IMPROVING THE POWER QUALITY ON MEDIUM VOLTAGE POWER LINES

A Dissertation presented to

The School of Electrical, Electronic and Computer Engineering

North-West University

In partial fulfilment of the requirements for the degree

Magister Ingeneria

by

Arnold Bothma

Supervisor: Prof JA De Kock

November 2006

Potchefstroom Campus

ACKNOWLEDGMENTS

I would like to thank the following people, because without them this thesis would not have been possible:

- GOD, without whom nothing is possible.
- Prof JA de Kock for his guidance and support, making my studies a worthwhile experience.
- Prof APJ Rens and Mr M Trümpelmann for their valuable advice and input.
- My parents, sisters and brother-in-law for their continued support.
- My fiancée (Rhoda) for her constant love, understanding and important contribution to my studies.
- Lastly my friends (Andries, Stefan and Jan) for their good company and motivation.

EXECUTIVE SUMMARY

The purpose of an electrical power system is to deliver energy to consumers. This should be done with the utmost reliability and economy. When power outages occur the normal routine of society is disrupted. A power system comprises of many diverse items of equipment and to improve the reliability and economy of a power system, this equipment must be of high standard, with good performance and consistency. The industries of today rely upon good power quality because poor power quality can cause a halt in production and in some cases a decrease in product quality. Power quality plays an import role in the efficiency and success of a business.

The purpose of this research is to investigate the possible causes of poor power quality that could be avoided by improving the configuration and condition of the network. The factors that are of concern for this study is the power flow distribution, steady state voltage and the dynamic voltage control of the network. This is done by investigating the current network layout for possible improvements. These layouts are compared with a power system simulation package to determine a suitable solution against poor voltage levels on the network. Recorded measurements of voltage dips and interruptions are characterized to determine a probable cause of these incidents. This in turn points out areas which affect the power quality of the network.

The focus area for this research is a banana farm located in Mpumalanga that produces 15% of the total banana crop in South Africa. They have to supply to their customers every day and any delay they have, reduces the quality of their product. Bananas have a three-week window period from the time of picking to being consumed by their customers. Temperature control of the cooler is an important factor that plays a major role in ripening cycles and the quality of the product. Each time the temperature of the cooler in which the bananas are kept during packaging and distribution, drops during a voltage dip or a power outage, the life-time of the product decreases by a few days.

OMVATTENDE OPSOMMING

Die doel van 'n elektriese kragstelsel is om op 'n betroubare en ekonomiese manier energie aan verbruikers te verskaf. Wanneer kragonderbrekings voorkom, word die normale roetine van die samelewing ontwrig. 'n Kragstelsel bestaan uit baie diverse toerusting en om die betroubaarheid en ekonomie van 'n kragstelsel te verbeter, moet hierdie toerusting aan hoë standaarde van werkverrigting, prestasie en deeglikheid voldoen. Vandag steun industrieë op goeie kragkwalitiet, omdat swak kragkwaliteit 'n stilstand in produksie en soms ook 'n afname in die kwaliteit van die produk te weeg bring. Kragkwaliteit speel dus 'n baie belangrike rol in die sukses en doeltreffendheid van 'n besigheid.

Die doel van hierdie navorsing is om ondersoek in te stel na die moontlike redes vir swak kragkwaliteit, wat vermy kan word indien die netwerk konfiguraie en toestand verbeter word of wanneer toerusting tot die netwerk bygevoeg word om die kragvloei te verbeter. Die faktore wat van belang is vir hierdie studie is die verspreiding van drywing, bestendige toestand en die dinamiese spanningsbeheer van 'n netwerk. Dié konfigurasies word vergelyk met 'n kragstelsel simulasie pakket om 'n gepaste oplossing te vind vir lae spanningsvlakke in die netwerk. Meterlesings van variasies in spanning (*voltage dips*) en toevoer onderbrekings in spanning word gekategoriseer om vas te stel wat die moontlike oorsake van hierdie verskynsels is. Dit verwys dan weer na areas wat die krag kwaliteit van 'n netwerk kan beïnvloed.

Die fokusarea van die studie is 'n piesangplaas in Mpumalanga wat 15% van die piesangs in Suid-Afrika produseer. Hulle moet elke dag piesangs aan hul verbruikers voorsien en enige vertraging wat hulle ondervind, verlaag die kwalitiet van hul produk. Piesangs het 'n drie-week-vensterperiode vanaf die dag wat hulle gepluk word totdat hulle deur die verbruikers geëet word. Temperatuur beheer van yskaste is baie belangrik met betrekking tot die ryp word siklus en kwaliteit van die finale produk. Wanneer 'n variasie in spanning of 'n kragonderbreking 'n afname veroorsaak in die temperatuur van die yskas waarin die piesangs gestoor word, word die leeftyd van die produk met 'n paar dae verkort.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF DEFINITIONS AND ABBREVIATIONS

DEFINITIONS

Customer: A person or legal entity that has entered into an electricity supply agreement with a utility.

Declared voltage: Is the voltage that is declared by the utility at the point of supply.

Interruption: A phenomenon that occurs when one or more phases of a supply to a customer are disconnected for a period exceeding 3 s.

Point of common coupling (PCC): That point in a network where one or more customers are connected or will be connected.

Utility: A body that generates, transmits and distributes electricity.

Voltage dip/sag: Voltage dips are defined as the short-duration reduction in rms voltage. According to NRS 048 standards the dip duration is a period of between 20 ms and 3 s, of any or all of the phase voltages of a single-phase or a polyphase supply. The duration of a voltage dip is the time measured from the moment the rms voltage drops below 0,9 per unit of declared voltage to when the voltage rises above 0,9 per unit of declared voltage.

Harmonics: Sinusoidal components of the fundamental waveform (i.e. 50 Hz) that have a frequency that is an integral multiple of the fundamental frequency.

Voltage regulation: The ability of the steady-state rms voltage to remain between the upper and lower limits.

ABREVIATIONS

SLGF: Single-line-to-ground fault

LLF: Line-to-line fault

2LGF: Double line-to-ground fault

pu: Per unit.

rms: Root mean square

LN voltages: Line-to-neutral voltage

LL voltages: Line-to-phase voltage

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION TO THE POWER QUALITY PROBLEM

Power quality can be defined as a measurement of the quality of supply regarding the power provided to the user. The aspects affecting the quality of supply consist of flickering, voltage unbalance, harmonics, dips and swells as well as transients. All the aspects mentioned above are caused by different conditions, for example lightning strikes, poor network design, load configurations and human errors. In turn these aspects can influence sensitive electronic devices, decrease the lifetime of motors, cause malfunctioning of protective devices and interfere with network security.

When looking at an agricultural industry such as the banana farm, voltage dips and network typology were identified as the two pronounced problems that will receive attention in this research. Voltage dips is one of the aspects already mentioned above that can influence the quality of power from the supplier and it can be defined as disturbances caused by power system faults. It has become one of the most important power quality problems facing industrial customers, because of the increasing amount of motors, modern electronic devices and industrial automation which are all sensitive to voltage variations.

Not a lot of focus was placed on power quality in the past, but with the development of the new technological era it became more pronounced and more important to focus on the quality of power provided for maintaining electric equipment, as this could influence the performance and production of plants (customers) that relies on the electrical supply.

1.2 MOTIVATION FOR THE RESEARCH

The banana farm under investigation is a large agricultural enterprise operating at two branches in Mpumalanga – the one near Hazyview, the other near Hectorspruit. To maintain an independent professional view and due to possible legal action between the two parties the names of the banana farm and distribution utility is kept anonymous. Their core business is growing, ripening and distributing bananas to leading chain stores throughout the country. These customers have very demanding requirements – requirements that managers of the farms does its best to meet, whilst working with a crop that is very perishable and sensitive. Electricity is a vital business resource for their company. They are considered to be a relatively large power user, at least in terms of agricultural clients. They have a long history of complaints and problems with their distribution Utility. Their complaints revolve around poor quality of supply, gross negligence in maintaining equipment, inferior standards of service and poor management. The motivation for this research is that they are tired of the substandard service and quality of supply, which adversely affects their business.

From the claim documents [18] the losses that they experience due to poor power quality can be summarized under the following headings:

Administrative Losses

- Include time lost due to administrative staff at the applicable point being unable to effectively carry on with their work during a power failure.

Irrigation Losses

- Numerous pumps at pumping stations consume a substantial amount of the electricity. Banana plantations are very dependant on irrigation, more so than most other crops. Any significant loss of irrigation affects the quality of the product. Moreover, the interruptions in irrigation supply will not only affect the quality of bananas, but also the quantity each tree is able to produce.

- Pumps are programmed to run during off-peak billing hours. Loss of power during these off-peak hours causes pumps to run during peak billing hours, thus accumulating unnecessary costs.

- Intermittent starting and stopping of pumps due to power failures, causes maximum demand to be higher than required and may also damage the electric and hydraulic systems.

- During times of water restrictions, there is a limited window period during which pumps may be operated. Loss of power, results in a loss during important pumping opportunities

Labour Losses

- Hundreds of workers are employed in pack-houses and workshops. Loss of power prevents systems (conveyors, scales, etc) from running and results in labourers standing around unproductively.

Management Losses

- Loss of power results in management being unable to effectively continue with their tasks and forces them to waste time on the phone trying to rectify the problem.

- Every power failure forces management to start up systems again and check up on equipment and processes that are affected by the loss of electricity.

Production and Quality Losses

- The farm produces thousands of tons of bananas each month. Every day, each pack-house is required to meet certain targets in their packing schedules. Any delays to do so due to power failures cost thousands of rands per hour in lost production, in addition to all the other associated losses.

- The two farms has more than 50 ripening rooms (each of which holds ± 30 tons of fruit) between its two farms. Bananas are a very perishable crop; very sensitive to temperature changes and gas levels during the ripening process – a process that typically extends over several days. Loss of power during this cycle adversely affects the quality of the product.

- Loss of power results in refrigeration systems peaking in power consumption in an attempt to bring temperatures under control again. This causes unrealistically high peak demands for which they have to pay excessive charges.

The motivation for doing the research regarding the power quality on the banana farm was mainly due to the fact that they would like to prevent malfunction and failure of their equipment and minimise unnecessary and unscheduled power outages, which could increase their productivity, lengthen product life and ensure greater competence. This in turn would ensure that their organisation would benefit financially.

These research observations could also lead to the identification of possible aspects for improvement by the distribution Utility, which for them could lead to an increase in effectiveness, customer satisfaction and conservation of power.

1.3 AIM AND RESEARCH OUTLINE

The purpose of this research is to investigate and analyze the distribution network of the banana farm in order to identify problem areas on the customer's network, which is affected by poor power quality. This was done by simulating the interconnected grid that is connected to the Koorsboom substation and was done by using PSAF (a power system simulation package used for the analysis of power systems).

This software package was used to perform a feasibility study on the network to determine whether the present layout meets the system requirements. This study (Chapter 4) includes a power flow and fault level analysis of the network. From the results of the power flow study it is possible to indicate points on the network that are affected by poor quality and that might be the cause of poor power quality. Through careful inspection of the results and the layout of the existing network suggestions were made on how to improve the power quality. Six additional system layouts were analyzed to determine which one would provide the best solution for improving the network security.

The other important aspect is the analysis of voltage dips (Chapter 5) that was recorded with a class A power quality recorder. These recorded measurements of voltage dips and interruptions were characterized to determine a probable cause of these incidents, which in turn points out areas that affect the power quality of the network. The characterization was done by considering various aspects that influence the dip propagation across the network such as the transformation of line-to-line voltages to line-to-neutral voltages.

1.4 MAIN CONTRIBUTION OF RESEARCH

The contribution of this research is multi-fold, because of the fact that the banana farm will benefit from these findings on a variety of levels, but they will not be the only company to do so. The results of these findings could also be adapted to create solutions for the power quality problems experienced by a wide range of agricultural companies across the country. These results could furthermore be expanded to address the needs of many small businesses or farms situated in rural areas.

On another level the distribution Utility as a company also benefits from these findings, not only with concerns to the farm, but also because these results could serve as possible guidelines to increase the power quality in South Africa, especially with regards to industry upgrades. In this instance the research would serve as a useful and practical alternative to provide solutions for improving the general power quality of the country.

CHAPTER 2
LITERATURE OVERVIEW

2.1 INTRODUCTION TO POWER QUALITY

The distribution or transportation of electrical power is one of the most important processes in everyday life. It is perhaps the most essential raw materials used by industry, small businesses and people all over the world. Electricity supply is required as a continuous flow and cannot be inspected or subjected to quality assurance checks before it is used. In short, the supply is not something that can be predicted or checked before use, the user receives what is available at any moment.

Power quality is a broad term that is used to describe the quality of electric power supplied to electrical equipment. Poor power quality can cause failure to equipment, mal-operation of sensitive equipment like protective relays and variable speed drives (VSDs). Power quality has several defects that cause the deviation from perfection; here are a few:

- Harmonic distortion
- Transients
- Voltage unbalance
- Voltage fluctuations
- Under- and overvoltage
- Voltage dips and swells
- Network topology

Each of these defects has a different cause and some are the result of the shared infrastructure of the interconnected grid. Causes of poor power quality include natural causes, load-, and transmission line and feeder operation. Examples of natural causes are falling trees, vegetation growth, equipment failure and weather conditions. The most common cause for load related problems are power electronic devices. These devices serve a great purpose in the industry however, they draw non-sinusoidal currents from the source which reacts with systems impedances to causes the above mentioned power quality issues. Transmission line layout and feeder operation does not necessarily cause poor power quality, it mainly influences the propagation and severity of power quality aspects. A more detailed description of the causes of voltage dips are described later in this chapter.

Every consumer of electrical power ought to be protected by a standard. The South African standard is the *"NRS 048: Preferred requirements for applications in the electricity supply industry"* [13]. This is used as a basis for evaluating the quality of supply (QOS) delivered to consumers and to determine whether utilities meet the minimum required standard set by the National Electricity Regulator (NER).

Two time related variations that lead to poor power quality are disturbances and steady state variations. Disturbances are defined as abnormalities that occur in the voltages and currents due to faults on the system or some abnormal operation. Steady state variations are the deviation of nominal quantities and the influence of harmonics in the system.

2.2 POWER FLOW DISTRIBUTION IN MEDIUM VOLTAGE POWER LINES

The power flow through a network is an important factor when it comes to power quality. A transmission network is designed to carry a certain power transfer capability. Therefore, when the electrical supply is no longer sufficient, due to industrial expansion and power consumption, the power quality deteriorates. This means that the network configuration (power lines, transformers, etc) is not performing at its optimum efficiency and will cause a poor power factor, decreased bus voltages and increase unnecessary trips.

The flow of power can be improved by performing a power flow study on a network and thus identifying the problem areas such as overloaded lines and transformers.

These problems can then be solved by changing the transformer sizes, adding equipment such as inline boosters and on-load tap changers to transformers as well as reconfiguring the network layout.

Steady state voltage means the small variation in nominal voltage magnitude during normal system operation. For example, if a distribution bus is rated at 1 pu, but it is operated at 0.9 pu when it is measured, then the steady state voltage is below the nominal rated value. The reduction in steady state voltage is a result of large loads that consume reactive power.

When the loads across a network are distributed unequally, an uneven load flow occurs that causes some power lines to be overloaded. The problem with this is that when one line's breaker opens to clear a fault, the power from that line is distributed through the other connected lines. This can cause the overloading of some lines, which will lead to the opening of their breakers. The process can have a snowball effect and lead to total system blackout.

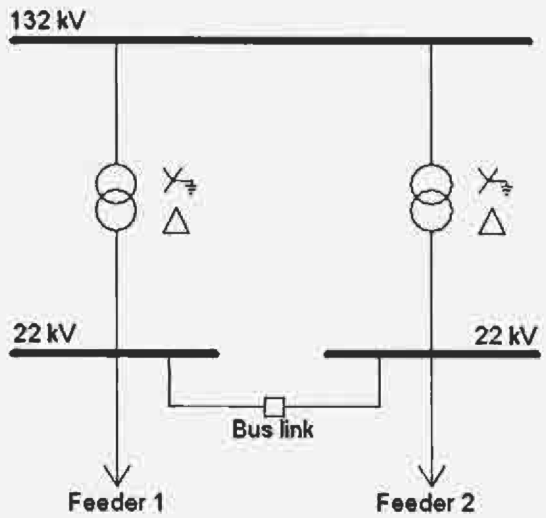


Figure 2.1: Parallel supply transformers with bus link

The effect the network topology has on number of dips can be illustrated with the following example: for instance, if two parallel transformers supply a large area with two feeders connected via the bus link as shown in figure 2.1. If voltage dips is generated at some point on feeder 1 it will have a large effect on feeder 2 as well.

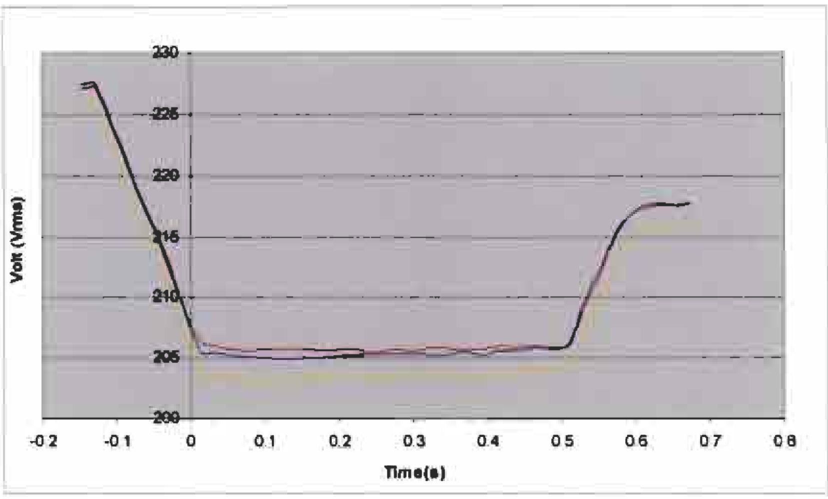
However, if the bus link is opened, the impact of the dips would be less on feeder 2. This is because the dips generated on the infected feeder are propagated back through its transformer to the 132 kV side, and then back through the transformer of feeder 2 to the rest of the network. In the first case however, the dips are directly propagated to the second feeder through the bus link. The damping of the dips is caused by the extra reactance of the transformer.

2.3 VOLTAGE DIPS IN DISTRIBUTION SYSTEMS

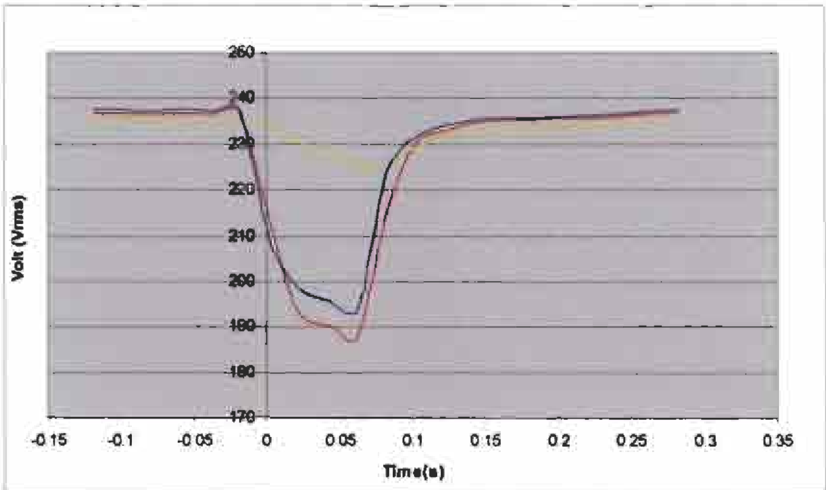
Voltage dips are considered one of the most important power quality aspects due to its regular occurrence and the damage it causes to consumers. Voltage dips are defined as the short-duration reduction in rms voltage caused by faults in the electricity supply system, the starting of large loads such as induction motors and the energizing of transformers.

The NRS 048 standard used in South Africa defines a voltage dip as *"a sudden reduction in the rms voltage, for a period of between 20 ms and 3 s, of any or all of the phase voltages of a single-phase or a polyphase supply. The duration of a voltage dip is the time measured from the moment the rms voltage drops below 0.9 per unit of the declared voltage to when the voltage rises above 0.9 per unit of the declared voltage"* [13].

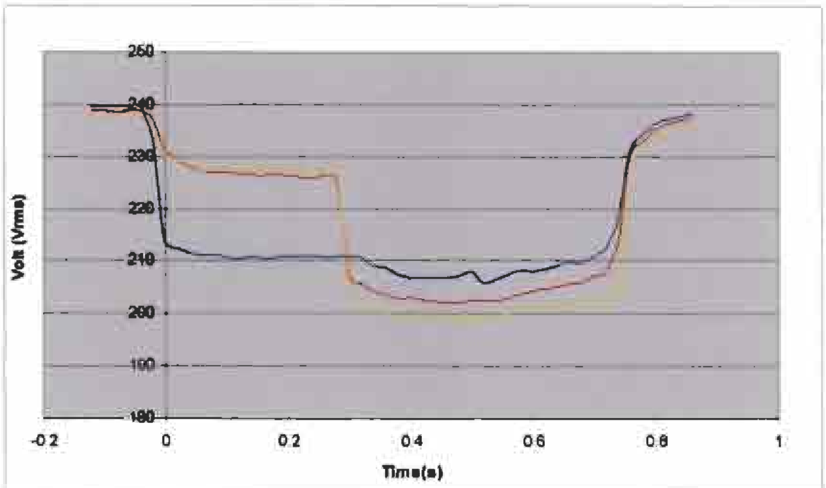
Figure 2.2 (a) and (b) shows an example of a balanced three-phase dip caused by a large induction motor starting and a two-phase voltage dip that was caused by a fault on a distribution network. Figure 2.2 (c) is a multistage dip that presents different levels of magnitude before normal voltage levels are restored and is caused by changes in system configuration while the protection tries to isolate the fault or if the nature of the fault changes [4].



(a)



(b)



(c)

Figure 2.2: (a) Three-phase balanced voltage dip, (b) unbalanced two-phase voltage dip and (c) is a multistage dip

Voltage dips are usually characterized by the percentage drop in magnitude and duration of the dip. However a dip caused by a specific fault is far more complicated, it has a phase angle jump and usually the dips are unbalanced. Also, the fact that the equipment/load is connected at a different voltage level to which the fault occurs, and as a consequence it does not experience the same dip that was originally inflicted at the fault. Therefore this method of characterizing dips has its limitations.

Understanding and analysing voltage dips is a multifaceted and complicated task due to its complexity. The existing method for characterizing dips uses the lowest of the three voltages and the longest duration [2], [7]. However, this method causes erroneous results on single- and three-phase systems. A method proposed by M.H.J. Bollen and L.D. Zhang to characterize dips is described in section 2.3.2.1 and is used to determine the dip type and the probable cause of the dips experienced on the banana farm [2], [10], and [11]. This method is based on symmetrical components and corresponds to methods currently used and recommended by international standards [7].

