0.0580 | 0.5957 | 0.3427 | 1.5112 |
| Modder East Tee / Benoni DS 1 132kV | 15.25 | 0.0580 | 0.5957 | 0.3427 | 1.5112 |
| Nevis / Benoni DS - Modder Tee 132kV | 0.38 | 0.0580 | 0.5957 | 0.3427 | 1.5112 |
| Nevis / Sappi 132kV | 13.64 | 0.0580 | 0.5957 | 0.3427 | 1.5112 |
| Sappi / Enstra 132kV | 2.17 | 0.0580 | 0.5957 | 0.3427 | 1.5112 |
| Enstra / Modder East Tee 132kV | 4.82 | 0.0580 | 0.5957 | 0.3427 | 1.5112 |
| Enstra / Benoni DS - Modder Tee 132kV | 0.38 | 0.2037 | 0.4328 | 0.4873 | 1.3481 |
| Modder East Tee / Benoni DS 2 132kV | 15.29 | 0.2037 | 0.4328 | 0.4873 | 1.3481 |
| Benoni DS / Dunswart Tee 1 44kV | 10.98 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Dunswart Tee / Brakpan North 44kV | 0.04 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Benoni DS / Brakpan North - Dunswart Tee 44kV | 7.77 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Benoni DS / SAR Apex - Dunswart 44kV | 3.46 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Benoni DS / Dunswart Tee 2 44kV | 2.80 | 0.0744 | 0.1084 | 0.1572 | 0.0533 |
| Dunswart Tee / SAR Apex 44kV | 5.07 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| SAR Apex / Modder Shaft Tee 44kV | 4.75 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| SAR Apex / Ergo Booster - Modder Shaft Tee 44kV | 0.13 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Modder Shaft Tee / Ergo Booster 44kV | 4.46 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Brakpan North / Ergo Booster 44kV | 3.72 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Nevis / Struben DS 1 132kV | 0.33 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Nevis / Struben DS 2 132kV | 0.33 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Struben DS / Welgedacht Town 44kV | 7.98 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Welgedacht Town / SAR Welgedacht Tee 44kV | 0.53 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| SAR Welgedacht Tee / Welgedacht | 0.40 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Welgedacht Town / Welgedacht - SAR Welgedacht Tee 44kV | 0.05 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Welgedacht Town / SAR Cowles 44kV | 4.40 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| SAR Cowles / East Geduld Refinery 44kV | 3.34 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| East Geduld Refinery / Ergo Geduld 44kV | 1.10 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| East Geduld Shaft / East Geduld Refinery 44kV | 2.20 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Struben DS / East Geduld Shaft 44kV | 12.46 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Struben DS / Grootvlei Shaft 44kV | 8.20 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Grootvlei Shaft / East Geduld Mine 44kV | 4.88 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Grootvlei Three / East Geduld Mine 44kV | 6.44 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Palmiet South / Grootvlei Three 44kV | 3.61 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Palmiet South / Astonlake Tee 44kV | 0.47 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Astonlake Tee / Struben 44kV | 1.62 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Palmiet South / Struben DS - Astonlake Tee 44kV | 0.02 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Struben DS / Holfontein & SABC Welgadacht Tee 44kV | 6.70 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Holfontein & SABC Welgedacht Tee / SAR Sundra 44kV | 1.16 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Struben DS / SAR Sundra - Holfontein & SABC Welgedacht Tee 44kV | 0.41 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| SABC Welgedacht Tee 44kV | 0.02 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Holfontein Tee 44kV | 3.89 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Struben DS Tee / Endicott 44kV | 11.40 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Endicott Tee 44kV | 0.02 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Struben / Endicott Tee - RWB Bloemendal / Uitkyk Tee | 4.52 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| RWB Bloemendal Tee 44kV | 0.40 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Uitkyk Tee 44kV | 9.74 | 0.1441 | 0.2062 | 0.2761 | 0.6682 |

| | | | | | |
|---|---|---|---|---|---|
| Blesbok Tee 44kV | 2.86 | 0.2033 | 0.4027 | 0.4927 | 1.4520 |
| Struben DS / Delmas DS 132kV | 17.72 | 0.1155 | 0.4227 | 0.3950 | 1.3242 |
| Struben DS / Umbilo Tee 132kV | 20.33 | 0.1155 | 0.4227 | 0.3950 | 1.3242 |
| Umbilo Tee / Delmas DS 132kV | 4.44 | 0.1155 | 0.4227 | 0.3950 | 1.3242 |
| Struben DS / Delmas DS - Umbilo Tee 132kV | 0.06 | 0.1155 | 0.4227 | 0.3950 | 1.3242 |
| Struben DS / Springs Bulk 132kV | 15.40 | 0.5785 | 0.3480 | 0.3382 | 1.2803 |
| Springs Bulk / Springs Munic 132kV | 6.58 | 0.5785 | 0.3480 | 0.3382 | 1.2803 |
| Springs Munic / Struben DS 132kV | 12.71 | 0.5785 | 0.3480 | 0.3382 | 1.2803 |
| Delmas DS / SAR Druden 44kV | 9.62 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Delmas DS / Sundra Rural 44kV | 11.30 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Sundra Rural / SAR Eloff 44kV | 0.68 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Delmas / Dryden Rural - Sundra Rural Tee 44kV | 0.23 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Delmas DS / Sundra Rural Tee 44kV | 3.60 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Sundra Rural Tee / Dryden Rural 44kV | 0.03 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Delmas DS / SAR Eloff 44kV | 10.61 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Delmas DS / Delmas Munic 1 44kV | 3.60 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| Delmas DS / Delmas Munic 2 44kV | 3.56 | 0.1452 | 0.4008 | 0.4046 | 1.4810 |
| | | | | | |

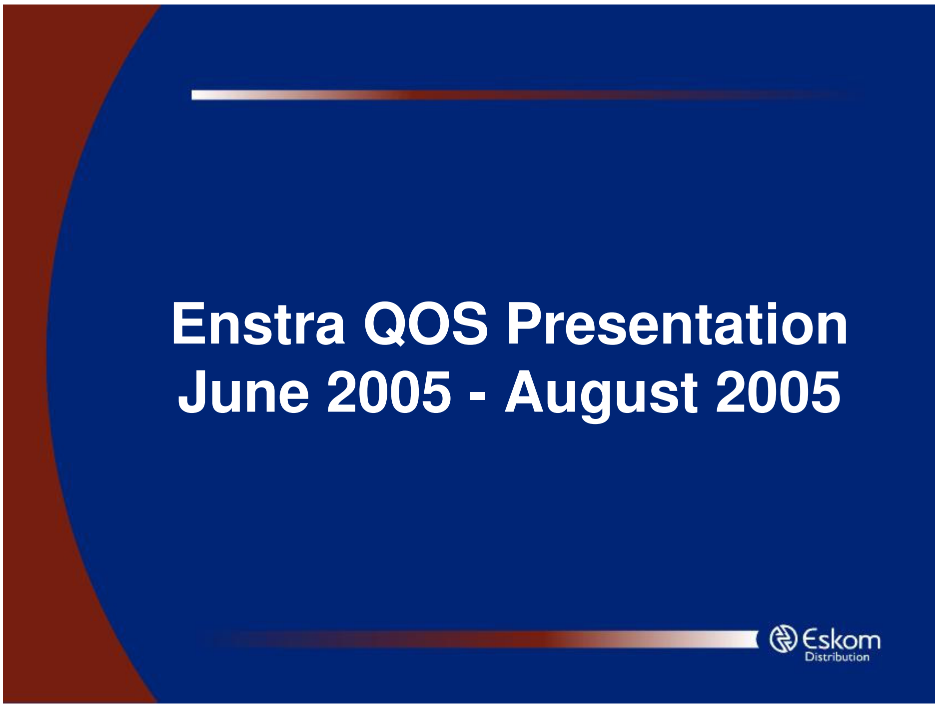
| Description | HV Side | MV Side | Tertiary | MVA | % Impedance | Volts / Tap | Min Position | Max Position | Neutral Tap |
|---|---|---|---|---|---|---|---|---|---|
| Delmas DS 132/44kV Trf 1 | 132 | 44 | | 90 | 10.6 | 1.43 | 1 | 10 | 4 |
| Delmas DS 132/44kV Trf 2 | 132 | 44 | | 90 | 10.6 | 1.43 | 1 | 10 | 4 |
| Struben DS 132/44kV Trf 1 | 132 | 44 | | 50 | 10.4 | 1.25 | 1 | 17 | 5 |
| Struben DS 132/44kV Trf 2 | 132 | 44 | | 50 | 10.4 | 1.25 | 1 | 17 | 5 |
| Benoni DS 132/44kV Trf 1 | 132 | 44 | | 90 | 10.8 | 1.25 | 1 | 17 | 5 |
| Benoni DS 132/44kV Trf 2 | 132 | 44 | | 90 | 10.8 | 1.25 | 1 | 17 | 5 |
| Nevis TS 275/132/11kV Trf 1 | 275 | 132 | 11 | 500 | 12.6 | 1.25 | 1 | 17 | 5 |

| Description | MW | MVAr |
|---|---|---|
| Sappi 6.6kV | 24.7 | 7.4 |
| Enstra 6.6kV | 12.9 | 0 |
| Modder East 6.6kV | 9 | 3.1 |
| Benoni DS 132kV | 142 | 17.5 |
| Benoni DS 44kV | 42 | 16 |
| Brakpan North 44kV | 4.1 | 0.6 |
| Dunswart 44kV | 2.1 | 1.4 |
| Ergo Booster 44kV | 5.3 | 0.1 |
| Modder Shaft 44kV | 0.8 | 0.3 |
| Wegedacht 11kV | 2.3 | 0.3 |
| SAR Welgedacht | 1 | 0.1 |
| Welgedacht Town 44kV | 3.2 | 1.1 |
| East Geduld Shaft 44kV | 0.7 | 0.3 |
| East Geduld Refinery 44kV | 15.3 | 7.5 |
| Ergo Geduld 44kV | 3.9 | 4.5 |
| SAR Cowles Dam 44kV | 2 | 0.8 |
| East Geduld Mine 44kV | 1.4 | 0.7 |
| Grootvlei Three 44kV | 11.8 | 7.1 |
| Palmiet South 44kV | 6.9 | 0 |

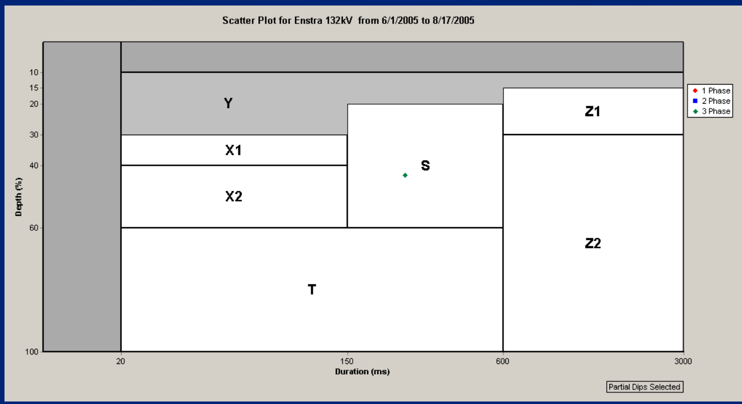
| | | |
|---|---|---|
| Grootveli Shaft 44kV | 12.8 | 0 |
| Grootveli Shaft 2.2kV | 3.8 | 2.1 |
| Holfontein 11kV | 1.4 | 0.2 |
| SAR Sundra 44kV | 0.1 | 0.1 |
| SABC Welgedacht 2.1kV | 1.6 | 0.5 |
| SAR Dryden 44kV | 2.7 | 0.9 |
| Sundra Rural 11kV | 7.3 | 2.4 |
| Delmas Munic 44kV | 11.2 | 3 |
| SAR Eloff 44kV | 2.7 | 0.9 |
| Dryden Rural 11kV | 5.7 | 1.9 |
| Springs Bulk 132kV | 53.2 | 13.2 |
| Springs Munic 132kV | 39.4 | 7.2 |
| Umbilo 132kV | 3.6 | 0.5 |