2.3.1 Characteristics of voltage dips

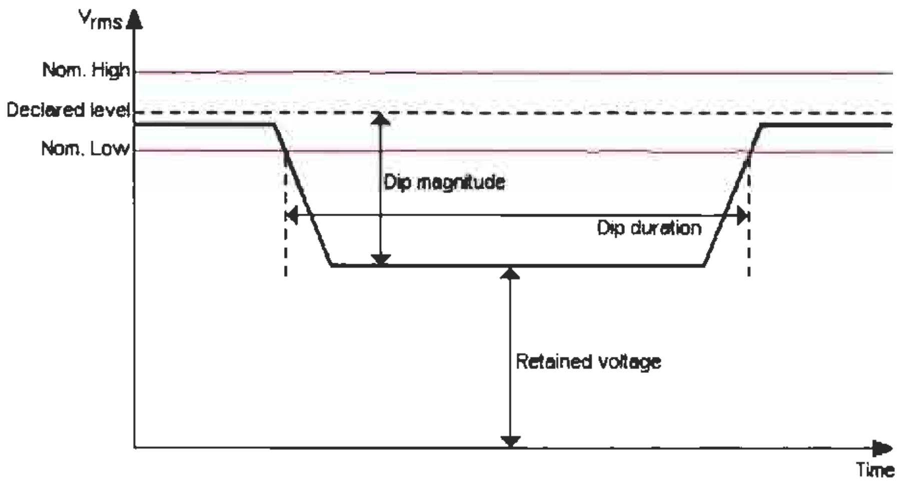


Figure 2.3: Voltage dip profile

2.3.1.1 Dip magnitude and duration

The two main characteristics that are used to define a voltage dip are magnitude and duration. There are two ways of describing the magnitude, voltage drop and remaining voltage. Voltage drop means the difference between the reference amplitude and the actual voltage. Retained or remaining voltage is the amplitude of the actual voltage. The duration of a dip is the time from which the voltage is lower than the declared limit until it rises above that limit. According to the NRS 048 that limit is 0,9 pu [13]. The duration of the fault or the type of protective device used determines sag duration.

The magnitude during a dip is obtained from the instantaneous waveforms by means of the root-mean-square method:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \qquad (2.1)$$

where v_i is the sampled voltages and N the number of samples per cycle [8].

If the impedance of the system is known the dip magnitude can be calculated from the voltage-divider rule as shown below [8]

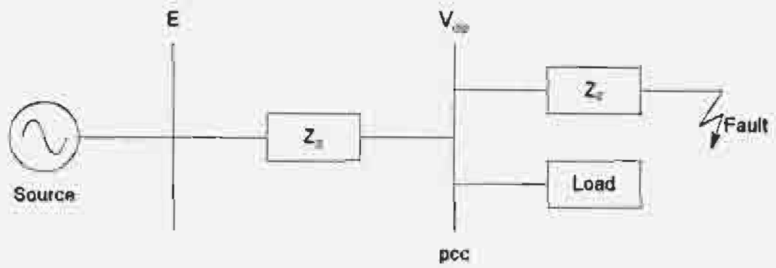


Figure 2.4: Determining dip magnitude from power system parameters

$$\overline{V}_{dip} = \frac{\overline{Z}_F}{\overline{Z}_F + \overline{Z}_S} \cdot E \qquad (2.2)$$

where E is the pre-fault voltage, Z_F is the fault impedance between the PCC and the fault and Z_S is the source impedance seen from the PCC [8], [9]. Thus the dip magnitude mainly depends on the source- and fault impedance. Therefore, lower source- and line impedances would cause smaller dip magnitudes.

Therefore, the factors affecting the sag magnitude due to faults at a certain point in the system are:

- Distance to the fault
- Fault impedance
- Type of fault
- Pre-sag voltage level

- System configuration
  - System impedance
  - Transformer connections

The effect of transformers and its connection on voltage dips are described in section 2.3.2.2.

2.3.1.2 Phase-angle jumps

During a fault it is not only the magnitude and duration of the phasors that are affected, but the angles of the phasors as well. This change is called the phase-angle jump and is associated with voltage dips. Phase-angle jumps that occur during a voltage dip are caused due to the difference in the X/R ration between the source and the feeder, and also due to primary to secondary voltage transformation through the transformer [8], [9].

From equation 2.2 where $\bar{Z}_F$ and $\bar{Z}_S$ is the complex impedances of the fault and the source. The voltage dip V_{dip} phase-angle jump is then given by [8]:

$$\Delta\theta = arg(\bar{V}_{dip}) = tan^{-1}\left(\frac{X_F}{R_F}\right) - tan^{-1}\left(\frac{X_S + X_F}{R_S + R_F}\right) \qquad (2.3)$$

From this equation it can be seen that the phase-angle jump would be zero if

$$\frac{X_F}{R_F} = \frac{X_S}{R_S}$$

The influence of phase-angle shift on equipment varies, depending on the type of equipment. Those using the phase-angle or zero-crossings of the source voltage as control information, may be very sensitive, for example, some controlled rectifiers and voltage source inverters.

2.3.2 Voltage Dip Relation with fault types

Balanced voltage dips are usually caused by the starting of large loads such as induction motors or when all three lines are shorted to ground, the latter situation is uncommon, but could happen. The most common types of unbalanced faults are single-phase-to-ground (SLGF), line-to-line (LLF) and double line-to-ground faults (LLGF). The main causes of these faults are characterized as follows [12]:

Mechanical failure: This is caused by the mechanical failure of insulators, conductors, shielding wires and protective equipment.

Electrical faults: Are caused by insulator pollution, design constraints, malfunctioning of protective devices, supply utility error and human errors.

Environment influence: Fires, wind, weather, vegetation growth (trees) and animal contact.

The environment has a significant impact on the frequency of faults that give rise to voltage dips, particularly in the case of overhead and distribution lines in rural areas. The network layout or topology in the vicinity of any customer's plant has a significant impact on the number of voltage dips, as well as on the magnitude and duration [12].

Figure 2.5 shows the four most common power systems faults that occur. It should be noted that the type of fault doesn't necessarily represent the type of dip. The dip type is determined by the type of fault and the winding connections of transformers between the fault location and measuring point [1].

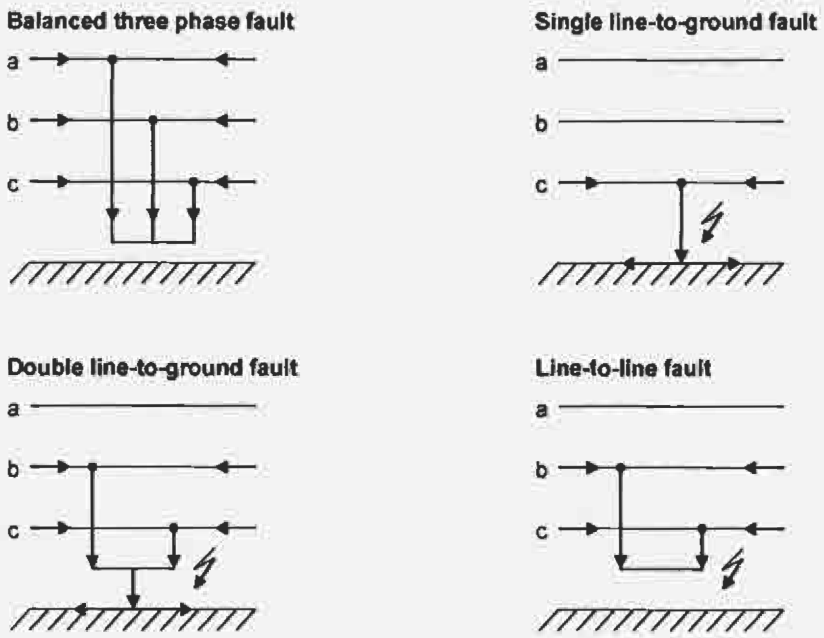


Figure 2.5: Four most common fault types in a power system

2.3.2.1 Voltage dip characterization

Two methods were developed by Bollen and Zang to classify unbalanced voltage dips, the "ABC classification" and "symmetrical component classification" [7], [15]. The ABC classification distinguishes between seven types of three-phase dips. This method is more commonly used due to its simplicity. However, due to incomplete assumptions the authors do not recommend the use of this method for obtaining the dip classification from measured instantaneous measurements. This classification was developed for the stochastic prediction of voltage dips, the propagation of dips across transformers and the testing of equipment against voltage dips. Expressions for the complex voltages and phasor diagrams for these seven dip types are given in Table 2.1. Where phase *a* is defined as the symmetrical phase, i.e. the fault at phase *a* for SLGF and a fault between phases *b* and *c* for LLF and LLGF. The complex pre-fault voltage is indicated by E_1 and the voltage in the faulted phase or phases is indicated by V^*. The reason for this classification was to describe the propagation of dips through transformers from transmission levels to distribution levels [3], [7].

ABC Classification

These dips are grouped based on the number of phases with the most severe voltage drop. The seven basic types of dips experienced by three-phase loads are [8]:

Type A: Due to three-phase faults, all voltages drop by the same amount and are referred to as three-phase drops.

Type B: Caused by SLGFs, one voltage drops in magnitude and the other two remains unchanged.

Type C: Caused by SLGFs and LLFs: two voltages drop in magnitude and change in phase angle while the third voltage does not change at all.

Type D: Also caused by SLGFs and LLFs faults: two voltages drop in magnitude and change in phase angle while the third voltage only drops in magnitude.

Type E: Dips caused by LLGFs (less common): two voltages drop in magnitude with no phase angle change while the third voltage remains unchanged.

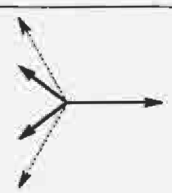
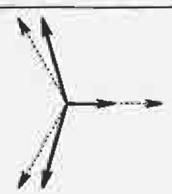
Type F: Dips caused by LLGFs: two voltages drop in magnitude and change in phase angle while the third voltage only drops in magnitude.

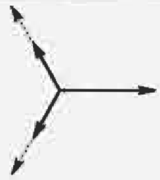
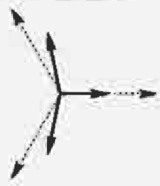
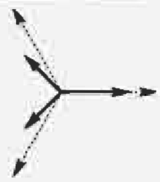
Type G: Dips caused by LLGFs: two voltages drop in magnitude and change in phase angle while the third voltage only drops in magnitude.

Type A voltages are referred to as three-phase drops, type B, D and F as single-phase drops and type C, E and G as two-phase drops.

Note for example that a single-phase drop does not refer to only one phase experiencing a drop, the other two phases also experience a small drop due to other phenomena such as phase angle jumps and zero-sequence quantities. In solidly grounded systems the change in voltage of the healthy phases are small. However, for resistance grounded and impedance grounded systems this change is much larger [5].

Table 2.1: ABC dips classification [7], [8]

Type	Voltages	Phasors
A	$U_a = V^*$ $U_b = -\frac{1}{2}V^* - \frac{1}{2}jV^*\sqrt{3}$ $U_c = -\frac{1}{2}V^* + \frac{1}{2}jV^*\sqrt{3}$	
B	$U_a = V^*$ $U_b = -\frac{1}{2}E_1 - \frac{1}{2}jE_1\sqrt{3}$ $U_c = -\frac{1}{2}E_1 + \frac{1}{2}jE_1\sqrt{3}$	
C	$U_a = E_1$ $U_b = -\frac{1}{2}E_1 - \frac{1}{2}jV^*\sqrt{3}$ $U_c = -\frac{1}{2}E_1 + \frac{1}{2}jV^*\sqrt{3}$	
D	$U_a = V^*$ $U_b = -\frac{1}{2}V^* - \frac{1}{2}jE_1\sqrt{3}$ $U_c = -\frac{1}{2}V^* + \frac{1}{2}jE_1\sqrt{3}$	

E	$U_a = E_1$ $U_b = -\frac{1}{2}V^{*} - \frac{1}{2}jV^{*}\cdot\sqrt{3}$ $U_c = -\frac{1}{2}V^{*} + \frac{1}{2}jV^{*}\cdot\sqrt{3}$	
F	$U_a = V^{*}$ $U_b = -\frac{1}{2}V^{*} - \left(\frac{1}{3}E_1 + \frac{1}{6}V^{*}\right)j\sqrt{3}$ $U_c = -\frac{1}{2}V^{*} + \left(\frac{1}{3}E_1 + \frac{1}{6}V^{*}\right)j\sqrt{3}$	
G	$U_a = \frac{2}{3}E_1 + \frac{1}{3}V^{*}$ $U_b = -\frac{1}{3}E_1 - \frac{1}{6}V^{*} - \frac{1}{2}jV^{*}\cdot\sqrt{3}$ $U_c = -\frac{1}{3}E_1 - \frac{1}{6}V^{*} + \frac{1}{2}jV^{*}\cdot\sqrt{3}$	

Symmetrical component classification

By taking phase *b* and *c* as symmetrical phases for dip types C and D, these dips can be further (sub) characterized into six different classes namely, C_a, C_b, C_c and D_a, D_b, D_c, which corresponds to the seven types of the ABC classification. The ABC classification is merely a general classification of the symmetrical component classification. Where C_c means a drop in phases *a*, *b* and a D_b dip indicates a drop in phase *b*, etc. The advantage of this method is that it can be used to analyze and extract characteristics from instantaneous voltage measurements, except for cases where the load has a severe influence on the fault voltages [7].

Table 2.2: The relation between the ABC- and symmetrical component classification (SCC) [7]

Type	
ABC	**SCC**
A	A
B	D_a
C	C_a
D	D_a
E	C_a
F	D_a
G	C_a

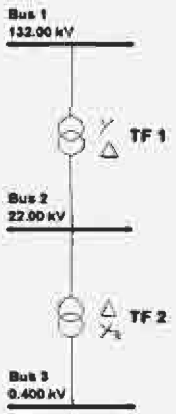
2.3.2.2 Propagation of voltage dips through transformers

The propagation of voltage dips due to different transformer winding connections between the fault and the measurement point causes different dips at the measurement point for unbalanced faults. Before analyzing voltage dips one should have a clear understanding of how voltage dips are propagated through transformers and the influence of the transformer winding connections [14]. This is due to two factors:

- Type of transformer which affects the filtering of zero-sequence components
- Transformation of line-to-line primary voltages into line-to-neutral secondary voltages

From [3] and [6] Table 2.3 can be derived that shows the propagation of dips to lower voltage levels from a star-delta to a delta-star transformer. For example, when there is a SLGF at bus 1, a dip type B is seen at this location. However, at bus 2 below the delta-star transformer the same fault is seen as a dip type C and at bus 3 the dip is observed as type D.

Table 2.3: Fault type and dip propagation through delta-star transformers



Fault type	Measurement location		
	Bus 1	Bus 2	Bus 3
3-phase	A	A	A
3-phase-ground	A	A	A
2-phase	C	D	C
2-phase-ground	E	F	G
1-phase-ground	B	C	D

During SLGFs and LLGFs all sequence components are involved; positive, negative and zero sequence. However during three-phase balanced voltage dips, only positive sequence quantities exists whereas only positive and negatives sequences exists in LLFs. Zero sequence components are related to and only exist when the fault is connected to ground, therefore during LLLF and LLF no zero sequence quantities exist during the fault. Thus, zero sequence components can only propagate further if the transformer winding connections allows it to flow. Therefore, transformer winding connections can be categorized into three main groups [6].

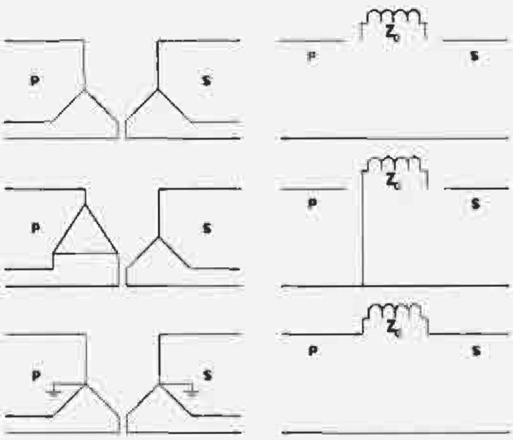


Figure 2.6: Equivalent zero-sequence circuits of corresponding transformer connections

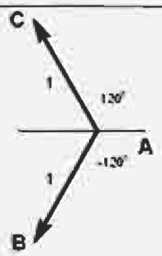
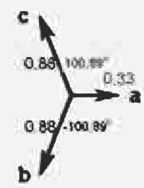
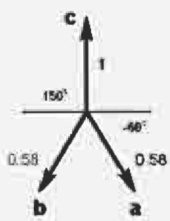
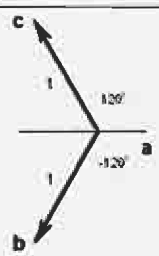
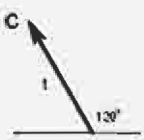
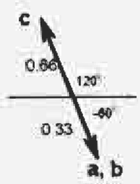
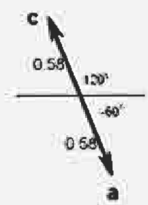
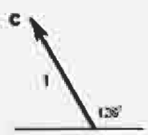
The three groups of basic transformer winding connections that are used to describe the propagations of dips are [6]:

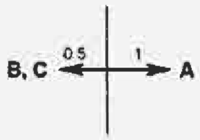
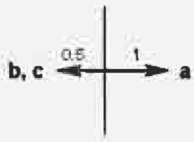
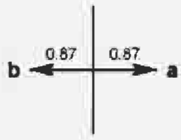
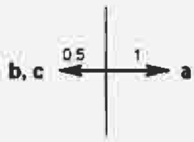
Group 1: Those that remove the zero-sequence voltage (Yy, Yyn, YNy, Dd)

Group 2: Those that change phase voltages into line voltages and the other way around (Dy, Yd, YNd, Dyn).

Group 3: Those that do not affect the individual phases (YNyn)

Table 2.4: Propagation of voltage dips through transformers caused by unsymmetrical faults

Type of fault	Propagated voltage dip		
	Group 1 (Yy, Yyn, YNy, Dd)	Group 2 (Dy, Yd, YNd, Dyn)	Group 3 (YNyn)
 SLGF	 A dip in all three-phases	 A dip in two-phases	 An identical dip
 LLGF	 A dip in all three-phases	 Dip in two phases and interruption on the other	 An identical dip

			
LLF	An identical dip	Dip in two phases and interruption on the other	An identical dip

The difference in voltage dip performance between group 1 and group 2 transformers is due to the phase-shift and the transformation of line-to-line voltages to line-to-neutral voltages that occur across group 2 transformers. This is because the phase-angle asymmetry is higher than the group 1 transformers [6]. The transformation of line-to-line voltages to line-to-neutral voltages across group 2 transformers accompanies a phase-shift, which is depended on how the transformer windings are connected.

This aspect affects the phases, which are affected by the dip on the secondary side. For example, to show how the connection affects the phases on the secondary side, consider a SLGF on phase A on the primary side. The delta windings can either be connected A`B, B`C, C`A or AB`, BC`, CA` as shown in Figure 2.7 (a) and (b). Due to the fault in (a); current flows from the source, winding AA` and CC` to ground as indicated by the arrows. The change of current in winding AA` and CC` affects the flux in each correlating leg in the transformer. This results in an increase of the current on the two opposite windings a`a and c`c on the secondary side. Increased current means a drop in voltage, therefore a drop in voltage would occur across V_a and V_c. In Figure 2.7 (b), winding AA` and BB` are affected by the fault, therefore the secondary side would experience a drop in V_a and V_b.

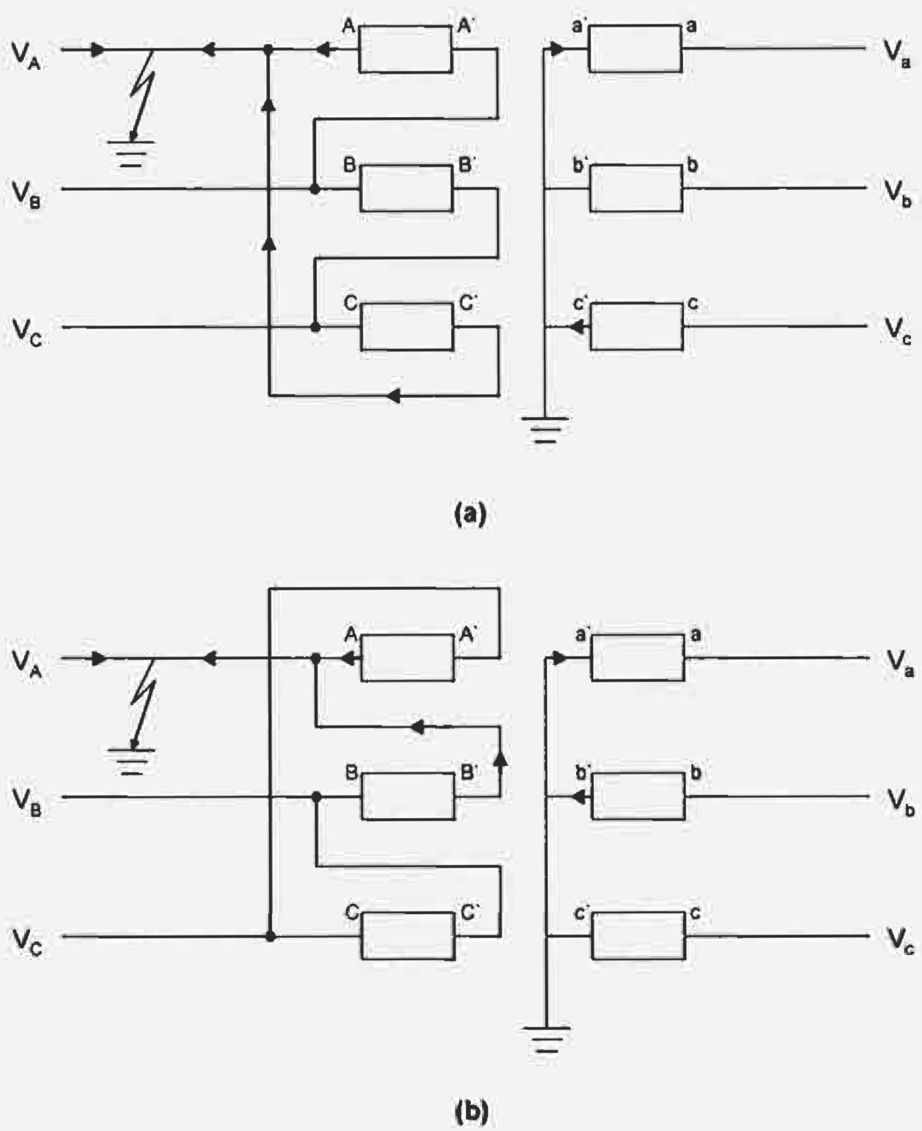


Figure 2.7: Effect of internal winding connections on voltage dip propagation

2.3.2.3 NRS 048 Voltage dip categorization

The NRS 048 voltage dip categorization (Figure 2.6) provides a uniform approach for classifying the performance of voltage dips [13]. This method addresses the most common effects of dips on customer plants and not the complex dip parameters such as phase angle jump at the inception of a dip, phase shift during a dip and the pre- and post-dip voltages. This method is based on a combination of network protection characteristics and customer load compatibility. The basis for assessing voltage dips is given in Table 2.6 [13].