**ANNEXURE E:**

**QOS PRESENTATION TO PULP & PAPER CUSTOMER**



# Enstra Voltage Dips

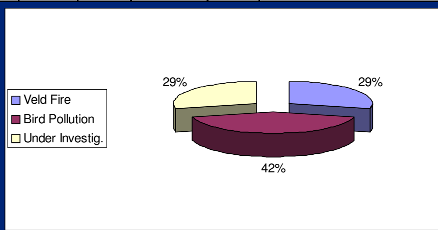



| DIP_DATE | PHASES | MAX DEPTH | MAX DURATION | CLASS | EQUIPMENT | CAUSE |
|---|---|---|---|---|---|---|
| 7/21/2005 08:28 | RWB | 42.6 | 250 | S | Matla Esselen 275kV Line | Under investigation |

Eskom Distribution

# Nevis Voltage Dips

| NAME | DIP DATE | PHASES | MAX DEPTH | MAX DURATION | CLASS | EQUIPMENT | CAUSE |
|---|---|---|---|---|---|---|---|
| Nevis 275/132kV | 6/2/2005 12:46 | R | 45.1 | 100 | X2 | Nevis Pieterboth No1 275kV Line | Veld Fire |
| Nevis 275/132kV | 6/2/2005 12:46 | R | 42.9 | 100 | X2 | Nevis Pieterboth No1 275kV Line | Veld Fire |
| Nevis 275/132kV | 6/7/2005 05:43 | B | 40 | 120 | X1 | Matla Nevis No2 275kV Line | Bird Pollution |
| Nevis 275/132kV | 6/29/2005 04:31 | W | 31.6 | 80 | X1 | Pieterboth Snowdon No1 275kV Line | Bird Pollution |
| Nevis 275/132kV | 6/29/2005 05:48 | W | 31.5 | 80 | X1 | Pieterboth Snowdon No1 275kV Line | Bird Pollution |
| Nevis 275/132kV | 7/21/2005 08:29 | RWB | 57.3 | 250 | S | Matla Esselen 275kV Line | Under investigation |
| Nevis 275/132kV | 8/20/2005 07:13 | W | 30.6 | 80 | X1 | Pieterboth - Snowdon No1 275kV | Under investigation |




- Installation of **Bird Guards** and **Bird Flappers** on 275kV lines is ongoing nationally.
- Matla – Nevis 1 & 2 project to in October 2005.
- Nevis – Snowdon 1 in October 2005.
- Pieterboth – Snowdon 1 in November 2005.

Eskom Distribution

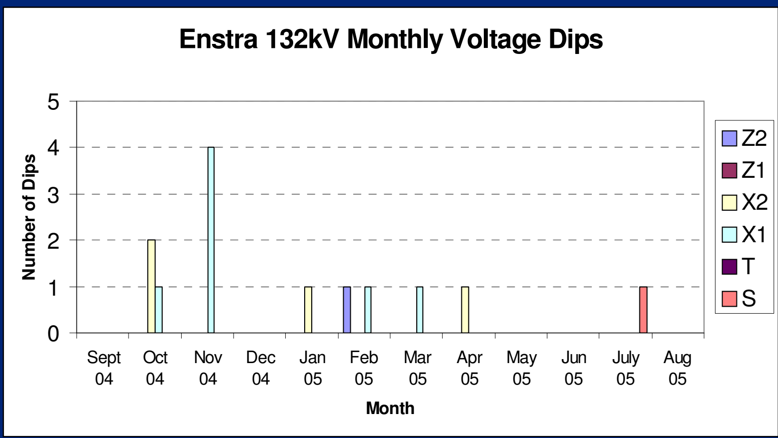
# Benoni, Springs Voltage Dips

| NAME | DIP_DT | PHASES | MAX DEPTH | MAX DURATION | CLASS | EQUIPMENT | CAUSE |
|---|---|---|---|---|---|---|---|
| Benoni Bulk 132kV | 6/2/2005 12:46 | RWB | 32 | 100 | X1 | Nevis Pieterboth No1 275kV Line | Veld Fire |
| Benoni Bulk 132kV | 6/7/2005 05:44 | RB | 32.7 | 120 | X1 | Matla Nevis No2 275kV Line | Bird Pollution |
| Benoni Bulk 132kV | 7/21/2005 08:30 | RWB | 52.4 | 310 | S | Matla Esselen 275kV Line | Under investigation |

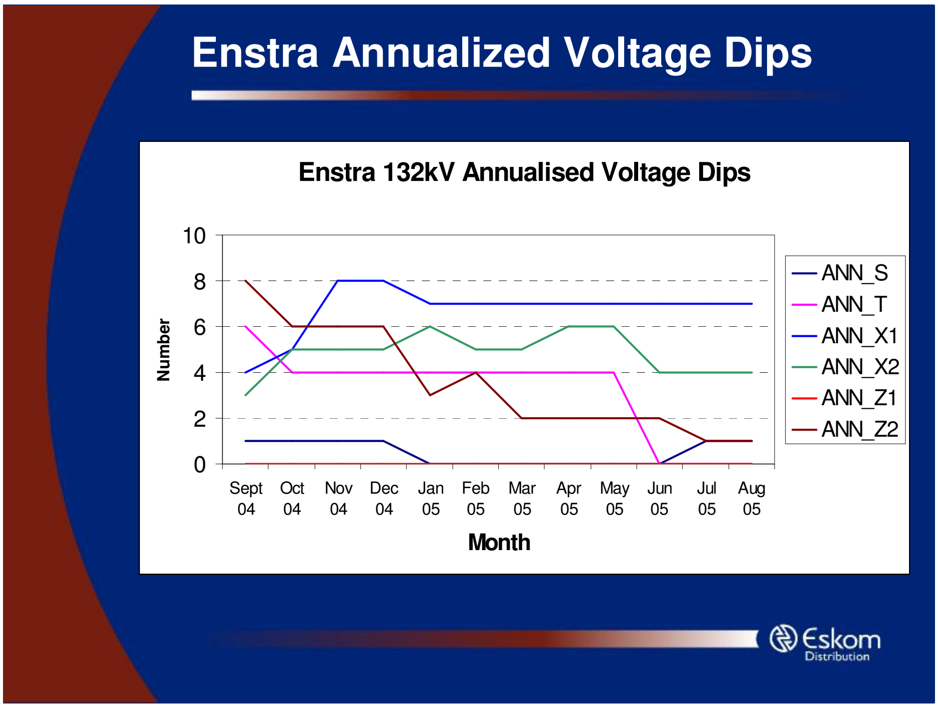
| NAME | DIP_DT | PHASES | MAX DEPTH | MAX DURATION | CLASS | EQUIPMENT | CAUSE |
|---|---|---|---|---|---|---|---|
| Springs Bulk 132kV | 7/21/2005 08:30 | RWB | 44.3 | 250 | S | Matla Esselen 275kV Line | Under investigation |

Eskom Distribution

# Enstra Monthly Voltage Dips




Eskom Distribution


Enstra Annualized Voltage Dips
Enstra 132kV Annualised Voltage Dips
Number
10
8
6
4
2
0
Sept 04
Oct 04
Nov 04
Dec 04
Jan 05
Feb 05
Mar 05
Apr 05
May 05
Jun 05
Jul 05
Aug 05
Month
ANN_S
ANN_T
ANN_X1
ANN_X2
ANN_Z1
ANN_Z2
Eskom
Distribution

## ANNEXURE F:
## NEW PROPOSED DIP COMMUNICATION APPROACH

**Note 1:**

Presentation is incomplete. At the time of presenting, dip influence zones were still being developed.

**Note 2:**

Sprunt and Minaar are the authors of the presentation. The author of this thesis conducted the analysis of dip data (graphs) that was presented by Sprunt and Minaar, using Excel, Event Viewer, NEPS and TIPPS. The reasons for involvement of Sprunt and Minaar are as follows:

- ⇨ This research study forms part of a series of studies on power quality. Sprunt, Minaar, Koch and the author of this thesis, were members of the power quality study group that oversees these studies, at the time of commencement of this research.
- ⇨ On the day of the presentation, it was logistically feasible for Sprunt and Minaar to present dip analysis results to the customer due to base locations (Minnaar – based in Germiston, Sprunt – based in Pietermaritzburg, the author of this thesis – based in Cape Town).

# Enstra QMS Report

**Draft 0 of proposed QMS reporting structures**

by U. Minnaar

A. Sprunt.

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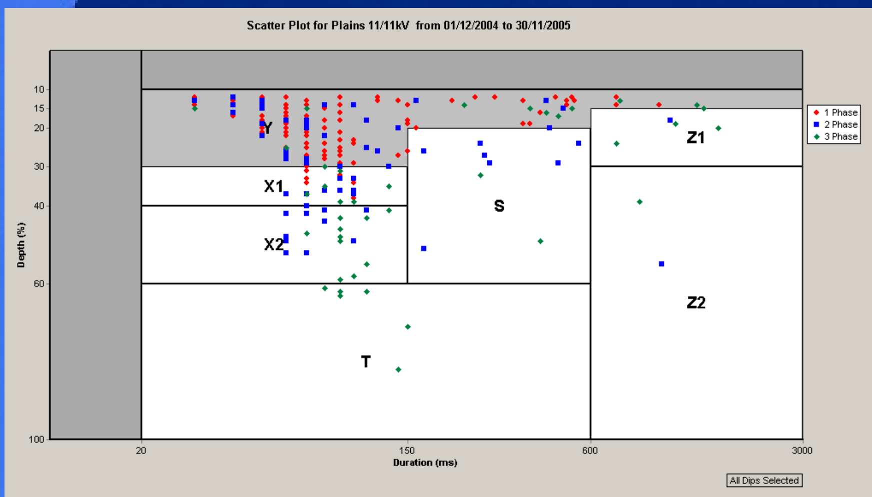
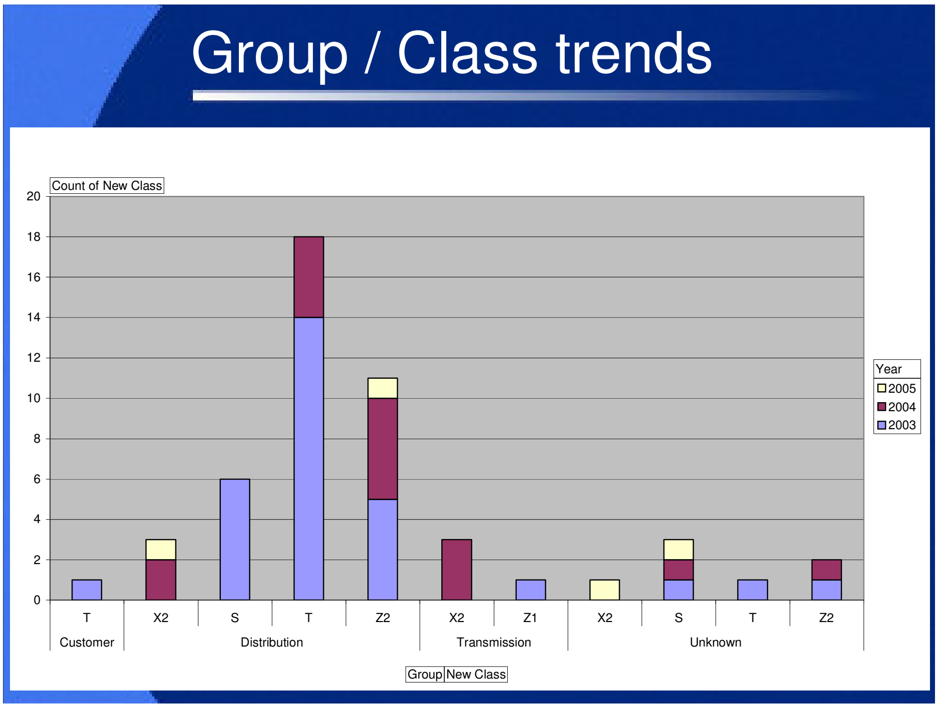
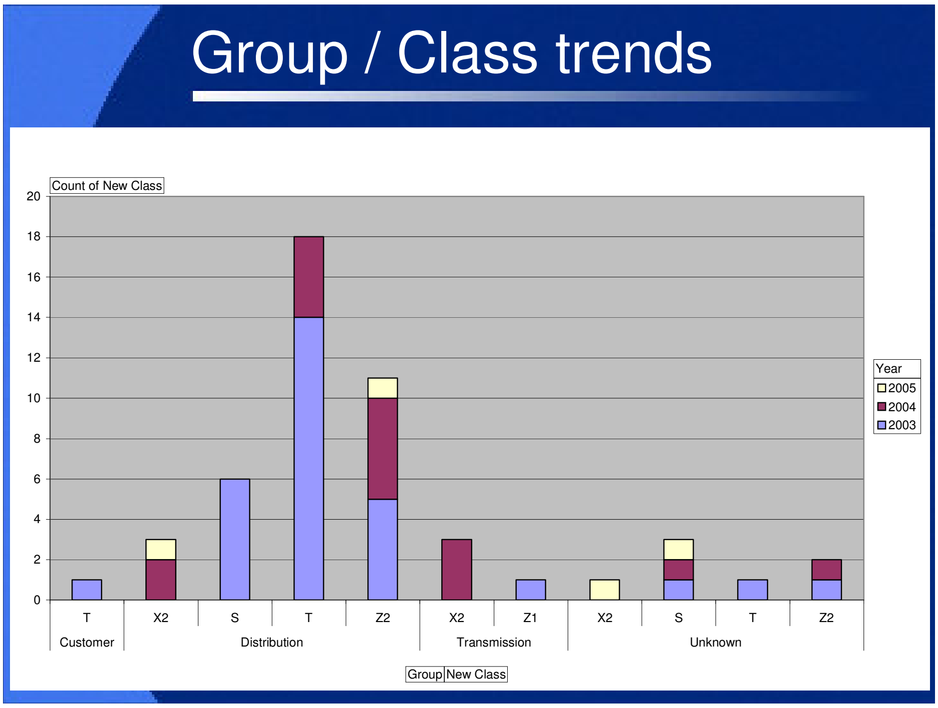
## SCATTER PLOT – Example of *New Window*