Table 2.5: Characterization of depth and duration of voltage dips [13]

<table>
<tr><th rowspan="2">Range of dip depth ΔV (expressed as a % of V_d)</th><th rowspan="2">Range of residual voltage V_r (expressed as a % of V_d)</th><th colspan="3">Duration (t)</th></tr>
<tr><th>20 < t ≤ 150 ms</th><th>150 < t ≤ 600 ms</th><th>0.6 < t ≤ 3 s</th></tr>
<tr><td>10 < ΔV ≤ 15</td><td>90 < V_r ≤ 85</td><td colspan="3">Y</td></tr>
<tr><td>15 < ΔV ≤ 20</td><td>85 < V_r ≤ 80</td><td colspan="2"></td><td rowspan="2">Z1</td></tr>
<tr><td>20 < ΔV ≤ 30</td><td>80 < V_r ≤ 70</td><td></td><td rowspan="3">S</td></tr>
<tr><td>30 < ΔV ≤ 40</td><td>70 < V_r ≤ 60</td><td>X1</td><td rowspan="3">Z2</td></tr>
<tr><td>40 < ΔV ≤ 60</td><td>60 < V_r ≤ 40</td><td>X2</td></tr>
<tr><td>60 < ΔV ≤ 100</td><td>40 < V_r ≤ 0</td><td colspan="2">T</td></tr>
</table>

Table 2.6: Basis for categorization of voltage dips [13]

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. 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. 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. Potential motor stalling

2.3.2.4 IEC61000-4-30 Voltage dip Categorization Method

This standard defines the methods for measurement and the interpretation of results for power quality parameters in 50 Hz or 60 Hz ac power supply systems. This standard only gives measurement methods and does not set thresholds.

Voltage dip detection

The value of the r.m.s. voltage ($U_{rms(1/2)}$) is measured over each cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle. The dip threshold is a percentage of either the declared voltage or the sliding voltage reference and is set by the user according to the use. The user shall declare the reference voltage in use. NOTE the sliding voltage reference is generally not used in LV systems. See IEC 61000-2-8 for further information and advice [20].

- For single-phase systems a voltage dip is initiated when the $U_{rms(1/2)}$ voltage falls below the dip threshold, and ends when the $U_{rms(1/2)}$ voltage is equal to or above the dip threshold plus the hysteresis voltage.
- On three-phase systems a dip is initiated when the $U_{rms(1/2)}$ voltage of one or more channels is below the dip threshold and ends when the $U_{rms(1/2)}$ voltage on all measured channels is equal to or above the dip threshold plus the hysteresis voltage.

Voltage dip evaluation

A voltage dip is characterized by a pair of data, either residual voltage (U_{res}) or by depth and duration:

- The residual voltage is the lowest $U_{rms(1/2)}$ value measured on any channel during the dip
- The depth is the difference between the reference voltage and the residual voltage. It is generally expressed in percentage of the reference voltage
- The duration of a voltage dip is the time difference between the beginning and the end of the voltage dip

2.3.2.5 Comparison of Voltage dip characterization methods

The characterization methods discussed in the previous section shows that the NRS 048 is based on the IEC61000-4. Where voltage dips are characterized by measuring the magnitude and duration. The problems with this type of characterization are discussed further in section 2.4.2. The Bollen method however characterizes the dips as the type of fault, i.e. SLGFs, LLFs or 3θ. This method is based on the sequence components of a dip and not the magnitude and duration. With this method the PN-factor and characteristic voltage will be calculated which indicates the impact of the dip. Currently there is no standard on the levels of these parameters to evaluate the impact of the dip.

A good method to categorise voltage dips would be a combination of the three methods mentioned above. One way would be by determining the dip type (A, $C_{a, b, c}$, and $D_{a, b, c}$) by using the Bollen definition and then contributing magnitude and duration thresholds for each type such as the NRS 048. Another way is to characterize the characteristic voltage and PN-factor for each type of the Bollen defined dip method and then using this characterization to evaluate the severity of dips.

2.3.3 Influence of Voltage Dips on loads

Voltage dips can cause unnecessary tripping of protective devices, which could result into the complete shut down of processes as well as a stop in production.

The basic observed effects of voltage sags on induction motors are:

- Speed loss
- Current inrush
- Transient torque peaks

Depending on characteristics of the motor, the motor may recover to its normal speed as the voltage amplitude recovers. The three main characteristics that dominate the response of a motor is the inertia constant (H), load torque (T_L) and the electrical transient time constant (T'_{do}) [16]. Low inertia motors rapidly decelerate and may stall whereas high inertia motors lose speed but reaccelerate on recovery. Similarly to the starting of an induction motor the reacceleration of the motor is accompanied by sudden increase in active and reactive power as well as a lower power factor. Another severe impact voltage dips can have on motors is when the supply voltage is out of phase with the motor flux, this causes torque oscillations at the beginning and at the end of the voltage dip. This could cause damage to the motor, for example the bearings [17], shaft and coupling.

The current inrush, which occurs during a dip, causes the thermal losses (I^2R) to increase by the square of the inrush current. This will heat up the motor and can have a degenerative effect on the motor winding insulation. A common problem that is experienced is that the high currents during recovery after the initial voltage sag can prolong the voltage sag long enough to trip the under-voltage protection, especially in cases with a large number of motors, or in a weak network [17].

The type of dip experienced by a load depends on its connection method. Table 2.7 shows the type of dip for different fault types that is experienced by a load when it is connected in either star or delta [5].

Table 2.7: Type of dip experienced by star or delta connected loads

Fault type	Load connection	
	Star	Delta
3-phase	A	A
2-phase	C	D
1-phase-ground	B	C

2.3.4 Obtaining the voltage dip type from instantaneous voltages

To determine the cause of the measured voltage dips at the measured points on the banana farm the symmetrical component algorithm proposed by Bollen [3] was used. It determines the dip type from the positive- and negative sequence components from the measured rms voltages. Two parameters, the characteristic voltage (V) and PN-factor (F) to quantify the dips, are introduced. The characteristic voltage is used to describe the event and PN-factor is a measure of the unbalance of the event. For SLGFs and LLFs the PN-factor is close to unity, for LLGFs it is less than unity and for three-phase faults the PN-factor is equal to the characteristic voltage [2]. The PN-factor is also an indication of the effect of the load on the voltage dip. Because of the complicated nature of the algorithm it won't be discussed as it falls outside the scope of this research and the reader is referred to the literature [3].

The algorithm to determine the dip type is given by equation 2.4 [10]. It determines the type from the difference between the angle of the positive- and negative sequence voltage.

$$k = \frac{1}{60^o} \times arg\left[\frac{V2}{1-V1} + 20^o\right] \tag{2.4}$$

With k rounded to the nearest integer the dips are classified by,

$k = 0 \rightarrow$ type C_a

$k = 1 \rightarrow$ type D_c

$k = 2 \rightarrow$ type C_b

$k = 3 \rightarrow$ type D_a

$k = 4 \rightarrow$ type C_c

$k = 5 \rightarrow$ type D_b

With the dip type known the characteristic voltage and the PN-factor can be calculated by determining the corresponding negative sequence voltage of the prototype dip [11]:

$$\overline{V_2^{\cdot}} = \overline{V_2} e^{-jk60^\circ} \tag{2.5}$$

K is obtained from (2.4) and $\overline{V_2}$ is the calculated negative sequence of the measured data. Then the characteristic voltage and PN-factor are calculated from (2.6) and (2.7) [10], [11]:

$$\overline{V} = \overline{V_1} - \overline{V_2^{\cdot}} \tag{2.6}$$

$$\overline{F} = \overline{V_1} + \overline{V_2^{\cdot}} \tag{2.7}$$

Both are complex values and the absolute value of the characteristic voltage gives the magnitude and the argument gives the phase-angle jump of the voltage dip [10], [11].

2.4 PROBLEMS CONCERNING THE ANALYSIS OF VOLTAGE DIPS

During the course of the research it was realised the there is still a lot of uncertainty in electrical engineering circles in relation to analysing voltage dips. This is because of a number of aspects that have to be considered. Two of these aspects that are of most concern are:

1. How to connect a voltage dip measuring device?
2. The current classifying methods for analysing the impact of dips on power systems and equipment

Note, the former is not referring to characterization of voltage dips as in section 2.3.2.1, but to the characterization of the impact of a voltage dip, such as the NRS 048 dip classification.

2.4.1 How to connect a voltage dip measuring device?

An important aspect that should be considered when connecting voltage dip-measuring devices is whether it should be connected line-to-line (LL) or line-to-neutral (LN). This connection and the internal functioning of the measuring device play a vital role in analyzing the characteristics and influence of dips at certain points in power systems.

If a dip meter is installed with a LN-connection, a single line-to-ground fault (SLGF) at the same voltage level can be clearly identified since this is the only fault resulting in a class B dip. Such a clear conclusion cannot be drawn if a SLGF occurs at the same voltage level where a meter is installed with a LL-connection. This meter registers a class C dip, being the same registration as for a two-phase fault at a higher or the same voltage level.

A small advantage of the LN-measurement is that it measures the most common faults, namely SLGFs, which enable the analysis of voltage dips to distinguish between SLGFs and LLGFs.

For example, a voltage dip-measuring device is connected to the secondary side of 22 / 0.4 kV transformer. Under normal operating conditions line-to-line and line-to-neutral voltages would be:

$$V_{AB} = 400\angle 30^{\circ} \qquad V_{AN} = 230\angle 0^{\circ}$$
$$V_{BC} = 400\angle -90^{\circ} \qquad V_{BN} = 230\angle -120^{\circ}$$
$$V_{CA} = 400\angle 150^{\circ} \qquad V_{CN} = 230\angle 120^{\circ}$$

Say for instance a SLGF occurs on phase b then the voltages would approximately be:

$$V_{AB} = 293\angle 17^{\circ} \qquad V_{AN} = 230\angle 0^{\circ}$$
$$V_{BC} = 293\angle -77^{\circ} \qquad V_{BN} = 100\angle -120^{\circ}$$
$$V_{CA} = 400\angle 150^{\circ} \qquad V_{CN} = 230\angle 120^{\circ}$$

If a voltage dip-measuring device is connected to the secondary side of the transformer to measure line-to-line and line-to-neutral voltages it would give a percentage drop of

$$V_{AB} = \pm 73\% \qquad V_{AN} = \pm 100\%$$
$$V_{BC} = \pm 73\% \qquad V_{BN} = \pm 43\%$$
$$V_{CA} = \pm 100\% \qquad V_{CN} = \pm 100\%$$

From this one can see that the LL-connection measurements would look like a LLF fault and the line-to-neutral measurements represent the original SLGF on phase b. These values are presented on the NRS 048 dip categorization chart shown in Figure 2.8, and shows that for the same type of fault it gives two different residual voltage levels when it is measured line-to-line and line-to-neutral.

Depending on the duration of the fault the LL-connection measurements characterizes the dip either as type Y, S or Z1 and the LN-connection measurements as X2, S or Z2. This concludes that the connection of a measuring device is critical in analyzing and characterizing voltage dip incidents, due to the fact that line-to-line measurements indicate a less severe dip type than the line-to-neutral measurements. Therefore utilities will benefit from measuring the line-to-line voltages, because of the fact that SLGFs are the most common faults that occur, which means that their statistics on measured network faults would look better.

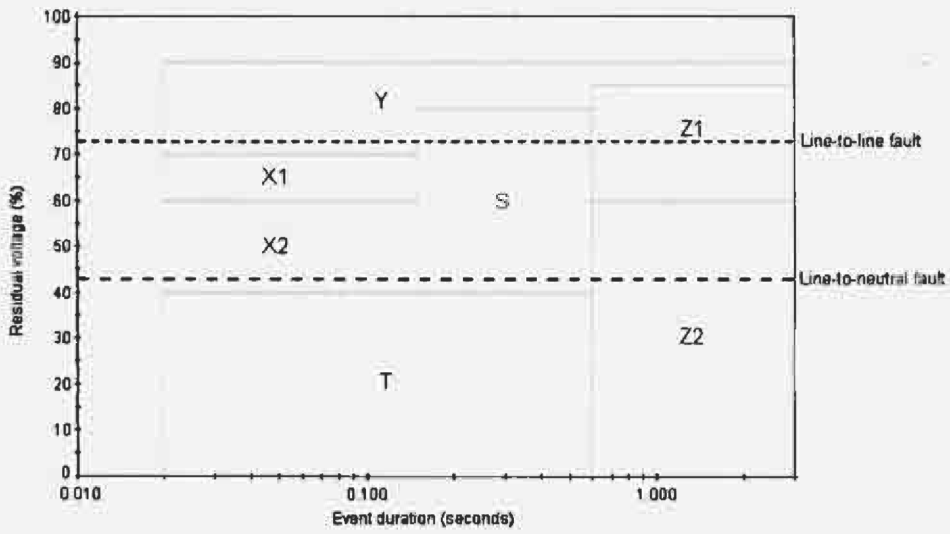


Figure 2.8: LL and LN measurements compared on the NRS 048 chart

The following table shows the type of dip that is measured when a measuring device is connected line-to-line or line-to-neutral on the primary and secondary side of a Dy or Yd transformer.

Table 2.8: Voltage dip types due to different measurement connections [7]

	Primary side		Secondary side	
Fault type	V_{LN}	V_{LL}	V_{ln}	V_{ll}
SLGF	B	C	C	D
LLF	C	D	D	D
Three phase	A	A	A	A

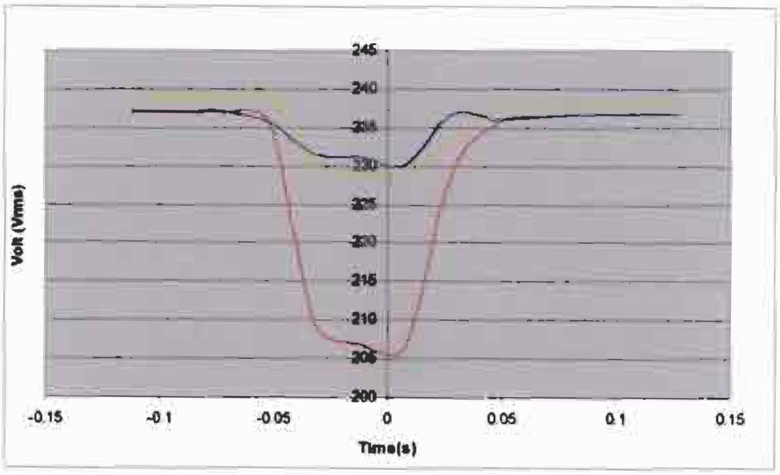
2.4.2 Problems with Current classifying methods for analysing the impact of dips on power systems and equipment

The problem with classification methods is that it uses the lowest retained voltage of the three-phases and the longest duration of all the phases to characterize the fault incident. This, as a consequence, has a number of erroneous results [7]:

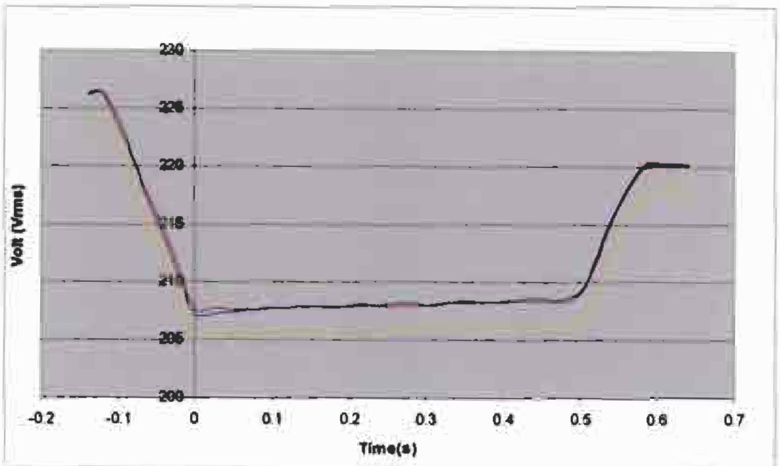
- A voltage drop in one phase is characterized as equally severe when compared to a drop in all three phases, whereas the latter event is typically more severe for the system and equipment.

- The dip due to an earth fault in a high-impedance grounded network will be seen as equally severe (or even more severe) than the dip due to a short-circuit fault, whereas the former has hardly any effect on equipment.
- There is no clear relationship between the dip characteristics at both sides of a transformer, or between a star-connected and a delta-connected monitor (This was discussed in section 2.4.1).

For example, in Figure 2.9 (a) the dip is probably caused by a SLGF (Table 2.3) and in (b) the dip is a three-phase dip caused by motor starting. These two dips were measured with the Impedograph power quality recorder and were classified as a dip Y (according NRS 048 standard), which means they are classified as equally severe. Where in turn their severity is not nearly the same and the latter has a greater impact on the system and equipment.



(a)



(b)

Figure 2.9: Dips classified with the same severity, (a) Single-phase drop, (b) three-phase drop

2.5 CONCLUSION

The research presented in this chapter offers the means for event classification and disturbance classification. From recorded waveform data, for example, the classification is in terms of the underlying event (cause of the dip) and the identified disturbance (type of dip). In contrast to other power quality aspects it requires good insight of the characteristics of voltage dips to fully understand how to analyse this phenomenon. The various factors that were studied in this research, which plays a role in understanding voltage dips are:

1. How it originates
2. How to determine the dip type
3. How the fault type affects the type of dip
4. How the dip changes/propagates through transformers
5. How to determine the cause of the fault from the dip type
6. How to measure voltage dips, line-to-line or line-to-neutral
7. Analysis of the dip

The research in this chapter is used in chapter 5 to analyze recorded voltage dip measurements from the banana farm to determine the cause of the dips and how they propagate through the network. The characterization method proposed by Bollen and Zang to classify unbalanced voltage dips is used for the analysis of these voltage dips. Before classifying these dips an algorithm also proposed by Bollen was used to determine the dip type. The method is applied to the recorded measurements from the distribution network of the banana farm and the results show that the method can be used in order to better understand the measurements.

This chapter also discusses the importance of measurement methods and the problems with current classifying methods for voltage dip characterizing. It is shown that line-to-line connection measurements doesn't truly reveal the severity for certain types of faults as it does for line-to-neutral measurements, especially in the case of single phase to ground faults. Problems concerning current classifying methods are that it uses the lowest retained voltage of the three-phases and the longest duration of all the phases to characterize the fault incident, which as a consequence has a number of erroneous results.

CHAPTER 3
NETWORK DESCRIPTION AND MODEL

3.1 INTRODUCTION

The power flow through a network is an important factor when it comes to power quality. A transmission network is designed to carry a certain power capability. Due to the increase in industry upgrades, which cause an increase in power consumption, the distribution of the power flow is not sufficient anymore, this affects the power quality of the distribution network.

This chapter is used to describe the layout of the complete network and it includes all the loads that are connected to the Koorsboom substation. The different layouts of the network that is used in chapter 4 are also described to determine the optimum power flow distribution for improved power quality.

3.2 BACKGROUND OF NETWORK

An example model of the network on the farm and the surrounding areas that is supplied by the Koorsboom substation was built using the program CYME PSAF (Power Systems Analysis Framework), which is a power system simulation program used for the analysis of power systems. It is used to investigate the voltage profiles and fault levels as well as the effect of motors starting at the pump stations. This is done for different layouts of the network to determine the best layout for optimum power quality. The layout configurations are discussed in section 3.3.

The Koorsboom substation consists of 1 x 20 MVA, 132 kV / 22 kV transformer that has three 22 kV distribution lines, which supplies power to the following areas; Marloth Park, Thankerton and Koorsboom. As mentioned before the area of interest is the banana farm that is connected to the Marloth line. Therefore the results of the other loads connected to the Thankerton and Koorsboom lines are not of significant interest to this research. These areas are only used to load and overload the network for simulation purposes.

The Thankerton and Koorsboom distribution lines supply power to the Thankerton and Koorsboom region. The Marloth line supplies power to the Citrus Corporation, residents and other farmers of Marloth Park and to the banana farm. These loads are divided into two main groups, which consist of:

- **Other loads:** Thankerton and Koorsboom residential loads, Citrus Corporation, pumps stations, ripening plants and pack houses of surrounding farmers.
- **Banana farm loads:** Farm pump station loads, residential loads, ripening rooms and pack houses.

In sections 3.2.2 and 3.2.3 follows a detailed description of these loads.

3.2.1 Network Layout

A single-line model of the distribution network is shown in Figure 3.1, which includes all the loads of the farm and the surrounding areas that are supplied by the Koorsboom substation. The model also includes all distribution lines, transformers, loads, power factor correction capacitors of the banana farm and summated loads for the rest of the network.

The blue areas indicated in the Figure 3.1 represent the Marloth line that supplies power to all the load points on the farm. The areas pointed out in red are the areas where layout changes were made to the network in order to determine optimum power flow. The black areas shown in the figure are the other loads connected to the network.

The load values of this network were collected during the investigation and are used as model parameters to represent a realistic representation of the farm. This model is used to identify the problem areas that affect the power quality in the network.

All the loads are represented by static loads where only active (P) and reactive power (Q) is needed.