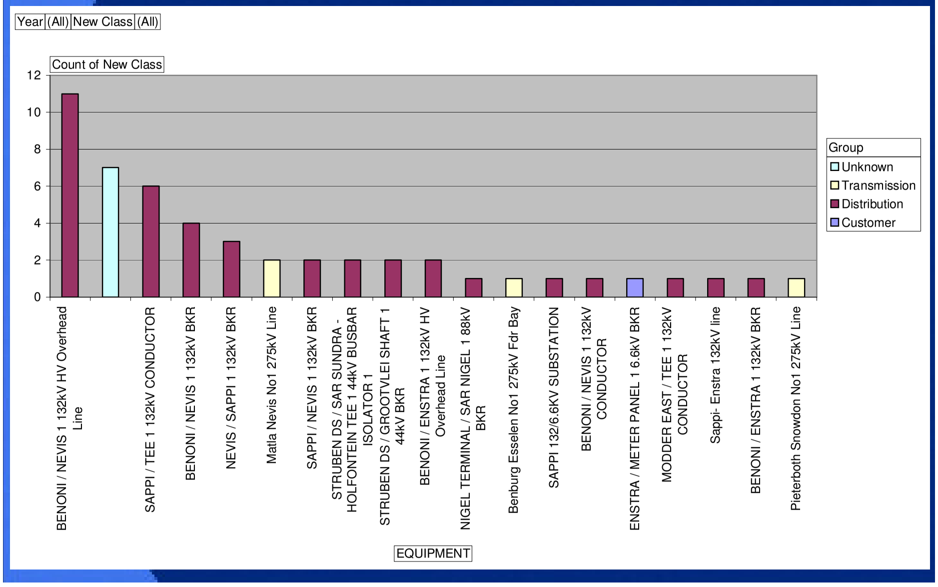



Eskom

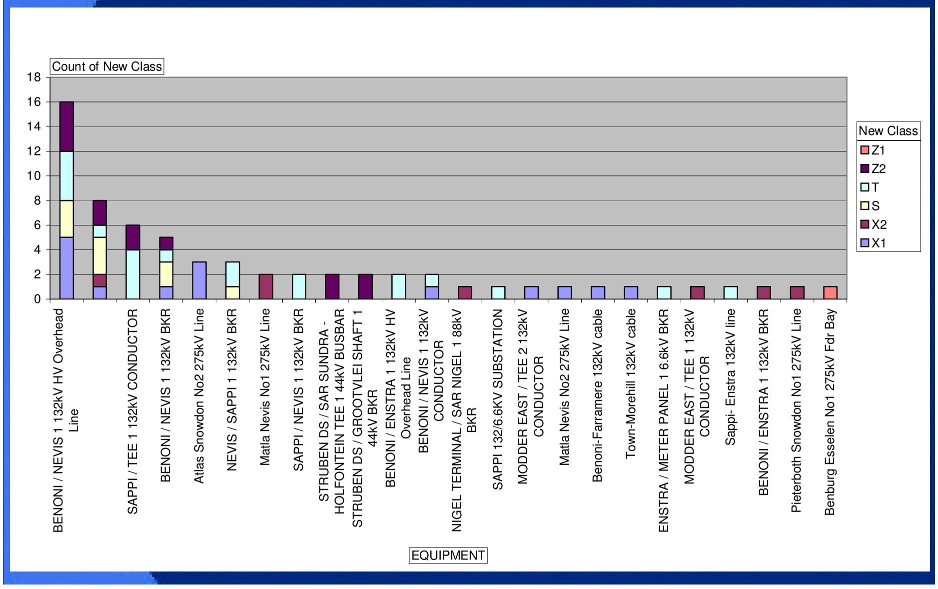

Group / Class trends
Count of New Class
20
18
16
14
12
10
8
6
4
2
0
T
X2
S
T
Z2
X2
Z1
X2
S
T
Z2
Customer
Distribution
Transmission
Unknown
Group
New Class
Year
2005
2004
2003


Group / Class trends
Count of New Class
20
18
16
14
12
10
8
6
4
2
0
T
X2
S
T
Z2
X2
Z1
X2
S
T
Z2
Customer
Distribution
Transmission
Unknown
Group
New Class
Year
2005
2004
2003

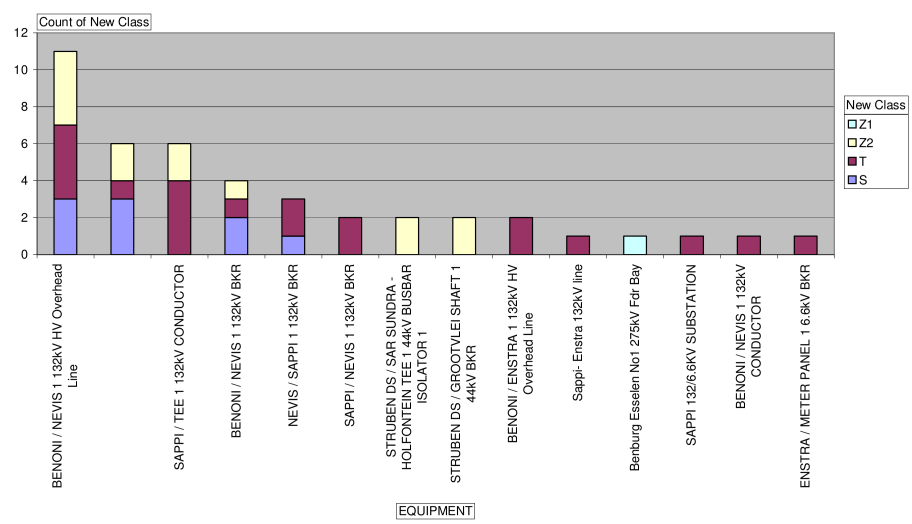
## Top 15 circuits Vs Ownership



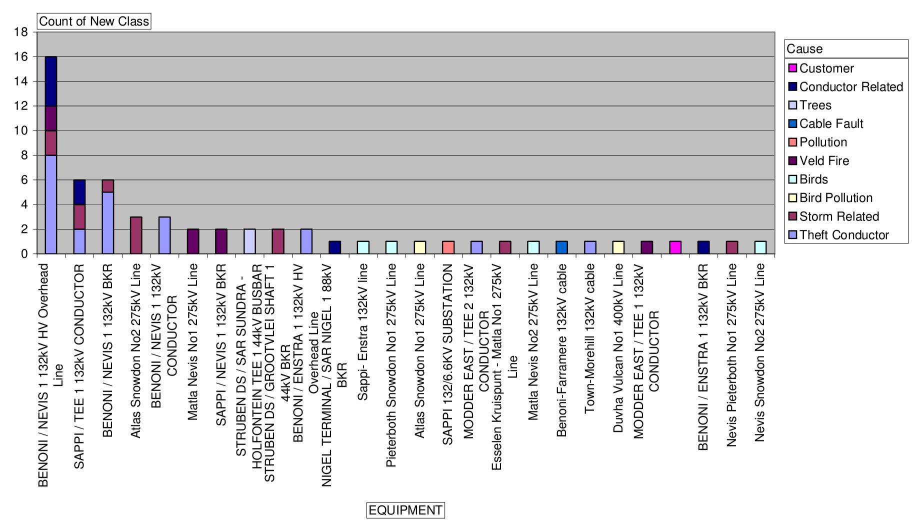

## Top 15 contributors Vs Severity (Dip class)

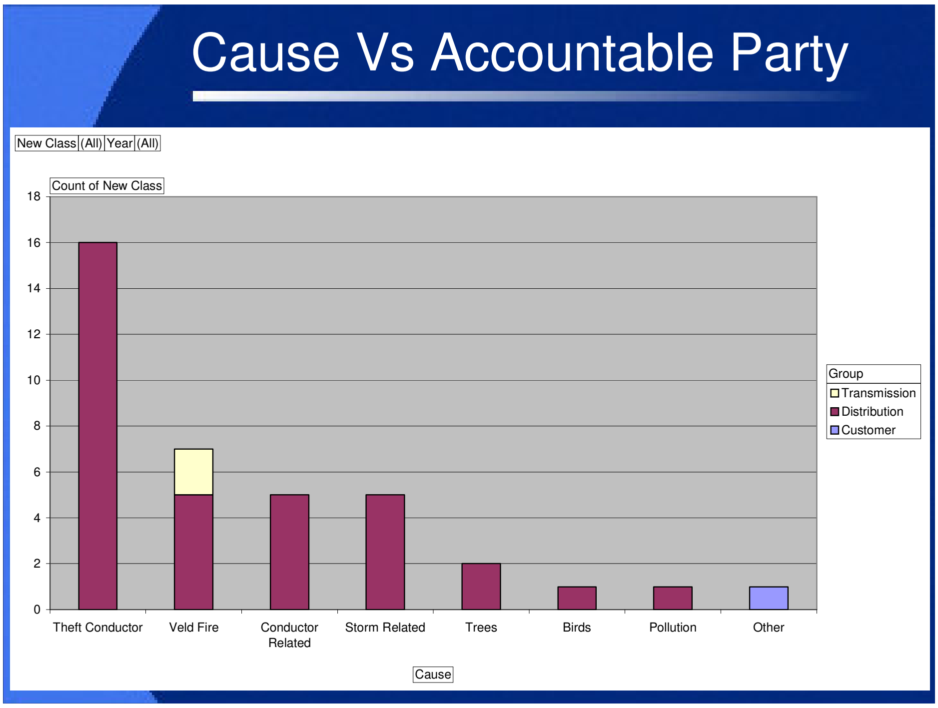


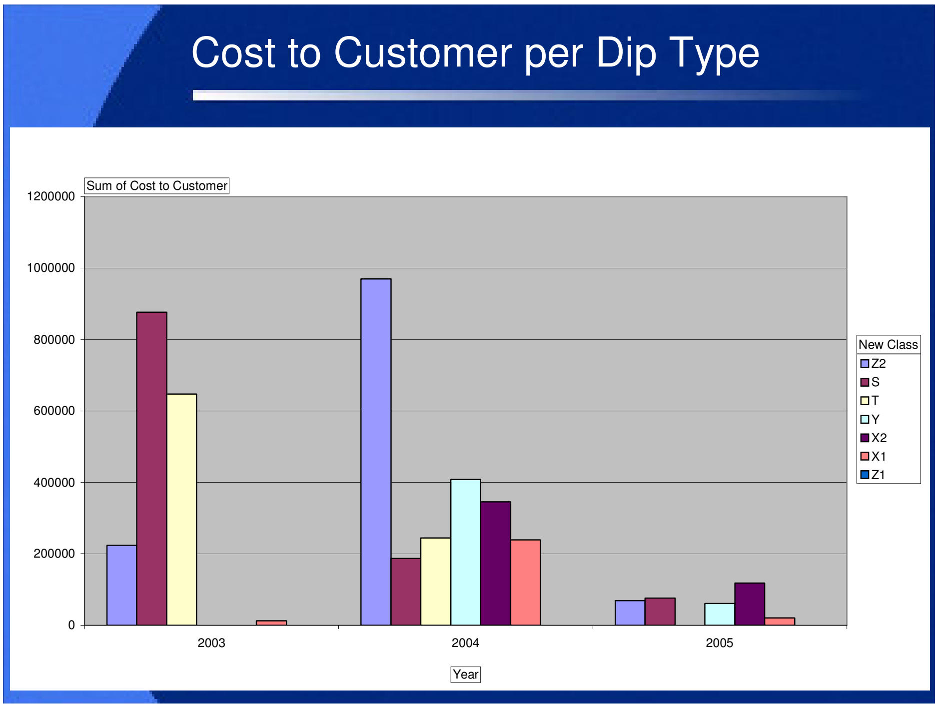
## Top 15 Major dip contributors (Excluding X1 &2 type dips)