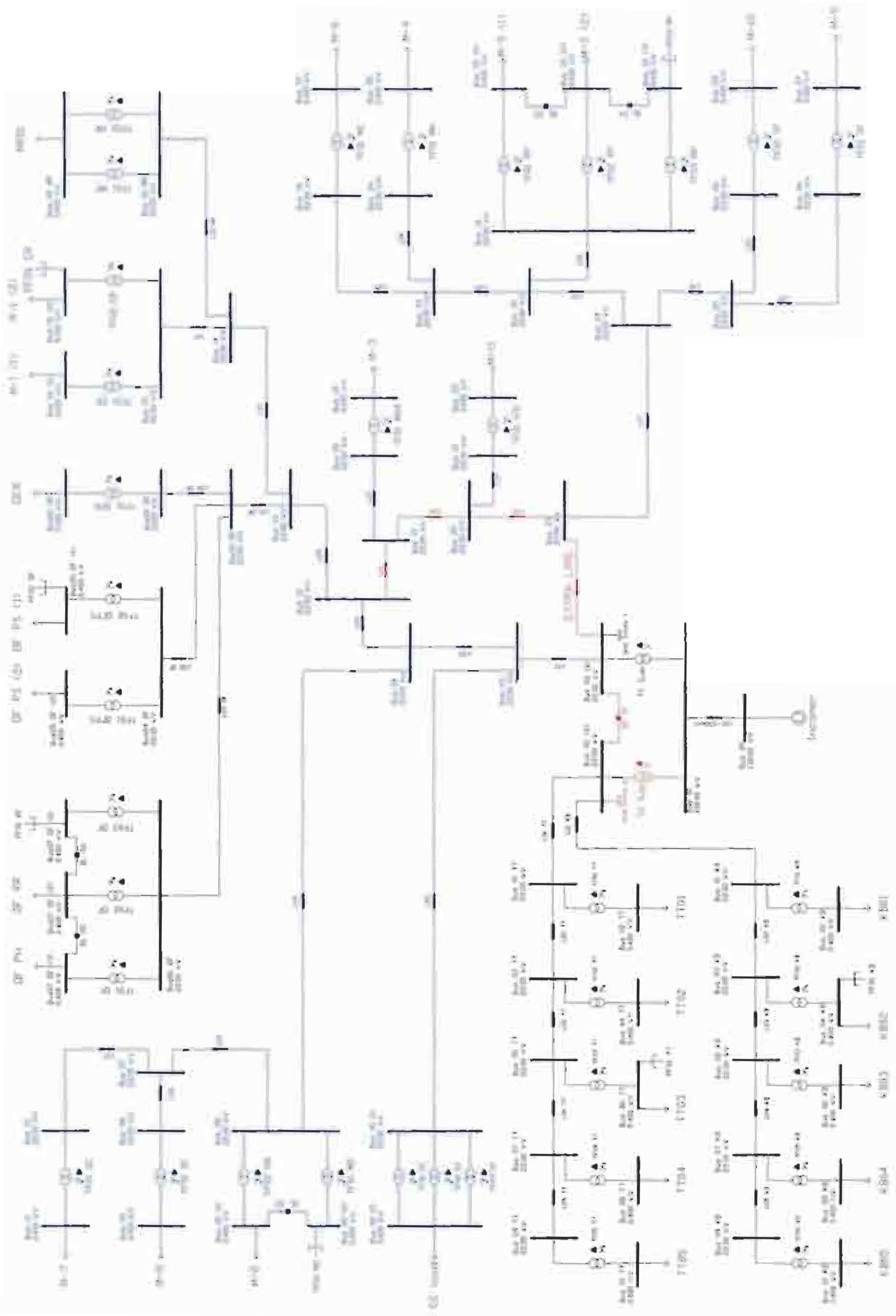


Figure 3.1: Layout of the complete network

3.2.2 Other Loads

As mentioned above these areas are only used for the completeness of simulations. These loads include Thankerton, Koorsboom, Citrus Corporation and the residents/farmers near Marloth Park. Table 3.1 gives a short description of each load associated with other loads. The number in the first column is associated with the name that is given to each load.

Table 3.1: Summary and description of the Other Loads

Number	Short description	Detailed description	Config.	P (kW)	Q (kvar)	S (kVA)	Power factor
TT-01	House	Thankerton houses		375.0	53.4	378.8	0.99
TT-02	House	Thankerton houses		1029.3	711.0	1251.0	0.82
TT-03	Pump station	Thankerton pump station		1029.3	711.0	1251.0	0.82
TT-04	House	Thankerton houses		375.0	53.4	378.8	0.99
TT-05	House	Thankerton houses		375.0	53.4	378.8	0.99
KB-01	House	Koorsboom houses		375.0	53.4	378.8	0.99
KB-02	Pump station	Koorsboom pump station		859.2	576.8	1034.9	0.83
KB-03	House	Koorsboom houses		375.0	53.4	378.8	0.99
KB-04	House	Koorsboom houses		375.0	53.4	378.8	0.99
KB-05	House	Koorsboom houses		375.0	53.4	378.8	0.99
CC-01	Citrus Corp	Citrus corporation		2000.0	1186.7	2325.6	0.86
MR-01	Marlothi residents	Marloth park residents		1500.0	375.9	1546.4	0.97
OF-PS	Other farmer pump station	Other farmer pump station	OF-PS (1)	214.8	144.2	258.7	0.83
			OF-PS (2)	214.8	144.2	258.7	0.83
OF-HL	Other farmer houses load	Other farmer house load		150.0	21.4	151.5	0.99
OF-RP	Other farmer ripening plant	Other farmer ripening plants	Ripe. plant	325.0	325.0	459.6	0.71
			Pack house	275.0	225.0	355.3	0.77
	Total	Thankerton, Koorsboom, Citrus corporation and other farmers		9622.4	4245.3	10729.3	0.90

3.2.3 Banana farm loads

The three main loads on the farm are M-1, M-2 and M-5. M-1 and M-2 are pump stations that have different configurations on which they are operated. M-5 is the ripening rooms, workshop, offices and pack house and it consists of large coolers, small motors, lights etc. Table 3.2 gives a description of each of the loads on the banana farm.

Table 3.2: Load description of banana farm

Number	Short description	Detailed description	Config.	P (kW)	Q (kvar)	S (kVA)	Power factor
M-1	MARL CROC RIVER	Main pump station at Crocodile River. Pumps to MARL DAM	M-1 (1)	214.8	144.2	258.7	0.83
			M-1 (2)	214.8	144.2	258.7	0.83
M-2	MARL DAM	Marlothi dam in game camp. Used for irrigation of all fields	Pump 1	360.0	210.8	417.2	0.86
			Pump 2+3	343.1	237.0	417.0	0.82
M-3	MARL HOUSE 4	Marlothi house 4 & borehole for house, nursery & compound		25.0	3.6	25.3	0.99
M-4	MARL RES B/HOLE	Marlothi Bore Hole for nursery & residences + manager's houses		100.0	14.2	101.0	0.99
M-5	MARL R-ROOMS	Marlothi ripening rooms, workshop, pack house		600.0	550.0	813.9	0.74
M-5	MARL R-ROOMS	Marlothi ripening rooms, workshop, pack house	Ripe. plant	325.0	325.0	459.6	0.71
			Pack house	275.0	225.0	355.3	0.77
M-6	MARL COMPOUND	Marlothi Compound only		50.0	7.1	50.5	0.99
M-7	MARL DONKEY CAMP	Marlothi donkey camp, game and cattle borehole		25.0	5.1	25.5	0.98
M-8	MARL B/CAMP MNGR	Marlothi bush camp, manager's house & borehole for house & nursery		64.0	16.0	66.0	0.97
M-9	MARL STAS. B/HOLE S	Marlothi Stassen borehole south of N4		32.0	8.0	33.0	0.97
M-10	MARL STAS. HOUSES	Marlothi manager's houses on Stassen farm		32.0	4.6	32.3	0.99
M-11	MARL VARKDAM	Marlothi borehole for pack house & nursery only		25.0	6.3	25.8	0.97
	Total	Total farm load		2325.7	1690.4	2922.7	0.80

3.2.3.1 Crocodile River pump station (M-1)

Due to insufficient motor data the load will be chosen from measured values as well as the configuration on which the pump station is run. The load at this pump station is divided into two separate loads referred to as M-1 (1) and M-1 (2). These two loads represent the two configurations on which the pump station is operated, where M-1 (1) and M-1 (2) consist of the following:

M-1 (1) - 2 main pumps together with 2 sump pumps run on 1 x 500 kVA transformer

M-1 (2)- 2 main pumps together with 4 sump pumps run on 1 x 500 kVA transformer

Note: There is no bus-links and bus section breaker between the transformers and the sump pump loads are not included in the total load of the pump stations, because it is only used to pump water to the main pumps. When the water reaches the main pumps the sump pumps are switched off.

3.2.3.2 Marlothi Intermediate dam pump station (M-2)

At this pump station there are three pumps that are used for irrigation of the banana plantations. There is one large 400 kW and two smaller 185 kW pumps. Either the 400 kW or the two 185 kW pumps are used. The three pumps are never run simultaneously. The Table 3.3 gives the rated and measured values of the two pump stations, as well as the calculated values that are used to model the pump station for the simulation.

Table 3.3: Crocodile river and Marlothi dam pump station data

	M-1			M-2			
	Main pump	Sump pump	Unit	Pump #1	Pump #2	Pump #3	Unit
	Rated values			Rated values			
P_{rated}	110	24	kW	400	185	185	kW
V_{rated}	400	400	V	380	400	400	V
I_{rated}	190	46	A	735	320	340	A
Power factor	0.88	0.79		0.88	0.88	0.87	
S_{rated}	131.64	31.87	kVA	483.76	221.70	235.56	kVA
Q_{rated}	72.30	20.97	kvar	272.08	122.18	145.82	kvar
	Measured values			Measured values			
P	107.4	23.4	kW	360	162.7	180.4	kW
pf	0.83	0.79		0.87	0.82	0.82	
V_{ab}	409	407	V	401	409	410	V
V_{bc}	402	407	V	404	407	415	V
V_{ca}	409	407	V	402	410	414	V

I_a	186	42	A	595	296	304	A
I_b	183	42	A	602	279	306	A
I_c	182	42	A	599	267	306	A
	Calculated values			**Calculated values**			
V_{avg}	407	407	V	402	409	413	V
I_{avg}	184	42	A	599	281	305	A
S	129.37	29.62	kVA	417.19	198.59	218.42	kVA
Q	72.12	18.16	kvar	210.82	113.88	123.13	kvar
pf	0.83	0.79		0.86	0.82	0.83	
$\%S$	98.3	92.9	%	86.2	89.6	92.7	%
$\%P$	97.6	97.5	%	90.0	87.9	97.5	%

3.2.3.3 Marlothi Ripening plant and Pack house (M-5)

The two main loads here are the ripening rooms and the pack house. Measurements at these points where taken with the Impedograph power quality recorder. The measured data of the average active, reactive and apparent power over a period of two weeks was used to calculate the average load at this point (shown in Figure 3.2 and Figure 3.3) to be represented in the network model.

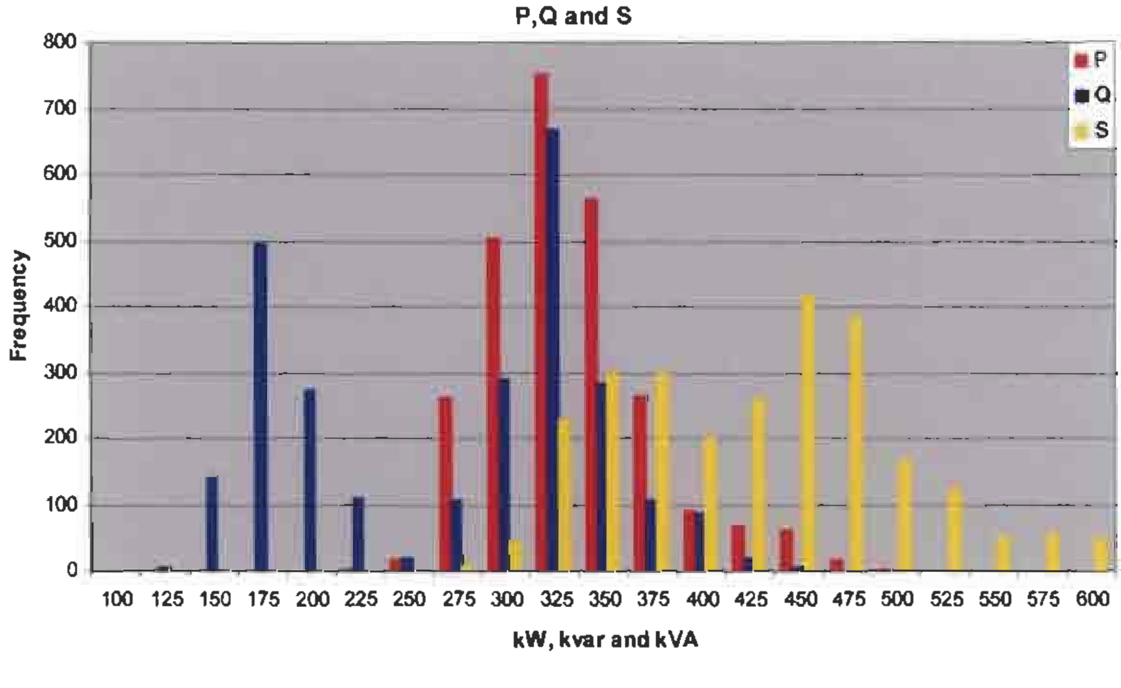


Figure 3.2: Histogram for active, reactive and apparent power at the ripening rooms

The load was chosen as the most frequent power delivery that occurred during the measuring time. This is P = 325 kW and Q = 325 kW for the ripening rooms and

P = 275 kW and Q = 225 kW for the pack house. The load for this point will then be the sum of the ripening room and pack house (total load is given in Table 3.2).

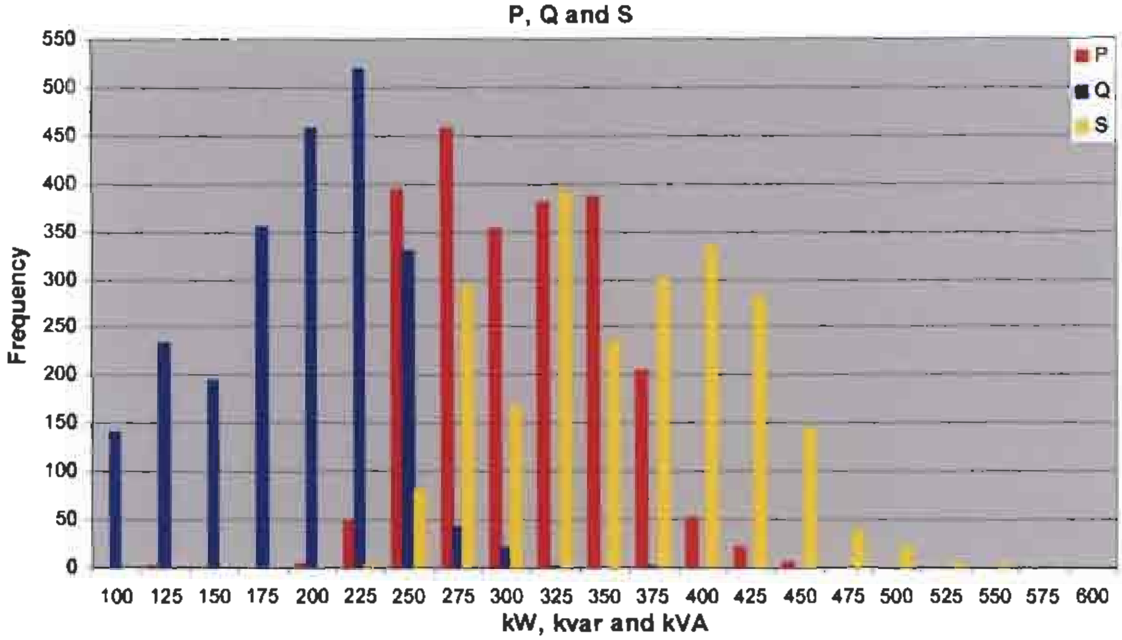


Figure 3.3: Histogram for active, reactive and apparent power at the pack house

3.2.3.4 Power Factor Correction Capacitors

The three loads mentioned above are each equipped with a switchable power factor correction capacitor bank. It is assumed that the power factor at each point should at least be approximately 0,98. The sizes of the capacitors are calculated using the measured values and shown in Table 3.4.

Table 3.4: PFC capacitor values

	M-1 (1)	M-1 (2)	M-2	M-5 (1)	M-5 (2)
PFC size (kvar)	101	101	167	150	77

3.3 NETWORK LAYOUTS

One way of improving the power flow and the distribution of power is to add extra substation transformers or by breaking long lines and adding extra lines. By careful inspection of the original network (Figure 3.1) there was decided on six layouts that might improve the power quality of the distribution network. These are simulated and compared with the original layout to determine the optimum layout of the network. The seven layouts are (see Figure 3.1):

- **A** Existing configuration that is currently used
- **B** The extra line connected to bus 23 with line L14 disconnected
- **C** The extra line connected to bus 23 with line L16 disconnected
- **D** The extra line connected to bus 23 with line L12 disconnected
- **E** 2nd Transformer installed at Koorsboom substation
- **F** 2nd Transformer installed at Koorsboom substation with the extra line connected to bus 23 and line L12 disconnected.
- **G** 2nd Transformer installed at Koorsboom substation with the Bus-link (BL 01) between the two disconnected

The motivation for adding an extra distribution line and disconnecting a part of the Marloth line in layouts B, C and D is that the Marloth line is in a sense a very long line, which means that a significant voltage drop could occur near the end points of the line. This option may alleviate the constraints caused by thermal limitations, because the power that is delivered is distributed among more paths.

The distribution Utility decided to implement Layout E as there solution to the power quality problem. This layout is chosen to compare its results to other layouts to see whether it is the best option for improving network power quality. One advantage of this layout is that it could prevent long-term blackouts if one transformer fails.

Layout F will provide more network security and better voltage profiles at load points. This option is a combination of both layout D and E. Layout F and G can be used for future upgrades. Layout G is chosen to see how the network is affected if the total load of the Koorsboom substation is split between two transformers.

3.4 CONCLUSION

In this chapter the layout of the network supplying power to the banana farm and surrounding areas, was discussed in detail. Attention was paid to the loads in the network, consisting mainly of residential loads in addition to pump station loads, i.e. motors. There was also looked at the different loads and their sizes.

Options are given for different network layouts that will be used in the simulations done in Chapter 4 in order to determine which layout will serve as the best option to improve voltage profiles on the busses. The layouts done in this chapter were also taken into consideration to establish which one will make the network the strongest and the most robust in order to deliver the optimum power quality.

CHAPTER 4
NETWORK SIMULATION AND ANALYSIS

4.1 INTRODUCTION

In the previous chapter, modelling of the loads and the layout of the network was discussed. In this chapter three studies are done on the different layouts of the network and are used to calculate the voltage profiles, fault levels and the effect of motor starting. These results are used to determine a suitable layout of the network that could be implemented by the Utility to improve the overall power quality of the interconnected grid.

4.2 ANALYSIS METHODS

The three studies that are used to analyse the network are:

1 Power flow,

2 Fault level, and

3 Motor start study

By using CYME PSAF a static power flow and fault level analysis was done. These results are used to analyse the performance of the network. The effect of motor starting on the network was also determined by the use of the power flow analysis.

4.2.1 Power Flow Study

Power flow studies, commonly referred to as load flow studies are the backbone of power system analysis and system design. Due to plant upgrades and expansions the increased flow of reactive power in a network is accompanied by a voltage drop on some of the busses. The source of reactive power in the network is the presence of large induction motors that are used at the pump stations.

This study is an analysis of the system's capability to supply sufficient power to the connected load. It provides useful information about real and reactive power flow, bus voltages, and power factor in each branch of the system. It is used to determine the voltage levels at the 22 kV and 400 V busses on the farm network. The results for each layout were compared to determine the network configuration for the optimum voltage levels.

4.2.2 Fault Level Study

A short-circuit study is performed to determine the maximum fault currents that are present in the branches of the network during a system disturbance. As the network expands, loads are moved and larger ones added, the fault levels change. Therefore it is important to perform a periodic fault analysis study to determine the fault levels.

4.2.3 Motor Start Study

The purpose of this study was to determine how a motor start effects the voltage levels of the network and what points/busses are affected by such an occurrence. When a motor is started the transient starting current flows from the source of the network to the motor and it causes a voltage drop at points located between the source and the motor.

For the motor start analysis the following method was used to determine the motor start up data.

At both pump stations star-delta starters are used to switch on the pump motors, which means the phase voltages and phase currents of the motor in star connection are reduced to $1/\sqrt{3}$ of the direct-on-line values in delta. The line current is 1/3 of the value in delta. For direct-on-line starting, the starting active power is

$$P_{start\Delta} = 1/3 \times P_n \qquad (1)$$

and the reactive power

$$Q_{start\Delta} = 5.8 \times Q_n \qquad (2)$$

Therefore with star-delta starting the starting active power is

$$P_{startY} = 1/9 \times P_n \tag{3}$$

and the reactive power is

$$Q_{startY} = 1/3 \times 5.8 \times Q_n \tag{4}$$

Measured data from the pump stations was used to determine the starting active and reactive power values.

For this study there are three start configurations, they are:

1. **Motor start A (Crocodile river pump station)**

   For this motor start analysis it is assumed that M-1 (1) is running at full load, and for M-1 (2) only 1 main and 1 sump pump are running and the 2nd main pump was then started for the analysis.

2. **Motor start B (Marloth dam pump station)**

   Starting of only the 400 kW pump

3. **Motor start C (Marloth dam pump station)**

   Pump #2 running at full load and then starting pump #3

Table 4.1 shows the calculated values for the motor start study.

Table 4.1: Motor start values

	P (kW)	Q (kvar)	S (kVA)	pf
		Motor start A		
Pump 1	107.40	72.12	129.37	0.83
Pump 2	107.40	72.12	129.37	0.83
Total	214.80	144.24	258.74	0.83
Pump 3	107.40	72.12	129.37	0.83
Pump 4	35.80	418.30	419.83	0.09
Total	143.20	490.42	510.90	0.28
		Motor start B		
Pump 1	120.00	1222.64	1228.51	0.10
Total	120.00	1222.64	1228.51	0.10
		Motor start C		
Pump 2	162.70	113.88	198.59	0.82
Pump 3	60.13	714.15	716.68	0.08
Total	222.83	828.03	857.49	0.26

4.3 VOLTAGE LEVEL ANALYSIS

4.3.1 Voltage levels on 400 V busses

Figure 4.1 indicates the per unit voltages of the 400 V busses located on the banana farm for each different layout that was discussed in Chapter 3 section 3.3.

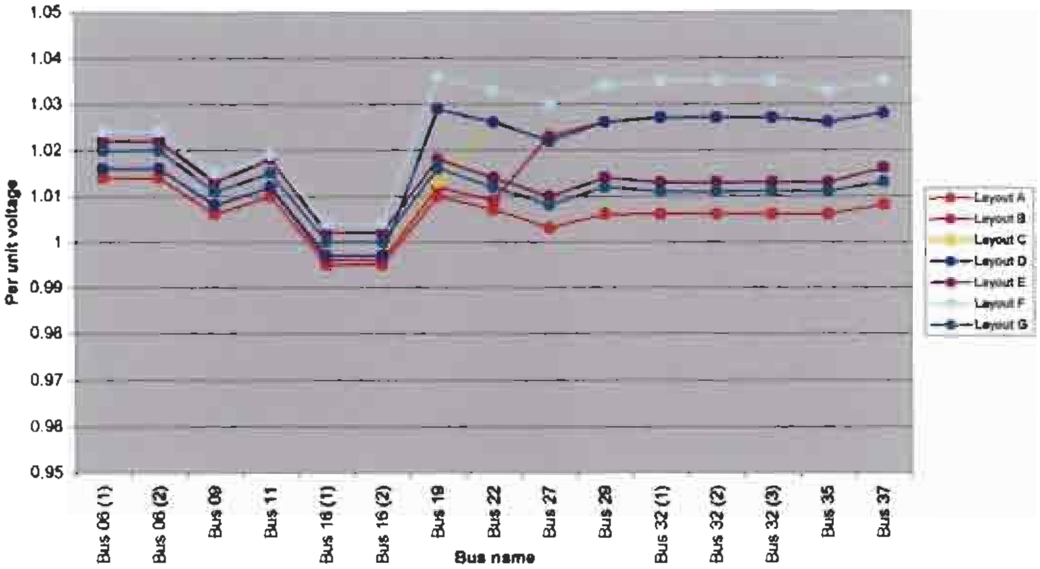


Figure 4.1: Per unit bus voltages on the 400 V busses

All of these could successfully be implemented to improve the voltage profiles, but the impact of each option on the network differs. It is obvious that layout F would be the best solution, but not the cheapest and most economically viable one.