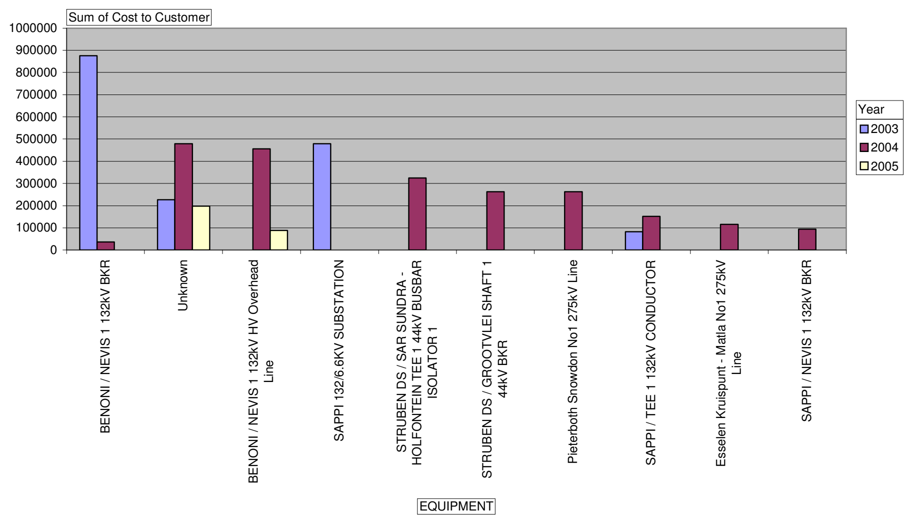

## Top 15 Contributors and associated causes



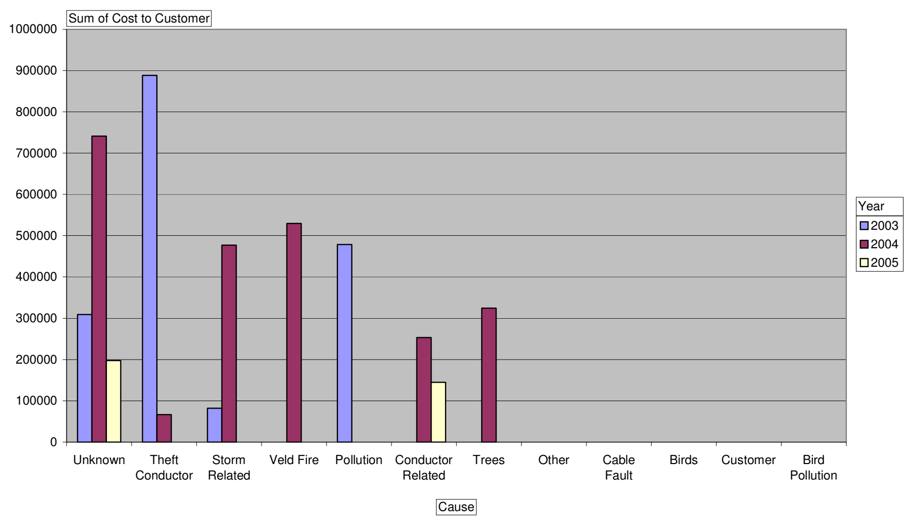

Cause Vs Accountable Party
New Class (All) Year (All)
Count of New Class
18
16
14
12
10
8
6
4
2
0
Theft Conductor
Veld Fire
Conductor Related
Storm Related
Trees
Birds
Pollution
Other
Cause
Group
Transmission
Distribution
Customer


Cost to Customer per Dip Type
Sum of Cost to Customer
1200000
1000000
800000
600000
400000
200000
0
2003
2004
2005
Year
New Class
Z2
S
T
Y
X2
X1
Z1