The second best option would be to add an extra line as done in layout B, C and D. The impact these options would have is approximately the same except at busses 19, 22 and 27. In other words layout D would be the best option of the three.

At first glance adding an extra substation transformer appeared to be a logical solution, but the results show that its impact is not very significant and the same applies for layout G.

The area that is most affected by low voltage levels are busses 19, 22, 27, 29, 32(1+2+3), 35 and 37, which indicate that these busses are more likely to be influenced by overloading of the network. The reason for this is that the Marloth line is in a sense very long and these busses are located near the end of the line, meaning there are a lot of other loads between these points and the substation.

Thus, because of the increased flow of reactive power due to pump station loads there was a voltage drop at these points.

Another aspect that should be considered is that the level of voltage increase for layout D on busses 06 (1+2), 09, 11, 16(1+2) is not as much for layouts E and G. The difference however is small thus the impact is not that significant.

It can be concluded that layout F, adding an extra transformer and distribution line, would be the best way of increasing the voltage levels at the load points. This isn't the most practical solution due to high cost implications. Hence, the second best solution would be layout D, where an extra line is connected to between bus 23 and the substation, and the line between bus 12 and 17 is disconnected. This is because of the substantial increase in the voltage at most of the busses as well as the fact that it is more cost effective than the other solutions. If this solution is implemented further improvements could also be made by adding the second transformer at the Koorsboom substation.

4.3.2 Voltage levels on 22 kV busses

Figure 4.2 indicates the per unit voltage on all 22 kV busses located on the banana farm.

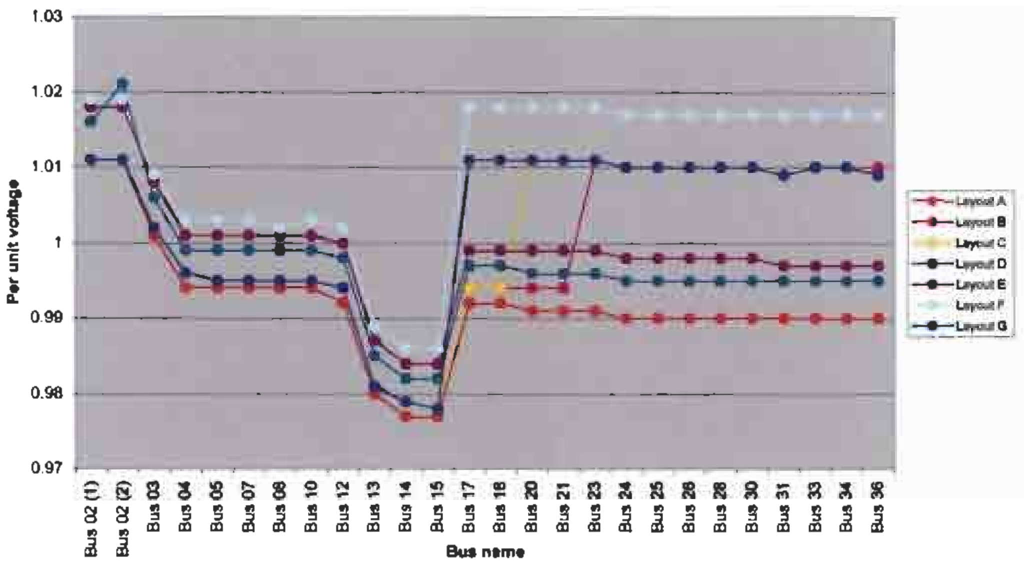


Figure 4.2: Per unit bus voltages on the 22 kV busses

From Figure 4.2 one can also see that the voltage levels for layout A at most of the busses were below 1 pu. However, the voltage magnitudes on the 22 kV busses are not of crucial importance, because tap-changers located on the transformers that are used to step up the secondary voltage. For layout A most of the transformers are set to their minimum tap position to lift the secondary voltage, which indicates that the network is overloaded. Thus by improving the voltage levels of these busses the tap changers of the transformers can be set back to their nominal tap.

The improvement of layout E and G is not as effective as the others. For the voltage profile simulations of the different layouts the best solution would therefore be F, but as mentioned in section 4.3.1 this is not the most economically viable solution. Thus the best solution for improving the 22 kV voltage levels would be layout D.

4.4 FAULT LEVEL ANALYSIS

4.4.1 Fault levels on 400 V busses

To see how the fault levels are affected by the changes in the network layout a short-circuit study was done. Figure 4.3 shows the fault levels for the three main load points on the farm. At busses 06 and 16 there is no real change in the faults levels for layouts A, B, C, D and G. The reason for the increase of fault levels at the busses for layout E and F is the extra substation transformer that results in the system impedance being lower. For Bus 32 there is a significant increase in the fault levels for B, C, D and F, which means that the network will be "stronger" at this point.

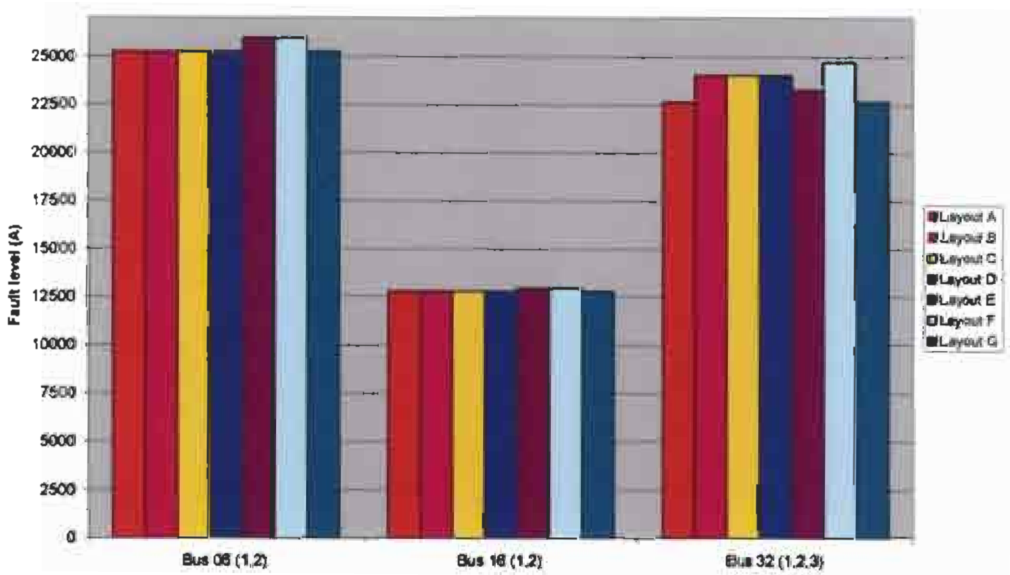


Figure 4.3: 400 V fault levels on the three main loads (M-1, M-2 and M5)

The fault levels of the different layouts shows that if one of the layouts is introduced to the network it won't adversely affect the protection settings that are currently employed.

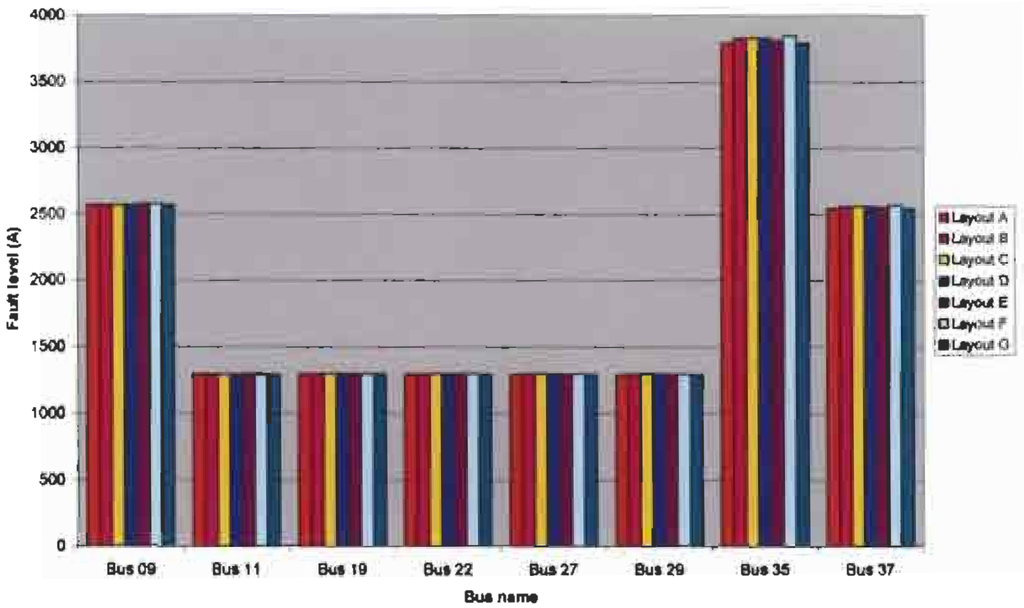


Figure 4.4: 400 V fault levels on smaller loads

Figure 4.4 shows the fault levels at the other points on the network that mainly consists of residential loads. Here the fault levels remain basically the same.

4.4.2 Fault levels on 22 kV busses

The fault levels on the 22 kV distribution lines also shows remarkable improvement that supports results from 400 V busses. Again Layout E and D in Figure 4.5 show large improvement of the fault levels at troubled busses 20, 23, 24, 25, 26, 28, 30, 31, 33, 34, and 36. These increases will make it possible for the network to carry a much higher load than its original configuration.

The real impact of the second transformer is restricted to the first few busbars on the 22 kV system, i.e. those close to the Koorsboom substation. Further along, from bus 20 to 34, the second transformer also has a significant impact, but only for layouts B, C, D and F. These increases in source strength will lessen the impact of dips at those points, in terms of magnitude and phase-angle jumps.

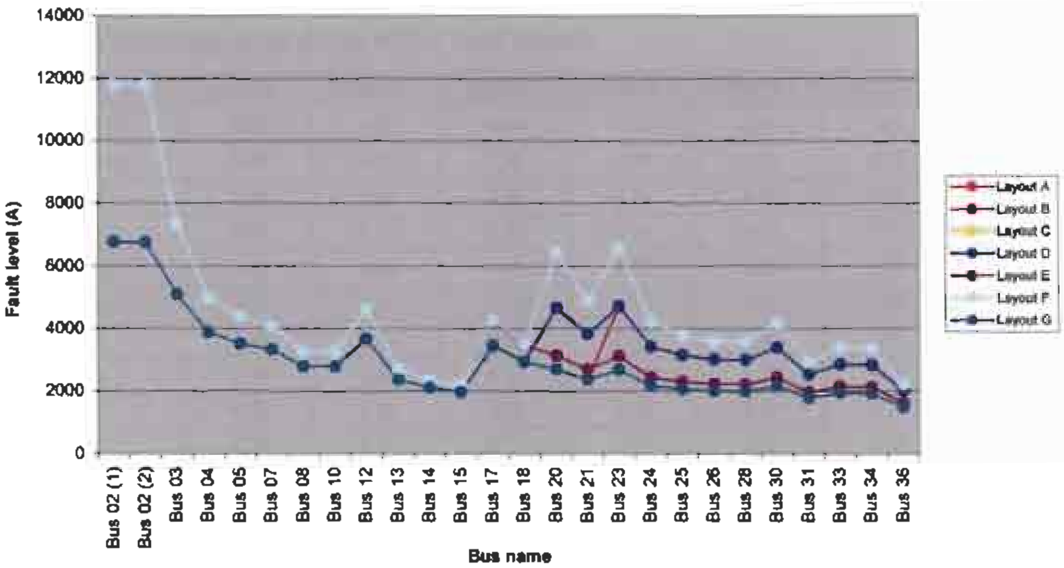


Figure 4.5: Fault levels on all 22 kV busses

Once again it could be concluded from these results that Layout D will provide the best solution on improving the power quality of the network layout, because of its significant impact it has on both 400 V and 22 kV fault levels and its economic advantages.

4.5 MOTOR START ANALYSIS

4.5.1 400 V Load busses

Table 4.2 shows the percentage drop in voltage that occurs on all the busses on the network during the three motor start studies. The highlighted rows indicate the bus at which the started motor is connected. From these results it can again be concluded that layout F would be the best solution for improving the bus voltages on the 400 V distribution points when a large motor (pump) is started. This is because it has the smallest effect on the rest of the network. Such an improvement would lead to less interruptions and voltage dips due to motor starts.

As mentioned in section 4.3.1, layout D would provide the best practical solution to the static voltage levels and it would provide the necessary security during a motor start condition. The difference in percentage drop between D and F is small, therefore D would be the best layout to implement.

Table 4.2: Percentage drop at the 400 V load busses

		Layout A	Layout B	Layout C	Layout D	Layout E	Layout F	Layout G
Motor start A (400 V levels)	Bus 06 (1)	0.20	0.20	0.20	0.20	0.20	0.20	0.29
	Bus 06 (2)	0.20	0.20	0.20	0.20	0.20	0.20	0.29
	Bus 09	0.20	0.20	0.20	0.20	0.10	0.10	0.20
	Bus 11	0.20	0.20	0.20	0.20	0.20	0.10	0.20
	Bus 16 (1)	0.40	0.30	0.40	0.40	0.30	0.30	0.40
	Bus 16 (2)	4.12	4.12	4.11	4.11	3.99	3.98	4.10
	Bus 19	0.20	0.20	0.30	0.10	0.20	0.00	0.20
	Bus 22	0.30	0.20	0.10	0.10	0.20	0.00	0.20
	Bus 27	0.20	0.20	0.10	0.10	0.10	0.10	0.20
	Bus 29	0.20	0.10	0.10	0.10	0.20	0.10	0.30
	Bus 32 (1)	0.30	0.10	0.10	0.10	0.10	0.10	0.20
	Bus 32 (2)	0.30	0.10	0.10	0.10	0.10	0.10	0.20
	Bus 32 (3)	0.30	0.10	0.10	0.10	0.10	0.10	0.20
	Bus 35	0.20	0.19	0.19	0.19	0.10	0.10	0.20
	Bus 37	0.20	0.10	0.10	0.10	0.20	0.00	0.20
Motor start B (400 V levels)	Bus 06 (1)	5.72	5.71	5.71	5.71	5.58	5.57	5.78
	Bus 06 (2)	5.72	5.71	5.71	5.71	5.58	5.57	5.78
	Bus 09	0.60	0.60	0.60	0.60	0.39	0.39	0.59
	Bus 11	0.50	0.59	0.59	0.59	0.49	0.39	0.59
	Bus 16 (1)	0.60	0.50	0.60	0.50	0.40	0.40	0.60
	Bus 16 (2)	0.60	0.50	0.60	0.50	0.40	0.40	0.60
	Bus 19	0.50	0.49	0.59	0.29	0.39	0.10	0.59
	Bus 22	0.60	0.50	0.29	0.29	0.39	0.10	0.59
	Bus 27	0.60	0.39	0.29	0.29	0.40	0.19	0.60
	Bus 29	0.50	0.29	0.29	0.29	0.39	0.19	0.59
	Bus 32 (1)	0.60	0.39	0.39	0.39	0.39	0.19	0.59
	Bus 32 (2)	0.60	0.39	0.39	0.39	0.39	0.19	0.59
	Bus 32 (3)	0.60	0.39	0.39	0.39	0.39	0.19	0.59
	Bus 35	0.50	0.39	0.39	0.39	0.39	0.19	0.59
	Bus 37	0.50	0.29	0.29	0.39	0.39	0.10	0.49
Motor start C (400 V levels)	Bus 06 (1)	3.35	3.44	3.44	3.44	3.23	3.32	3.43
	Bus 06 (2)	3.35	3.44	3.44	3.44	3.23	3.32	3.43
	Bus 09	0.40	0.40	0.40	0.40	0.20	0.20	0.30
	Bus 11	0.30	0.40	0.40	0.40	0.29	0.20	0.30
	Bus 16 (1)	0.40	0.30	0.40	0.40	0.20	0.20	0.40
	Bus 16 (2)	0.40	0.30	0.40	0.40	0.20	0.20	0.40
	Bus 19	0.30	0.30	0.39	0.19	0.20	0.10	0.39
	Bus 22	0.40	0.30	0.19	0.19	0.20	0.10	0.40
	Bus 27	0.40	0.29	0.20	0.20	0.20	0.10	0.30
	Bus 29	0.30	0.19	0.19	0.19	0.20	0.19	0.40
	Bus 32 (1)	0.40	0.19	0.19	0.19	0.20	0.10	0.40
	Bus 32 (2)	0.40	0.19	0.19	0.19	0.20	0.10	0.40
	Bus 32 (3)	0.40	0.19	0.19	0.19	0.20	0.10	0.40
	Bus 35	0.40	0.19	0.19	0.19	0.20	0.10	0.30
	Bus 37	0.30	0.19	0.19	0.19	0.30	0.10	0.30

4.5.2 22 kV distribution busses

For the 22 kV system there is no real difference between the layouts. There is only 0.1% difference in voltage drop between the existing and the other proposed layouts.

Table 4.3: Percentage drop at the 22 kV load busses

		Layout A	Layout B	Layout C	Layout D	Layout E	Layout F	Layout G
Motor start A (22 kV levels)	Bus 02 (1)	0.10	0.10	0.10	0.10	0.00	0.10	0.10
	Bus 02 (2)	0.10	0.10	0.10	0.10	0.00	0.10	0.00
	Bus 03	0.10	0.20	0.20	0.20	0.10	0.10	0.10
	Bus 04	0.20	0.30	0.20	0.20	0.10	0.10	0.20
	Bus 05	0.20	0.20	0.20	0.20	0.10	0.20	0.20
	Bus 07	0.20	0.20	0.20	0.20	0.10	0.20	0.20
	Bus 08	0.30	0.20	0.20	0.20	0.20	0.10	0.20
	Bus 10	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	Bus 12	0.20	0.20	0.20	0.20	0.20	0.20	0.30
	Bus 13	0.41	0.31	0.31	0.31	0.30	0.30	0.30
	Bus 14	0.31	0.41	0.41	0.41	0.20	0.30	0.31
	Bus 15	0.41	0.31	0.31	0.31	0.30	0.30	0.41
	Bus 17	0.20	0.20	0.20	0.20	0.10	0.10	0.20
	Bus 18	0.20	0.20	0.20	0.20	0.10	0.10	0.20
	Bus 20	0.20	0.20	0.20	0.20	0.20	0.10	0.20
	Bus 21	0.20	0.20	0.20	0.20	0.20	0.10	0.20
	Bus 23	0.20	0.20	0.20	0.20	0.20	0.10	0.20
	Bus 24	0.20	0.10	0.10	0.10	0.20	0.10	0.20
	Bus 25	0.20	0.10	0.10	0.10	0.20	0.10	0.20
	Bus 26	0.20	0.10	0.10	0.20	0.20	0.10	0.20
	Bus 28	0.20	0.10	0.10	0.20	0.20	0.10	0.20
	Bus 30	0.20	0.10	0.10	0.10	0.20	0.10	0.20
	Bus 31	0.30	0.10	0.10	0.10	0.10	0.10	0.20
	Bus 33	0.20	0.20	0.20	0.20	0.10	0.10	0.20
	Bus 34	0.20	0.20	0.20	0.20	0.10	0.10	0.20
	Bus 36	0.20	0.20	0.10	0.10	0.10	0.10	0.20
Motor start B (22 kV levels)	Bus 02 (1)	0.30	0.30	0.30	0.30	0.10	0.20	0.30
	Bus 02 (2)	0.30	0.30	0.30	0.30	0.10	0.20	0.00
	Bus 03	0.40	0.40	0.40	0.40	0.20	0.20	0.40
	Bus 04	0.50	0.60	0.60	0.50	0.40	0.40	0.60
	Bus 05	0.60	0.50	0.50	0.50	0.40	0.50	0.60
	Bus 07	0.60	0.50	0.50	0.50	0.40	0.50	0.60
	Bus 08	0.60	0.50	0.50	0.50	0.50	0.40	0.70
	Bus 10	0.60	0.50	0.50	0.50	0.40	0.50	0.70
	Bus 12	0.50	0.50	0.50	0.50	0.40	0.40	0.60
	Bus 13	0.61	0.51	0.51	0.51	0.41	0.40	0.61
	Bus 14	0.51	0.51	0.51	0.51	0.41	0.41	0.61
	Bus 15	0.61	0.51	0.51	0.51	0.41	0.41	0.61
	Bus 17	0.50	0.50	0.50	0.40	0.30	0.20	0.50
	Bus 18	0.50	0.50	0.50	0.40	0.30	0.20	0.60

	Bus 20	0.50	0.50	0.40	0.40	0.40	0.20	0.50
	Bus 21	0.50	0.50	0.40	0.40	0.40	0.20	0.50
	Bus 23	0.50	0.40	0.40	0.40	0.40	0.20	0.50
	Bus 24	0.51	0.40	0.40	0.40	0.40	0.20	0.50
	Bus 25	0.51	0.40	0.40	0.40	0.40	0.20	0.50
	Bus 26	0.51	0.40	0.40	0.40	0.40	0.20	0.50
	Bus 28	0.51	0.40	0.40	0.40	0.40	0.20	0.50
	Bus 30	0.51	0.40	0.40	0.40	0.40	0.20	0.50
	Bus 31	0.61	0.30	0.30	0.30	0.40	0.20	0.60
	Bus 33	0.51	0.40	0.40	0.40	0.40	0.20	0.60
	Bus 34	0.51	0.40	0.40	0.40	0.40	0.20	0.60
	Bus 36	0.51	0.40	0.30	0.30	0.40	0.20	0.60

Motor start C (22 kV levels)	Bus 02 (1)	0.20	0.20	0.20	0.20	0.10	0.10	0.20
	Bus 02 (2)	0.20	0.20	0.20	0.20	0.10	0.10	0.00
	Bus 03	0.30	0.30	0.30	0.30	0.10	0.10	0.20
	Bus 04	0.30	0.40	0.40	0.40	0.20	0.20	0.30
	Bus 05	0.40	0.30	0.30	0.30	0.30	0.30	0.40
	Bus 07	0.40	0.30	0.30	0.30	0.30	0.30	0.40
	Bus 08	0.40	0.40	0.30	0.30	0.30	0.20	0.40
	Bus 10	0.40	0.30	0.30	0.30	0.30	0.30	0.40
	Bus 12	0.30	0.30	0.30	0.30	0.30	0.30	0.40
	Bus 13	0.41	0.31	0.31	0.31	0.20	0.30	0.41
	Bus 14	0.31	0.41	0.41	0.41	0.20	0.20	0.31
	Bus 15	0.41	0.31	0.31	0.31	0.20	0.30	0.41
	Bus 17	0.30	0.30	0.30	0.30	0.20	0.10	0.30
	Bus 18	0.30	0.30	0.30	0.30	0.20	0.10	0.30
	Bus 20	0.30	0.30	0.20	0.20	0.30	0.10	0.30
	Bus 21	0.30	0.30	0.20	0.30	0.30	0.10	0.30
	Bus 23	0.30	0.20	0.20	0.20	0.30	0.10	0.30
	Bus 24	0.30	0.20	0.20	0.20	0.30	0.10	0.30
	Bus 25	0.30	0.20	0.20	0.20	0.30	0.10	0.30
	Bus 26	0.30	0.20	0.20	0.20	0.30	0.10	0.30
	Bus 28	0.30	0.20	0.20	0.20	0.30	0.10	0.30
	Bus 30	0.30	0.20	0.20	0.20	0.30	0.10	0.30
	Bus 31	0.40	0.20	0.20	0.20	0.20	0.10	0.40
	Bus 33	0.30	0.20	0.20	0.30	0.20	0.10	0.30
	Bus 34	0.30	0.20	0.30	0.30	0.20	0.10	0.30
	Bus 36	0.40	0.30	0.20	0.20	0.20	0.10	0.30

4.6 CONCLUSION

By improving the voltage levels the losses in the network are minimized. This is because the losses in transporting electricity are proportional to the current squared. Power is equal to the product of voltage and current, so as the voltage increases the current decreases. For example, if the current increases to double its value the losses in the system quadruple.

There are two ways of improving the capacity of a network, i.e. by upgrading the existing network or by adding new transmission lines. By adding substation transformers the capacity of the distribution network is increased, thereby improving power quality and reducing the probability of long and short-term interruptions. This one would expect to be an appealing idea. However, it was proved not to be the most viable option from the simulations. In addition, the transmission capacity is restricted by the thermal limitations on the distribution lines, which could cause the sagging of lines too close to the ground. This problem could be overcome by reconductoring (replacing the existing cables with thicker ones). This method is not the most economically viable option.

By adding additional lines it alleviates the constraints caused by thermal limitations because the power that is delivered is distributed among more paths. This enhances the overall system's voltage profile because it reduces the overall impedance of the network. Therefore, by only adding new lines to increase the difference between the power that the system is designed to handle and what actually flows, one could clearly enhance the power quality of the overall system as shown in the results for layouts B, C and D.

The best option to this problem is to add an extra distribution line to the network. This change however can only be seen as a temporary solution, because aspects like future plant upgrades at the banana farm will require new solutions to maintain good power quality.

CHAPTER 5
DISTRIBUTION OF VOLTAGE DIPS IN THE NETWORK

5.1 INTRODUCTION

The purpose of this chapter is to examine the voltage dips that occurred within the network during the period of investigation.

By the use of the Impedograph power quality recorder each dip incident during the investigation period was captured and is analyzed toward a possible cause. Most of the incidents are related to motor start and faults caused externally on the Utility network, therefore the goal of this section was to determine and quantify the number of dips caused by the Utility network. Each such an incident was investigated. Incidents caused internally, such as motor starts at Marlothi dam are not of great concern, as sensitive equipment is not fed from this point.

The propagation of voltage dips across transformers was studied to determine which type of faults that occurred in the network, most probably caused voltage dips at the load points. Data, measured simultaneously at the Marlothi dam on the secondary side of the transformer and the Ripening plant's primary side, were used to verify these findings.

5.2 CLASSIFICATION AND ANALYSIS OF MEASURED VOLTAGE DIPS

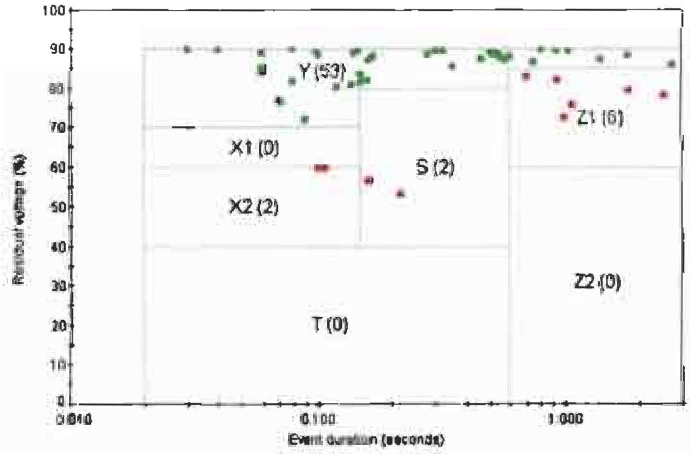
Each voltage dip incident, as captured by the Impedograph, was analyzed towards a possible cause. The classification of the NRS048 voltage dip report does not distinguish between dips internally and externally generated and therefore it was important to quantify the number of dips caused by the Utility network, each such an incident was investigated to determine the impact it has on the farm itself.

There were three different points on the farm where readings were taken with the Impedograph power quality recorders over a certain period of time:

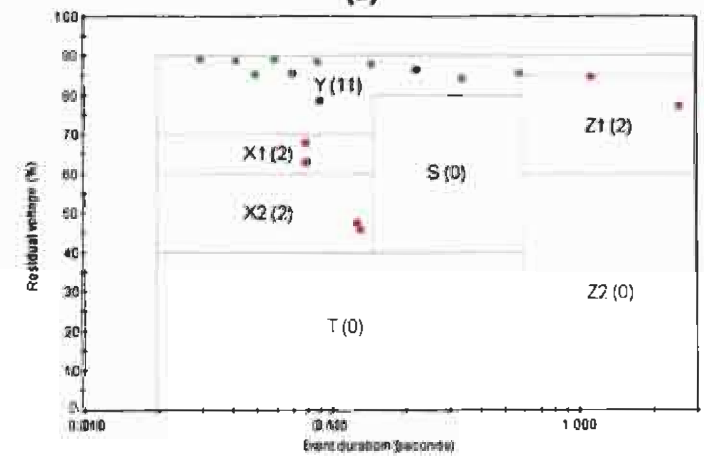
Marlothi dam pump station:	2005/08/21 – 2005/08/31	(duration 11 days)
	2005/09/15 – 2005/10/04	(duration 20 days)
Ripening plant:	2005/09/16 – 2005/10/05	(duration 20 days)
Pack house:	2006/03/04 – 2006/03/22	(duration 19 days)

Unfortunately no recordings of the Koorsboom substation and other 22 kV lines were made available for analysis purposes due to the ongoing battle between the utility and the customer.

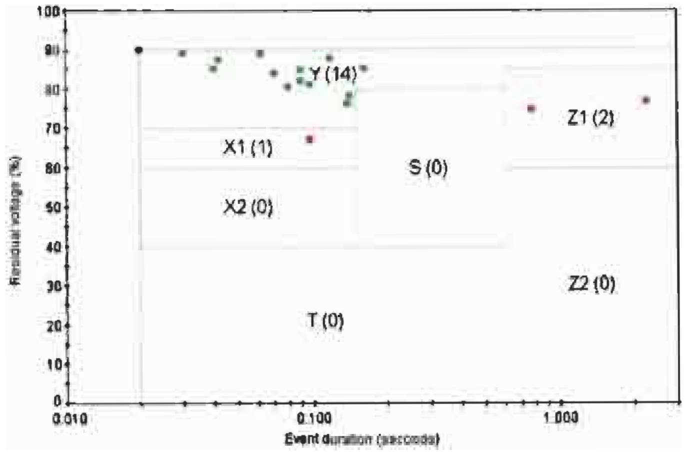
With the use of the Impedograph software [19] a NRS 048 scatter plot categorizing the voltage dips was generated for each point as shown in Figure 5.1.



(a)



(b)



(c)

Figure 5.1: NRS 048 dip classification for (a) Marlothi dam pump station, (b) ripening plant and (c) pack house

5.2.1 Marlothi Pack house

As mentioned in Chapter 3 the pack house only consist of small motors used for conveyor belts and large coolers. Therefore this is a site where poor power quality can have a crucial impact on production and delivery of the farms product. At this point the voltage dip recorder was connected in star to measure the three-phase 230 V line-to-neutral voltages. Table 5.1 shows all the dips captured by the Impedograph recorder. The dip type was determined using the algorithm given in chapter 2 and is then used to determine the possible cause of the dip. The problem with this analysis is that it is impossible to determine whether the fault occurred on the 22 kV distribution lines or on the 132 kV transmission system. Therefore, the cause of the fault is determined for both distribution and transmission system.

From the analysis it can be concluded that all dips were externally generated by the Utility network. Most of the SLG, LLF and LLGFs were caused by swinging conductors and trees touching the conductors due to strong winds and weather conditions. This problem could be related to the poor network condition and maintenance. The impact of these dips was not severe on the production and the functionality of the farm because none of these faults caused any severe interruptions. However an interruption that lasted for 54 s was recorded. Fortunately it occurred during non-working hours. It seems that it was caused by a three-phase fault that was generated externally on the network, cleared by the protection on the network and was successfully restored after 54 s.

Table 5.1: Measured voltage dips at the pack house

Pack house									
Nr.	**Date**	**Time**	**Drop in phases**	**Duration (s)**	**Retained voltage**	**Min. voltage**	**NRS 048 dip category**	**Dip type**	**Cause of dip (D: distribution, T: Transmission)**
1	Thu 16 Mar 2006	05:55:51	b, c	0.142	78.20%	179.9 V	Y	C_a	D: SLGF T: LLF or LLGF
2	Thu 16 Mar 2006	20:31:09	a	0.098	81.30%	187.0 V	Y	D_a	D: LLF or LLGF T: SLGF
3	Thu 16 Mar 2006	20:40:09	a	0.09	82.10%	188.9 V	Y	D_a	D: LLF or LLGF T: SLGF
4	Thu 16 Mar 2006	21:02:46	a, b	0.118	87.80%	202.0 V	Y	C_b	D: SLGF T: LLF or LLGF
5	Thu 16 Mar 2006	21:04:04	a	0.08	80.50%	185.2 V	Y	D_a	D: LLF or LLGF T: SLGF
6	Thu 16 Mar 2006	21:46:20	a, b, c	0.098	67.40%	154.9 V	X1	3θ	Not caused by motor start, probably due to a 3-phase fault at a higher voltage level
7	Thu 16 Mar 2006	21:54:32	a, c	0.162	85.30%	196.1 V	Y	C_c	D: SLGF T: LLF or LLGF
8	Thu 16 Mar 2006	22:04:33	a, b, c	0.138	76.40%	175.6 V	Y	C_c	D: SLGF T: LLF or LLGF
9	Thu 16 Mar 2006	22:14:33	c	0.042	87.50%	201.3 V	Y	D_b	D: LLF or LLGF T: SLGF
10	Thu 16 Mar 2006	22:24:47	c	0.062	89.10%	205.0 V	Y	C_c	D: SLGF T: LLF or LLGF
11	Mon 20 Mar 2006	15:10:02	a	0.03	89.20%	205.2 V	Y	D_a	D: LLF or LLGF T: SLGF
12	Mon 20 Mar 2006	22:52:06	a, b	0.09	84.80%	195.1 V	Y	Unknown	No recorded voltage waveforms available
13	Mon 20 Mar 2006	23:30:45	b, c	0.766	74.90%	172.3 V	Z1	C_a	D: SLGF T: LLF or LLGF
14	Tue 21 Mar 2006	00:43:23	a, b, c	2.251	76.80%	176.7 V	Z1	Multi	Externally generated 3-phase fault turning into a multistage dip
15	Tue 21 Mar 2006	01:38:43	a	0.02	89.90%	206.8 V	Y	D_a	D: LLF or LLGF T: SLGF
16	Tue 21 Mar 2006	01:50:03	b	0.04	85.20%	196.0 V	Y	D_c	D: LLF or LLGF T: SLGF
17	Wed 22 Mar 2006	13:03:55	b	0.07	84.00%	193.2 V	Y	D_c	D: LLF or LLGF T: SLGF

These short temporary dips could however have a degenerative effect on equipment that could later lead to plant shut down. Also, there are not a large number of sensitive electronic devices that can easily be affected by the dips. However in the future if plant upgrades take place due to the increasing development of technology these dips could have a more severe impact on the farm. It is therefore recommended that a close inspection should be done on the distribution network to locate problem areas to minimize the occurrence of dips.

5.2.2 Marlothi Ripening plant

At this point the voltage dip recorder was connected to the primary side of the distribution transformer to measure the 22 kV side line-to-neutral voltages. This transformer supplies large coolers, workshops, offices and the pack house. This means that poor quality at this point has a large impact on the important operations and processes of the farm.

Table 5.2: Measured voltage dips at the ripening plant

Ripening plant									
Nr.	**Date**	**Time**	**Drop in phases**	**Duration (s)**	**Retained voltage**	**Min. voltage**	**NRS 048 dip category**	**Dip type**	**Cause of dip (D: distribution, T: Transmission)**
1	Thu 22 Sep 2005	07:49:23	a, b	0.148	87.80%	19288.7 V	Y	Cb, 3θ	D: LLF or LLGF T: SLGF
2	Sun 25 Sep 2005	05:41:54	b	1.14	84.70%	18613.9 V	Z1	Dc	D: SLGF T: LLF or LLGF
3	Sun 25 Sep 2005	05:41:55	b	0.042	88.60%	19469.1 V	Y	Dc	D: SLGF T: LLF or LLGF
4	Sun 25 Sep 2005	05:41:55	b	0.222	86.30%	18968 V	Y	Dc	D: SLGF T: LLF or LLGF
5	Sun 25 Sep 2005	05:41:56	b	0.03	89.10%	19582.7 V	Y	Dc	D: SLGF T: LLF or LLGF
6	Sun 25 Sep 2005	05:41:56	b	0.586	85.40%	18767.6 V	Y	Dc	D: SLGF T: LLF or LLGF
7	Sun 25 Sep 2005	09:54:23	a, b, c	0.346	84.10%	18480.3 V	Y	3θ	Balanced 3θ dip, due to energizing of an area somewhere on Utility grid
8	Sun 25 Sep 2005	12:17:32	a	0.06	89.10%	19576.0 V	Y	Da	D: SLGF T: LLF or LLGF
9	Sun 25 Sep 2005	14:44:56	b, c	0.07	85.50%	18787.6 V	Y	Ca	D: LLF or LLGF T: SLGF
10	Sun 25 Sep 2005	16:27:48	a, b	0.05	85.40%	18754.2 V	Y	Cb	D: LLF or LLGF T: SLGF
11	Sun 25 Sep 2005	17:53:00	b	0.09	88.30%	19402.3 V	Y	Dc	D: SLGF T: LLF or LLGF
12	Sun 25 Sep 2005	18:08:40	a, b, c	0.08	63.00%	13836.8 V	X1	Dc	D: SLGF T: LLF or LLGF
13	Sun 25 Sep 2005	18:08:44	a	0.08	67.90%	14925.9 V	X1	Da	D: SLGF T: LLF or LLGF
14	Wed 28 Sep 2005	10:17:30	a, b, c	2.566	77.10%	16943.6 V	Z1	3θ	Not caused by motor start, probably due to a 3-phase fault at a higher voltage level
15	Thu 29 Sep 2005	11:35:49	a, b, c	0.128	47.40%	10416.0 V	X2	Da	D: SLGF T: LLF or LLGF
16	Thu 29 Sep 2005	11:37:09	a, b, c	0.132	45.80%	10055.2 V	X2	Da	D: SLGF T: LLF or LLGF
17	Tue 4 Oct 2005	22:07:52	a, c	0.091	78.50%	17244.2 V	Y	Cc	D: LLF or LLGF T: SLGF

From Table 5.2 it was concluded that all the dips recorded at this site were mostly caused by SLG and LLFs, which were mainly due to poor network conditions.

5.2.3 Marlothi Intermediate dam

Most of these incidents at Marlothi intermediate dam pump station are temporary incidents caused by the starting of their own pumps. An induction machine has a lagging power factor due to the dominantly inductive effect of motor winding impedance. During acceleration the increased internal slip and armature reaction caused temporarily lower winding impedance and resulted in higher load currents. The reactive power flow increases gradually. This specific dip is not a cause of concern as sensitive equipment is not fed from this substation and normal voltage levels are restored after less than 0.7 s.

An important aspect that was noted during the analysis of the Impedograph data was the regular occurrence of voltage dips caused by transformer saturation shown in Figure 5.2 at Marlothi pump station.

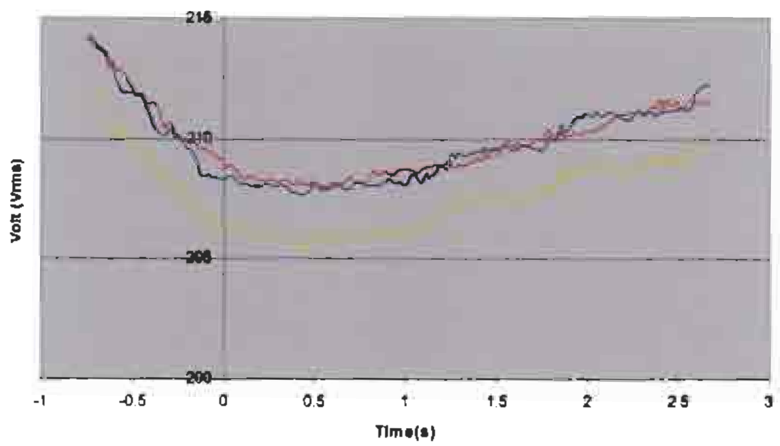


Figure 5.2: Voltage dip caused by magnetizing inrush current in transformers

Here, two 500 kVA transformers feed the pump station and no other load is connected to them. So when the pumps are not working zero current flows through the transformers. During starting of a motor it draws a large amount of inrush current, which causes the energising and a drop in the terminal voltage of the transformers. This incident causes a transient that changes the flux in the core of the transformer to a new steady state value. The flux goes above the saturation limit twice during each cycle until the average flux over every cycle has decayed to almost zero. This over-fluxing in the core of the transformer causes high values of magnetising current, which decays exponentially. This is known as magnetising inrush current. The magnitude for each phase is not entirely the same because the amount of saturation is different for each phase. During the dip the voltage drops sharply and recovers gradually as the magnetising current decreases. An additional feature is the presence of temporary harmonic distortion caused mostly by the second and fourth harmonics as seen in Figure 5.2. The magnitude and duration of these dips depend on the following factors: point on the wave where switching takes place, the residual flux in the core and the damping ability of the network [4].

Pump starting is not a cause for concern as sensitive equipment is not fed from this distribution point and normal voltage levels are restored after approximately 600 ms for each start. Therefore these dips are not analyzed and thus ignored further.

Table 5.3: Measured voltage dips at Marlothi dam

Marlothi intermediate dam pump station									
Nr.	**Date**	**Time**	**Drop in phases**	**Duration (s)**	**Retained voltage**	**Min. voltage**	**NRS 048 dip category**	**Dip type**	**Cause of dip (D: distribution, T: Transmission)**
1	Mon 22 Aug 2005	14:05:12	a, b, c	1.835	79.40%	182.5 V	Z1	Unknown	3θ fault with arcing between conductors and object that caused the fault
2	Mon 22 Aug 2005	14:05:14	a, c	0.465	87.50%	201.3 V	Y	Unknown	3θ fault with arcing between conductors and object that caused the fault
3	Tue 23 Aug 2005	07:36:41	a	1.412	87.30%	200.9 V	Y	C_c	D: SLGF T: LLF or LLGF
4	Tue 23 Aug 2005	07:36:42	a	1.807	88.30%	203.1 V	Y	C_c	D: SLGF T: LLF or LLGF
5	Tue 23 Aug 2005	15:49:25	a, b, c	0.162	56.40%	129.8 V	S	C_a	D: SLGF T: LLF or LLGF
6	Tue 23 Aug 2005	15:49:31	a, b, c	0.218	53.30%	122.7 V	S	C_a	D: SLGF T: LLF or LLGF
7	Wed 24 Aug 2005	08:25:11	a, b, c	2.74	86.00%	197.8 V	Y	C_c, 3θ	D: SLGF T: LLF or LLGF
8	Wed 24 Aug 2005	09:27:36	a, c	0.938	82.10%	188.7 V	Z1	C_b	D: SLGF T: LLF or LLGF
9	Thu 25 Aug 2005	06:02:50	a	0.16	82.20%	189.0 V	Y	D_a	D: LLF or LLGF T: SLGF
10	Fri 26 Aug 2005	13:05:21	a, b, c	1.082	75.70%	174.1 V	Z1	D_c, 3θ	D: LLF or LLGF T: SLGF
11	Fri 26 Aug 2005	13:05:25	a, b, c	1.007	72.50%	166.8 V	Z1	3θ	3-phase fault
12	Fri 26 Aug 2005	14:04:19	a, b, c	0.12	80.30%	184.6 V	Y	C_a	D: SLGF T: LLF or LLGF
13	Fri 26 Aug 2005	18:40:55	a, b	0.15	83.50%	192.1 V	Y	D_a	D: LLF or LLGF T: SLGF

14	Fri 26 Aug 2005	18:48:03	a, b	0.15	81.40%	187.3 V	Y	D_a	D: LLF or LLGF T: SLGF
15	Fri 26 Aug 2005	18:48:07	a, b	0.138	80.80%	185.7 V	Y	D_a	D: LLF or LLGF T: SLGF
16	Fri 26 Aug 2005	20:10:20	b	0.162	87.20%	200.5 V	Y	C_a	D: SLGF T: LLF or LLGF
17	Fri 26 Aug 2005	23:14:35	a, b	0.06	89.00%	204.6 V	Y	C_c	D: SLGF T: LLF or LLGF
18	Sat 27 Aug 2005	14:17:49	a, b, c	0.756	86.70%	199.3 V	Y	D_c, 3θ	D: LLF or LLGF T: SLGF
19	Sat 27 Aug 2005	14:17:52	a, b, c	0.708	83.00%	190.9 V	Z1	3θ	3-phase fault
20	Sun 28 Aug 2005	19:12:13	a, c	0.08	81.90%	188.3 V	Y	C_b	D: SLGF T: LLF or LLGF
21	Sun 25 Sep 2005	05:41:53	a	0.606	88.10%	202.5 V	Y	C_c	D: SLGF T: LLF or LLGF
22	Sun 25 Sep 2005	05:41:54	a	0.102	88.40%	203.4 V	Y	C_c	D: SLGF T: LLF or LLGF
23	Sun 25 Sep 2005	05:41:54	a	0.1	89.30%	205.3 V	Y	C_c	D: SLGF T: LLF or LLGF
24	Sun 25 Sep 2005	05:41:55	a	0.282	88.70%	204 V	Y	C_c	D: SLGF T: LLF or LLGF
25	Sun 25 Sep 2005	09:54:22	a, b, c	0.354	85.60%	196.8 V	Y	3θ	Balanced 3θ dip, due to energizing of an area somewhere on Utility's grid
26	Sun 25 Sep 2005	14:44:55	a	0.06	85.30%	196.2 V	Y	D_a	D: LLF or LLGF T: SLGF
27	Sun 25 Sep 2005	16:27:47	b	0.06	84.00%	193.2 V	Y	D_b	D: LLF or LLGF T: SLGF
28	Sun 25 Sep 2005	18:08:39	a, c	0.09	72.00%	165.6 V	Y	C_b	D: SLGF T: LLF or LLGF
29	Sun 25 Sep 2005	18:08:43	b, c	0.07	76.90%	176.9 V	Y	C_a	D: SLGF T: LLF or LLGF
30	Wed 28 Sep 2005	10:17:15	a, b, c	2.552	78.40%	180.2 V	Z1	3θ	3-phase fault
31	Thu 29 Sep 2005	11:35:32	a, b, c	0.102	59.70%	137.2 V	X2	C_a	D: SLGF T: LLF or LLGF
32	Thu 29 Sep 2005	11:36:52	a, b, c	0.108	59.90%	137.7 V	X2	C_a	D: SLGF T: LLF or LLGF
33	Sat 1 Oct 2005	05:40:52	a	0.142	89.10%	204.9 V	Y	C_c	D: SLGF T: LLF or LLGF
34	Mon 3 Oct 2005	20:04:53	b	0.148	89.50%	205.9 V	Y	Unknown	No recorded voltage waveforms available
35	Tue 4 Oct 2005	22:07:34	c	0.072	76.40%	175.7 V	Y	D_c	D: LLF or LLGF T: SLGF

5.2.4 Effect on Loads

The voltage dips measured at the different points could have had the following effect on the following equipment. Electronic equipment such as computers and PLCs employ a reservoir capacitor to smooth out the peaks of the full wave rectified waveform, so they should be inherently resilient to short duration dips. Therefore the dip magnitude and duration are the main influence that will determine whether these devices would shut down. According to [17] a dip of approximately 40 % and 7 cycles would already cause the devices to shut down or restart.