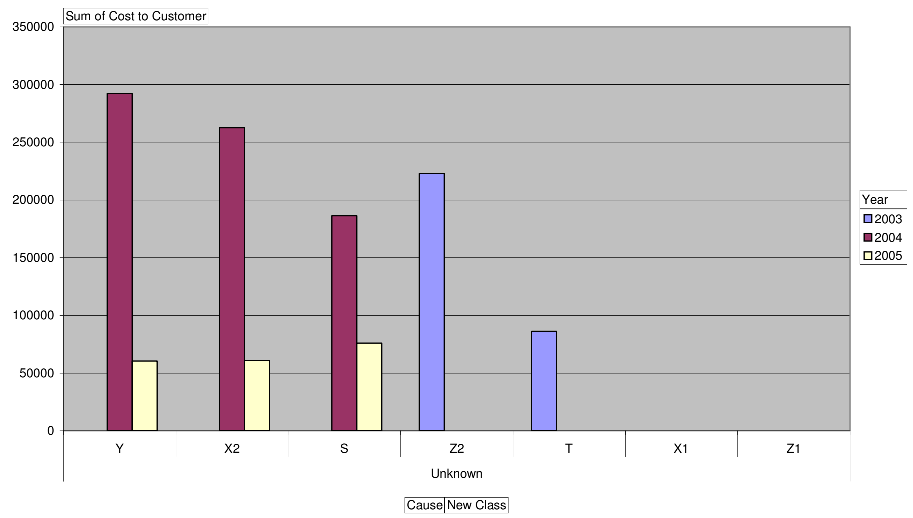
## Equipment Vs Cost contribution



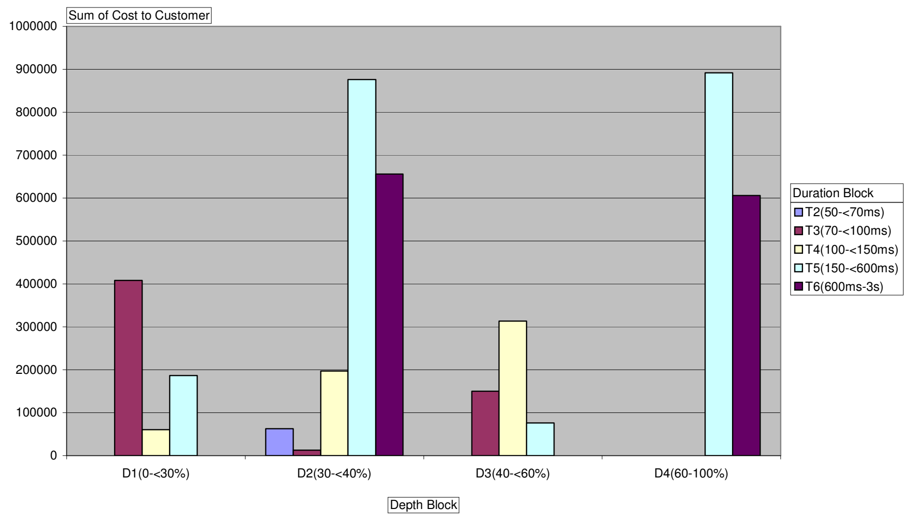

## Cost Contribution Vs Cause of Dip

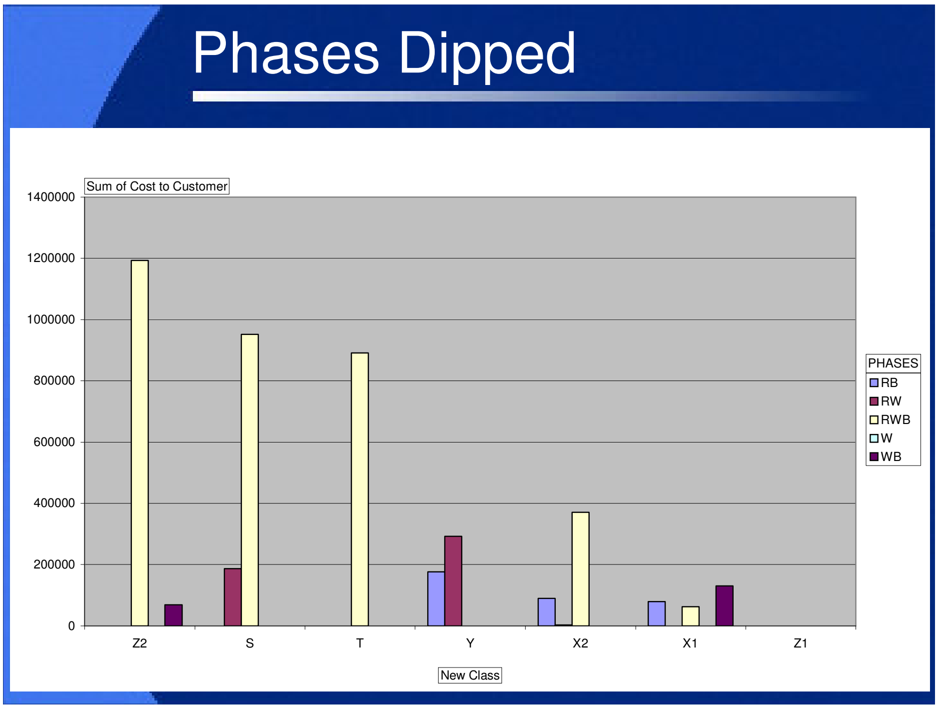


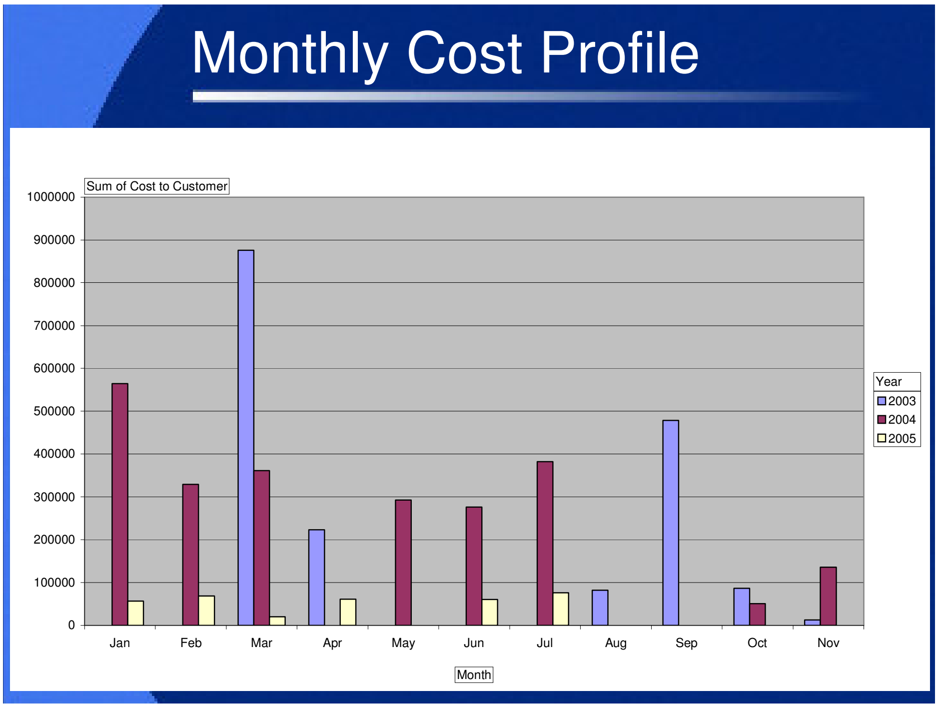
# Cost of Unknown Dip Causes Vs Dip Class




# Depth Vs Duration




Phases Dipped
Sum of Cost to Customer
1400000
1200000
1000000
800000
600000
400000
200000
0
Z2
S
T
Y
X2
X1
Z1
New Class
PHASES
RB
RW
RWB
W
WB


Monthly Cost Profile
Sum of Cost to Customer
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Month
Year
2003
2004
2005


THE END
Eskom