Although induction motors have inertia to support the load during a short dip, i.e. converting momentum into power as they slow down, the energy has to be replaced as the motor re-accelerates. If the speed has reduced by more than 10% it will draw nearly the full start-up current. Since all the motors are 'starting' together, this may be the cause of further problems.

Relays and contactors are also sensitive to voltage dips. The devices may drop out during a dip even when the retained voltage is higher than the minimum steady state hold-in voltage. The resilience of a contactor to dips depends not only on the retained voltage and duration, but also on the point on the waveform where the dip occurs, the effect being less at the peak.

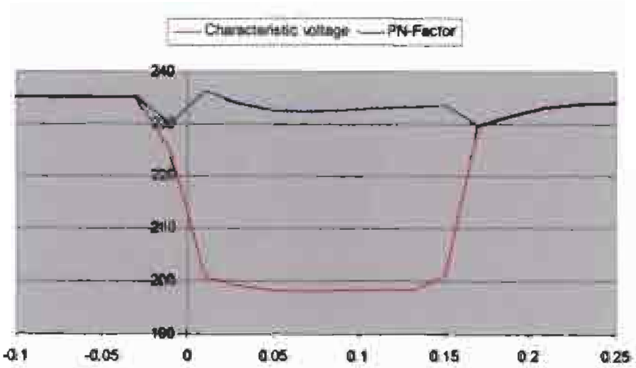
5.2.5 Comparison between Bollen Classification method and NRS 048

When comparing the two methods the Bollen dip classification defines the type of dip that is experienced and the NRS 048 defines the severity. The problem with the NRS 048 classification is that it does not distinguish between the type of fault, i.e. SLGF or LLGF. For example, in table 5.3 nr 1 NRS 048 defines the dip as a type Y and Bollen characterizes it as a type C_b turning into a 3θ dip. This means a voltage drop in one phase is characterized as equally severe when compared to a drop in all three phases, whereas the latter event is typically more severe for the system and equipment.

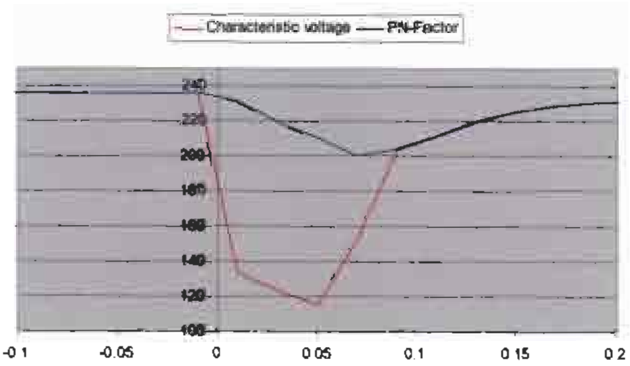
With Bollen classification the characteristic voltage is the main quantifier for the severity of the event. For many applications the characteristic magnitude (absolute value of characteristic voltage) may be sufficient to characterize an event. The PN-factor is a measure for the effect of the system load on voltages at the equipment terminals during the fault. Neglecting system load gives a PN-factor equal to one. In many cases the PN-factor is close to one and can thus be neglected. The PN-factor needs to be considered for specific applications in systems with a large amount of induction motor loads.

5.2.6 Characteristic Voltage and PN-Factor

The characteristic voltage is used to describe the event and PN-factor is a measure of the unbalance of the event. For SLGFs and LLFs the PN-factor is close to unity, for LLGFs it is less than unity and for three-phase faults the PN-factor is equal to the characteristic voltage [2]. The PN-factor is also an indication of the effect of the load on the voltage dip. Calculating each individual characteristic voltage and PN-factor of each dip was considered to be a futile exercise, therefore only the basic pattern is discussed.



(a)



(b)

Figure 5.3: Characteristic voltage and PN-factor for a LLF

Figure 5.3 indicates the characteristic voltage and PN-factor for two LLFs at the pump station. Figure 5.3 (a) shows a PN-factor close to unity and (b) also indicates a

PN-factor close to unity, it is however lower than (a). The difference between the two is attributed to the severity of dip (b) with a characteristic voltage of 118 V.

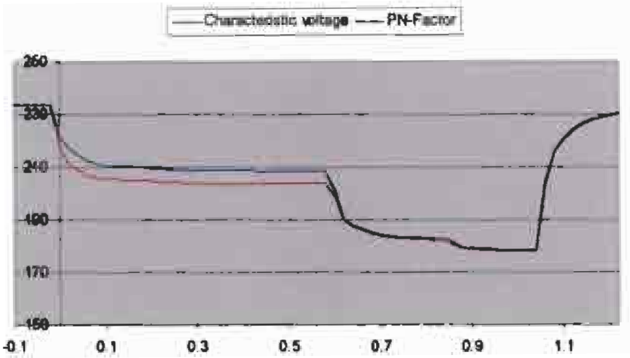


Figure 5.4: Characteristic voltage and PN-factor for a LLGF and 3θ fault

Figure 5.4 represents a multistage dip that started as a LLGF and turned into a 3θ fault. The rapid decay of the PN-factor indicates that the dip was caused by a LLGF. As the dip changes to a 3θ fault the characteristic voltage and PN-factor becomes basically the same.

5.3 VOLTAGE DIPS MEASURED SIMULTANEOUSLY

Overlapping measurements taken at Marlothi dam and the Ripening plant were used in this section to indicate the propagation of voltage dips from higher to lower voltage levels. The following dips in Table 5.4 were measured simultaneously at both points. Some of these dips were similar, meaning that it was caused by the same type of fault, therefore not all of these are discussed separately.

Table 5.4: Simultaneously measured dips at Marlothi dam and the Ripening plant

			NRS 048 dip category		Drop in phases		Duration (s)		Retained voltage		Minimum voltage	
Nr.	Start Date	Start Time	MD	RP	MD	RP	MD	RP	MD	RP	MD	RP
1	25 Sep 2005	05:41	Y	Z1	a	b	1.09	2.02	88.63%	86.82%	203.8 V	19080 V
2	25 Sep 2005	09:54	Y	Y	a, b, c	a, b, c	0.354	0.346	85.60%	84.10%	196.8 V	18480 V
3	25 Sep 2005	14:44	Y	Y	a	b, c	0.06	0.07	85.30%	85.50%	196.2 V	18788 V
4	25 Sep 2005	16:27	Y	Y	b	a, b	0.06	0.05	84.00%	85.40%	193.2 V	18754 V
5a	25 Sep 2005	18:08	Y	X1	a, c	a, b, c	0.09	0.08	72.00%	63.00%	165.6 V	13837 V
5b	25 Sep 2005	18:09	Y	X1	b, c	a	0.07	0.08	76.90%	67.90%	176.9 V	14926 V

6	28 Sep 2005	10:17	Z1	Z1	a, b, c	a, b, c	2.552	2.566	78.40%	77.10%	180.2 V	16944 V
7	29 Sep 2005	11:35	X2	X2	a, b, c	a, b, c	0.102	0.128	59.70%	47.40%	137.2 V	10416 V
8	29 Sep 2005	11:36	X2	X2	a, b, c	a, b, c	0.108	0.132	59.90%	45.80%	137.7 V	10055 V
9	4 Oct 2005	22:07	Y	Y	c	a, c	0.072	0.091	76.40%	78.50%	175.7 V	17244 V

The results of the following figures shows that table 2.3 in Chapter 2 holds true for the propagation of voltage dips through transformers.

For dip 1 in Figure 5.5 the dip experienced at the ripening plant was a single-phase drop in phase *c* and at Marlothi dam a two-phase drop in phases *a* and *b*. The figure shows that although there is an unbalance in the voltage and current supply the load is not severely affected, because the active power stabilizes to its original value. However there is a decrease in the reactive power due to the relationship of $Q \propto V^2$, which means a decrease in voltage causes the reactive power to decrease by the value of the voltage squared. The fact that power stabilized during the incident means that the fault probably occurred on one of the other 22 kV distribution lines.

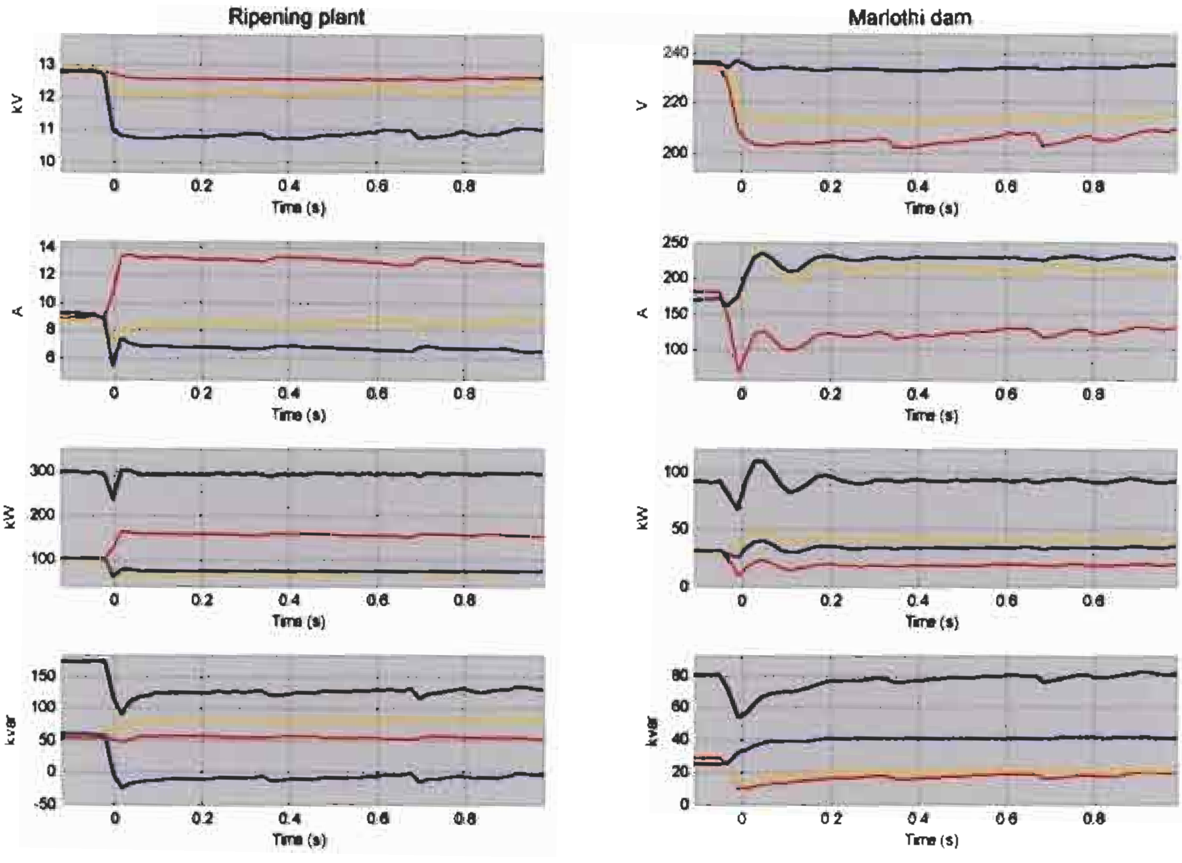


Figure 5.5: Simultaneously measured voltage, current, active and reactive power for dip 1

Dip 3, 4 and 9 are single-phase voltage dips caused by either a LLF on the 22 kV Marloth line or a SLGF on the 132 kV network and dips 5a, 5b, 7 and 8 are phase-to-phase dips caused by either a SLGF on the 22 kV Marloth line or a LLF on the 132 kV network. Figure 5.6 and Figure 5.7 shows the recorded values for dip 9 and dip 5a from the Impedograph. It is again a typical short circuit condition in the supply network, most probably caused by line conductors being temporarily short-circuited by wind-induced movement.

The impact of these dips weren't severe and the system restored to its original operating state. The duration of these dips are short so its effect on equipment is minimal, however if the fault persists it could lead to tripping of the 22 kV line at the substation which will cause the farm to be without any electricity for some time.

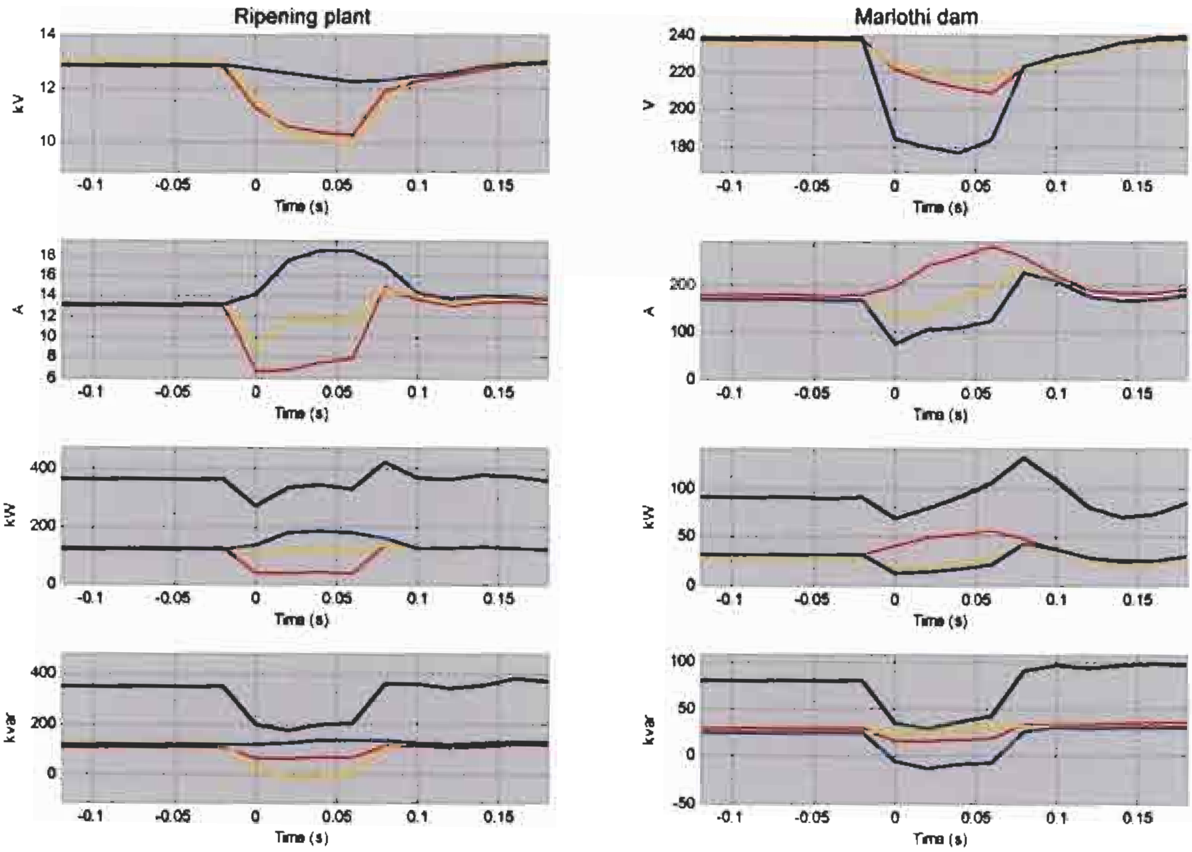


Figure 5.6: Simultaneously measured voltage, current, active and reactive power for dip 9

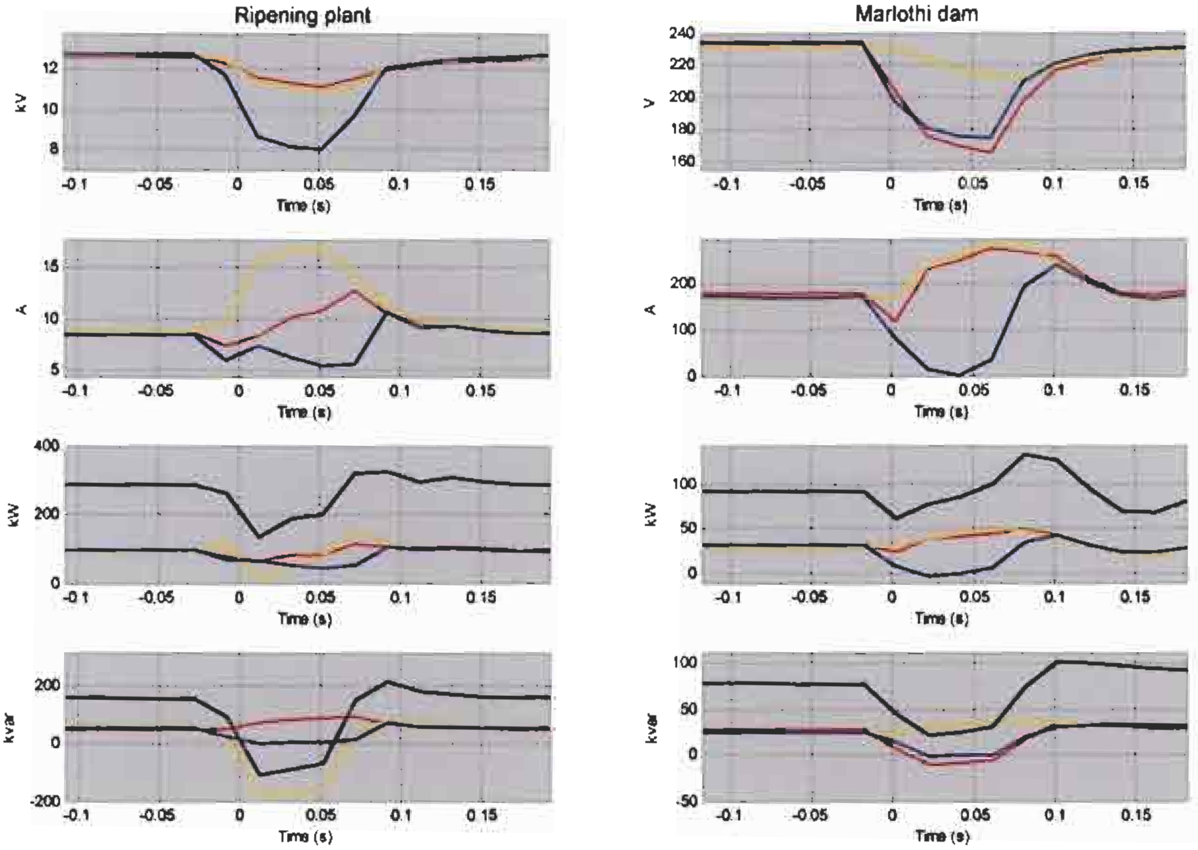


Figure 5.7: Simultaneously measured voltage, current, active and reactive power for dip 5a

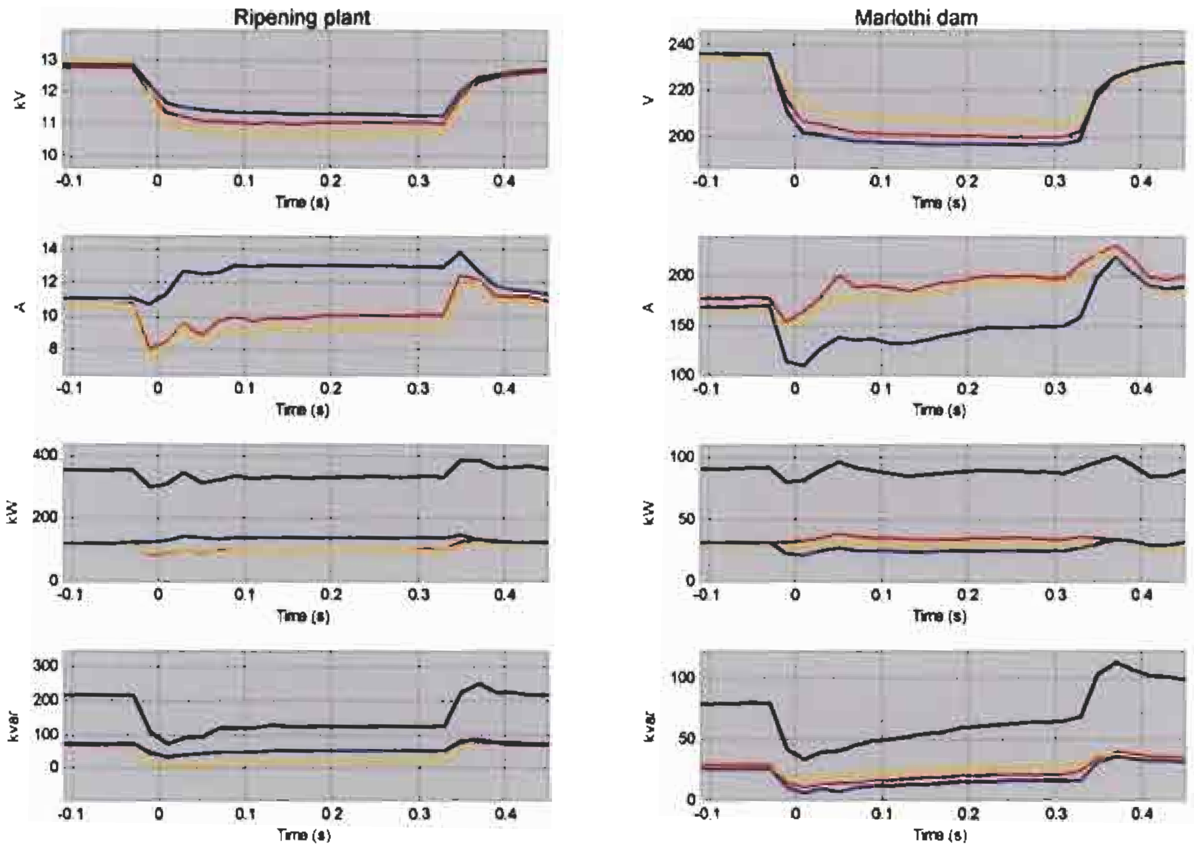


Figure 5.8: Simultaneously measured voltage, current, active and reactive power for dip 2

Dip 2 shown in Figure 5.8 is classified as a three-phase dip. The origin of this dip wasn't caused by a three-phase fault, because of its gradual decrease and restoring of the voltage supply. Three-phase dips are usually associated with the starting of large induction motors and the dip is accompanied by a steep increase in current, in this case the dip wasn't caused by the starting of a motor. It appears that one of the other 22 kV lines was down and when it was restored it caused the three-phase dip on the other lines, because of the large current inrush of the restored line.

Dip 6 in Figure 5.9 also shows a three-phase dip, however this dip was caused by an actual three-phase fault, which is a very uncommon occurrence. The current from the ripening plant in the figure below shows that this fault caused some equipment of the farm to trip. This could be due to under-voltage protection on motors. Looking at the pump station this dip caused the pumps to slow down, which could lead to the stalling of the motors if the dip had been any longer. Note the sudden increase in current, active and reactive power at the end of a dip, this is due to the reacceleration of the motors which are situated at the ripening plant and pump station.

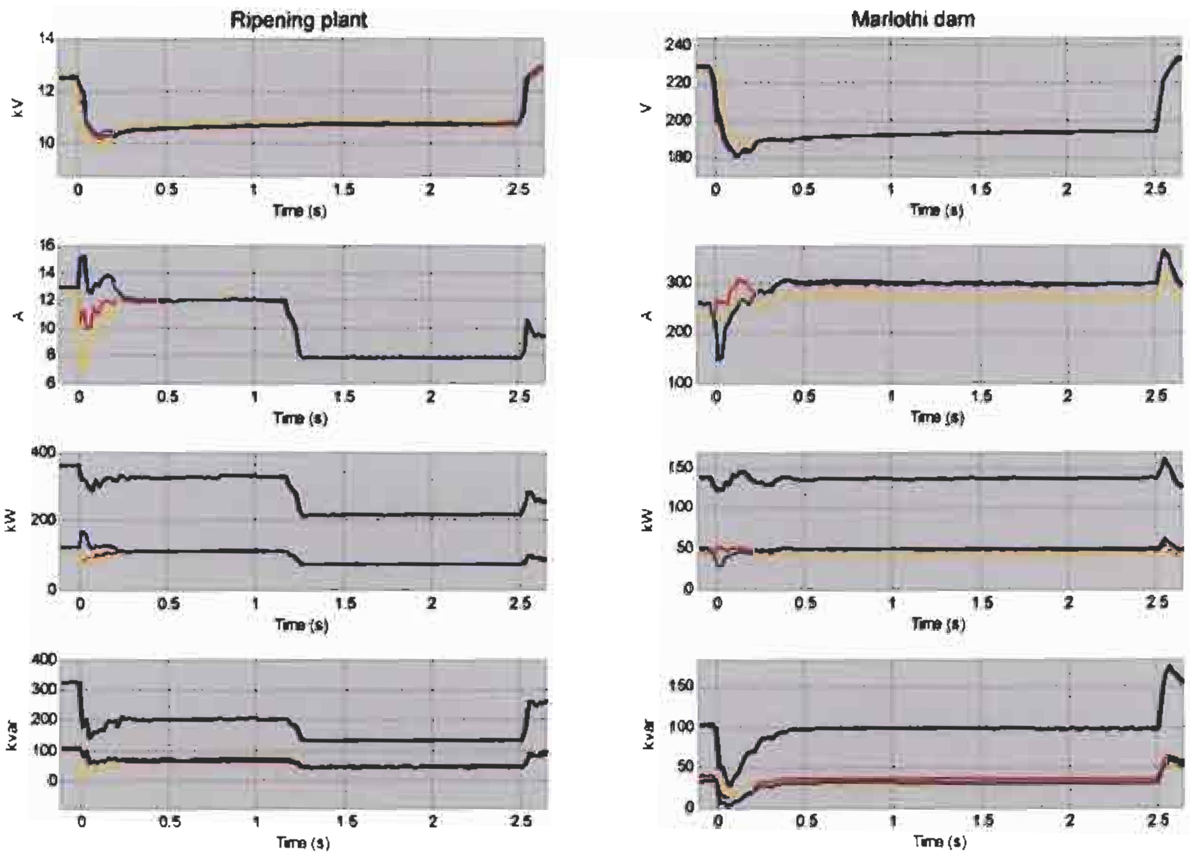


Figure 5.9: Simultaneously measured voltage, current, active and reactive power for dip 6

5.4 SUPPLY INTERUPTIONS

Interruptions in the electrical supply that were recorded by the Impedograph are shown in Table 5.5. Unfortunately the cause cannot be determined because no fault was recorded before the inception of the interruption. Momentary interruptions are classified by the NRS 048 as longer than 3 s and less than 5 min and sustained interruptions as longer than 5 min. When looking at the electrical systems used by the farm, momentary interruptions don't have such a hefty effect on the business when compared to that of other companies. The reason for this is that even though momentary interruptions cause plant shut down, the restart process used by the farm is relatively easy to implement and can get the whole system running again within a short space of time. Where as sustained interruptions cause labour and production losses and decreases product quality due to refrigeration systems shutting down.

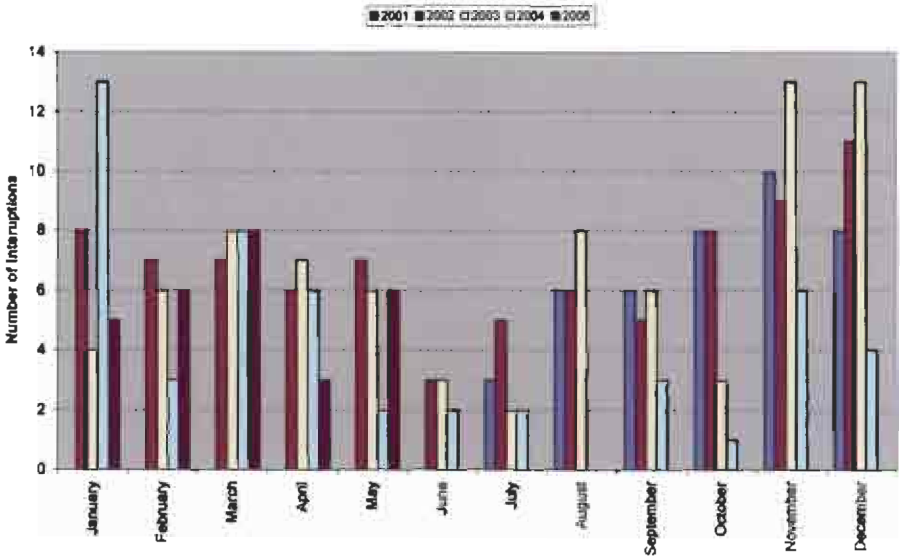
Table 5.5: Recorded voltage supply interruptions

Point	Date	Time	Duration	NRS 048 Classification
Ripening plant	Tue 27 Sep 2005	18:59:21	02:00:52	Sustained interruption
Ripening plant	Tue 27 Sep 2005	21:00:28	00:06:11	Sustained interruption
Ripening plant	Tue 27 Sep 2005	21:45:37	00:02:00	Momentary interruption
Pack house	Tue 21 Mar 2006	00:16:55	00.53.64	Sustained interruption
Marlothi dam	Wed 24 Aug 2005	09:04:15	00:02:48	Momentary interruption
Marlothi dam	Fri 26 Aug 2005	20:27:34	00:01:51	Momentary interruption
Marlothi dam	Tue 27 Sep 2005	18:59:10	02:00:48	Sustained interruption
Marlothi dam	Tue 27 Sep 2005	21:00:16	00:06:10	Sustained interruption
Marlothi dam	Tue 27 Sep 2005	21:45:24	00:01:43	Momentary interruption

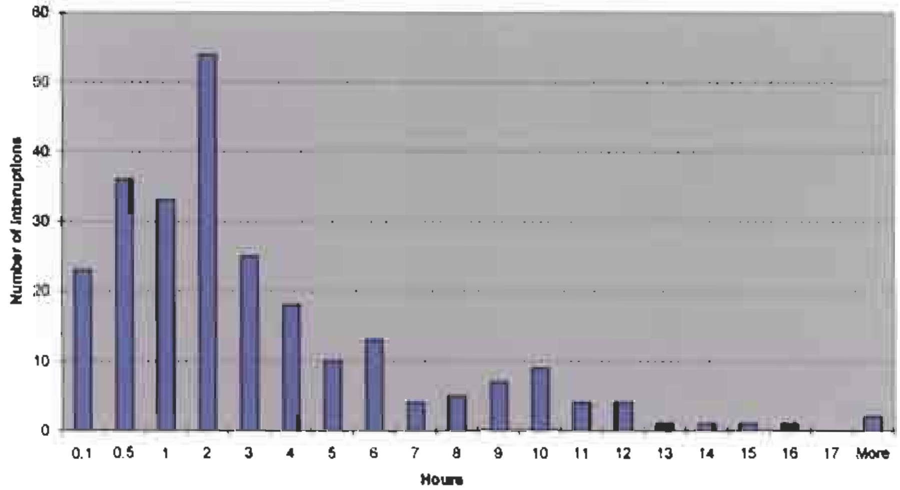
The measured data from the Impedograph shows no incidents/events that could have caused these interruptions. An interesting observation that was made is that it seems that the protection settings at the Koorsboom substation are not working properly. Usually if a fault occurs and the line protection trips the breaker clears the fault, the breaker is then supposed to auto-reclose. If the fault persists the line protection will once again trip the breaker or when the fault is cleared the breaker will remain closed. In this case there is no sign of auto-reclosers because the Impedograph would have recorded multiple interruptions.

Using recorded statistics regarding the power interruptions at the farm over the past five years, a histogram was plotted (Figure 5.10) to indicate the number of interruptions and the duration occurring within the twelve months of each year. When looking at (a), it was concluded that the number of interruptions in each year could be related to seasonal changes, including natural occurrences such as veldt fires, lightning, rain and wind.

Figure 5.9 (b) indicates the frequency of interruption durations of the above recorded incidents as experienced by the banana farm. The graph indicates that the duration of interruptions is quite long and that a large number of interruptions were recorded to be between two to three hours. Any interruptions longer than five minutes have a significant impact on production and product quality.



(a)



(b)

Figure 5.10: (a) Distribution of interruptions and their (b) duration from 2001 to 2005

These incidents also cause refrigeration systems peaking in power consumption in an attempt to bring temperatures under control again, which causes unrealistically high peak demands for which they have to pay excessive charges.

5.5 OTHER POWER QUALITY ASPECTS

Voltage unbalance (UB) arises in a polyphase system when the magnitudes of the phase voltages or the relative phase displacements of the phases (or both) are not equal. Voltage unbalance can be described in terms of the contribution of zero sequence voltages and the contribution of negative sequence voltages.

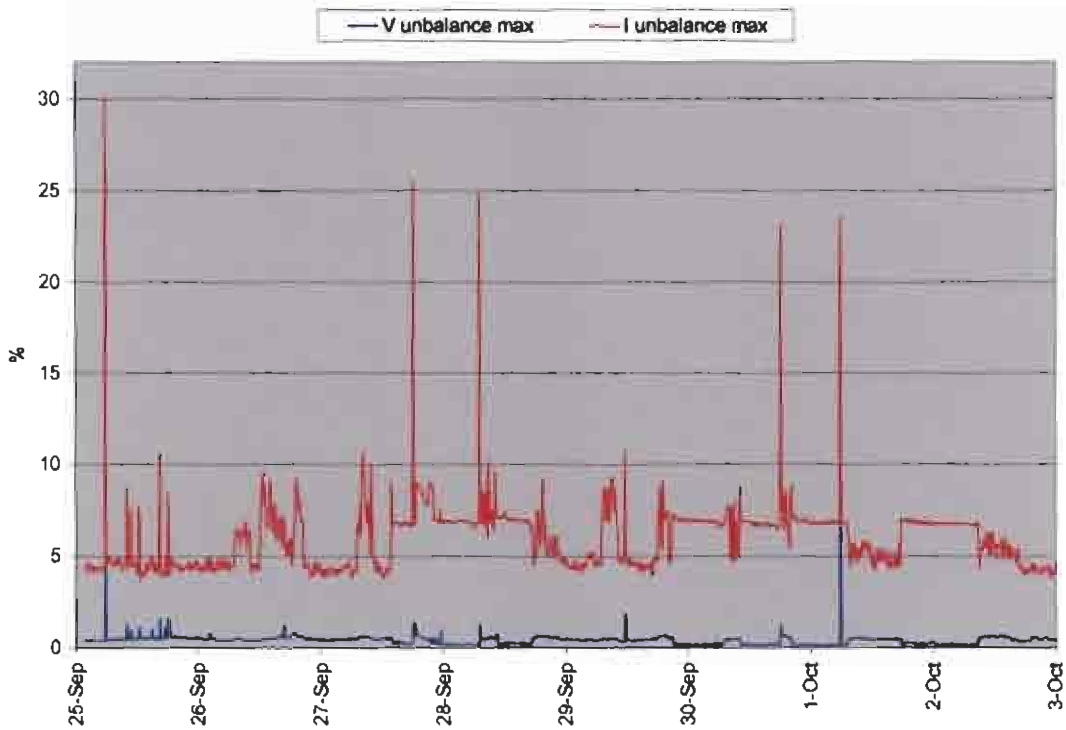


Figure 5.11: Voltage and current unbalance at Marlothi dam pump station

The compatibility level for UB on LV, MV and HV three-phase networks is 2 % and on networks where there is a predominance of single-phase or two-phase customers, a compatibility level of 3 % may be applied.

Figure 5.11, 5.12 and 5.13 shows that there was no significant voltage unbalance at the three measuring points, except for a few instances. The current unbalance however shows a concern. According to the NRS 048 standards, only limitations placed on voltages are taken into account. This has certain advantages because these voltages can be regulated and therefore seems to be more appropriate in specified instances. On the one hand this could however be seen as being problematic, due to the fact that current limitations have a larger effect on electrical appliances than voltages.

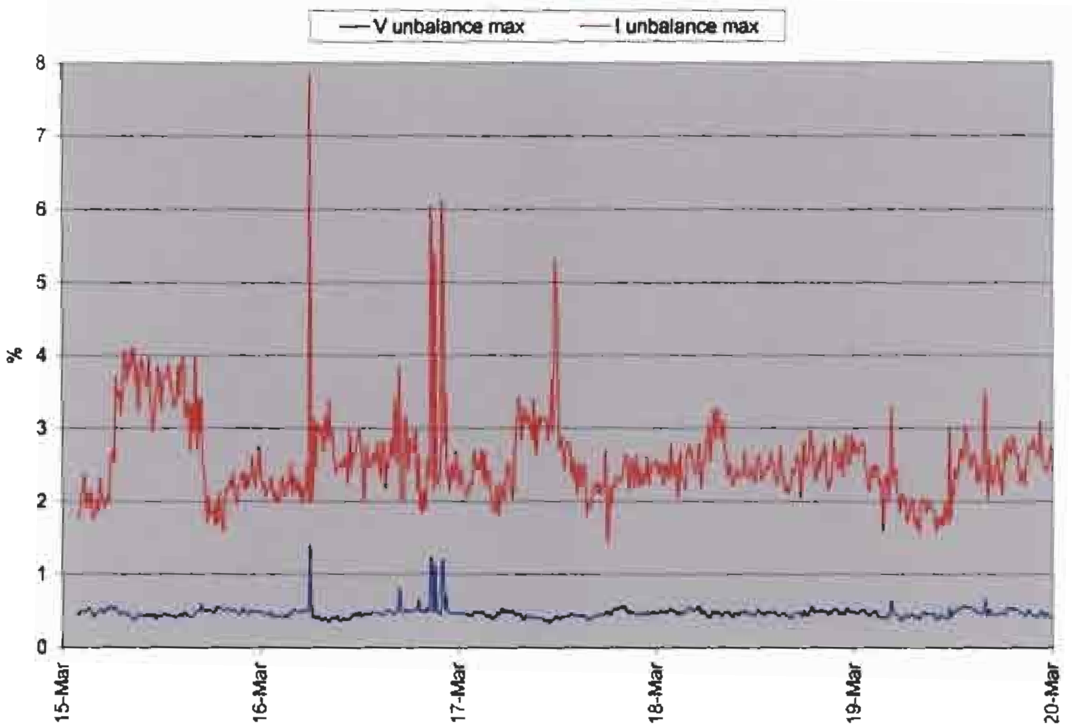


Figure 5.12: Voltage and current unbalance at the Pack house

Unbalance of voltage and current is a common feature in a power system, and can be the result of one or more of the following:

1. A higher neutral current due to unequally distributed single-phase loads.
2. Saturation of power transformers as a result of periodic overloading and load rejections.
3. Increased ripples in the rectifier circuits which causes harmonics.
4. Malfunctioning of some equipment, possibly because of a fault.
5. Oscillating torque in the rotating machines as a result of load variations and harmonics present in the system.
6. Feeding non-linear loads such as:
    - Induction furnaces
    - Arc furnaces and arc welders

- Steel rolling mills
- Large motors with periodic loading
- Many loads which may have to be frequently switched

All such loads generate harmonics and cause variations in the fundamental power frequency of the supply system, which leads to distortion in the sinusoidal waveform of the voltage. This distortion may affect the quality of the supply system (voltage) beyond desirable limits. A non-sinusoidal and distorted supply system may adversely affect the different loads connected to the system, besides leading to outage of the system itself.

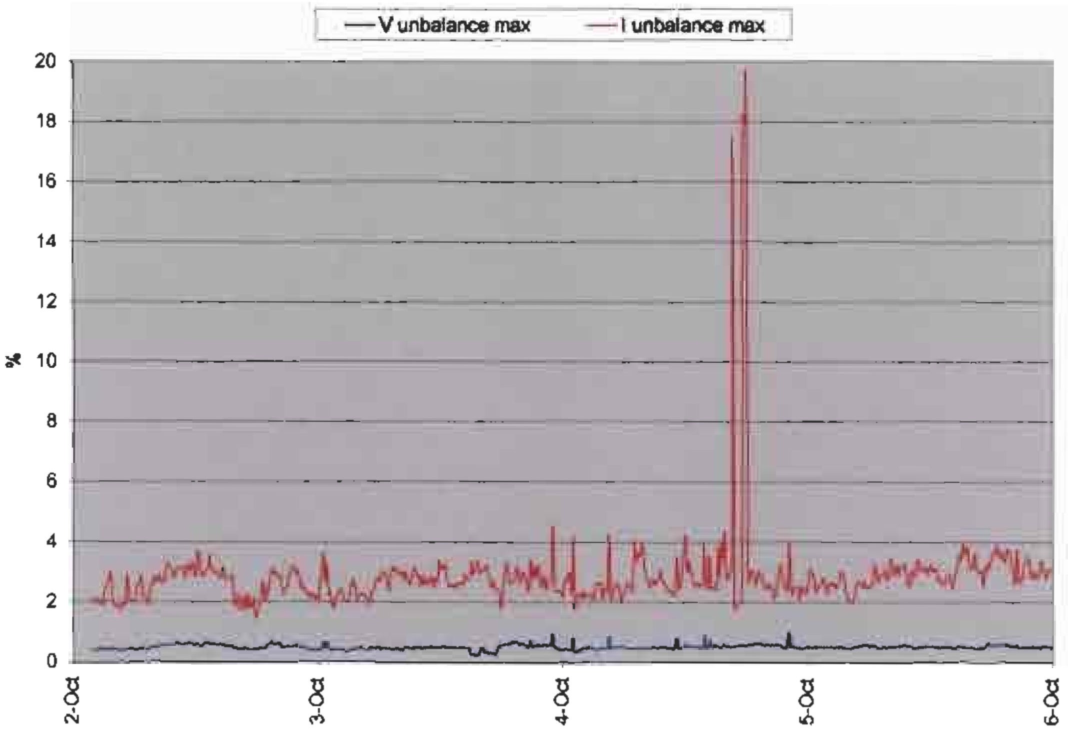


Figure 5.13: Voltage and current unbalance at the Ripening plant

According to the NRS 048 compatibility levels for harmonic voltages the 5th harmonic voltage shall not exceed 5 % of the fundamental voltage. From the measured harmonic data at Marlothi dam this limit is frequently exceeded as shown in figure 5.14.

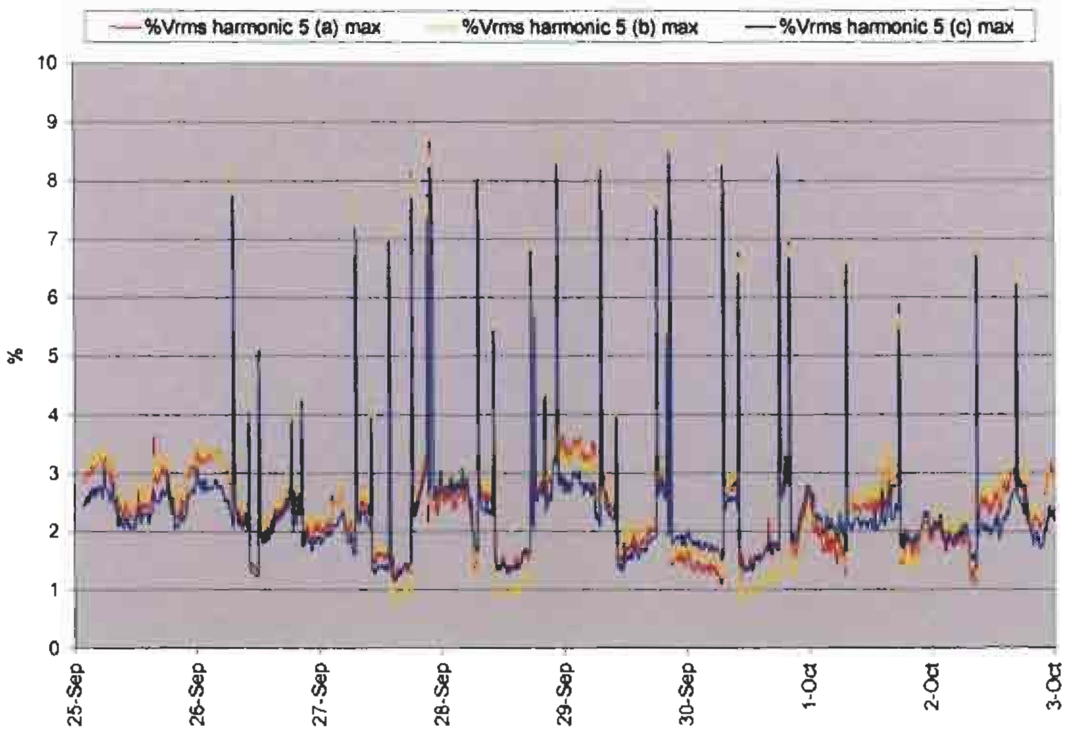


Figure 5.14: The 5th harmonic as a percentage of the fundamental voltage at Marlothi dam pump station

These harmonics could lead to the following problems:

- Poor power factor
- Interference to equipment which is sensitive to voltage waveform
- Excessive heating of neutral conductors
- Excessive heating of induction motors and transformers
- Resonance
- Damage to power factor correction capacitors

At the Ripening plant this is not the case and the 5th harmonic voltages stay well within the limit.

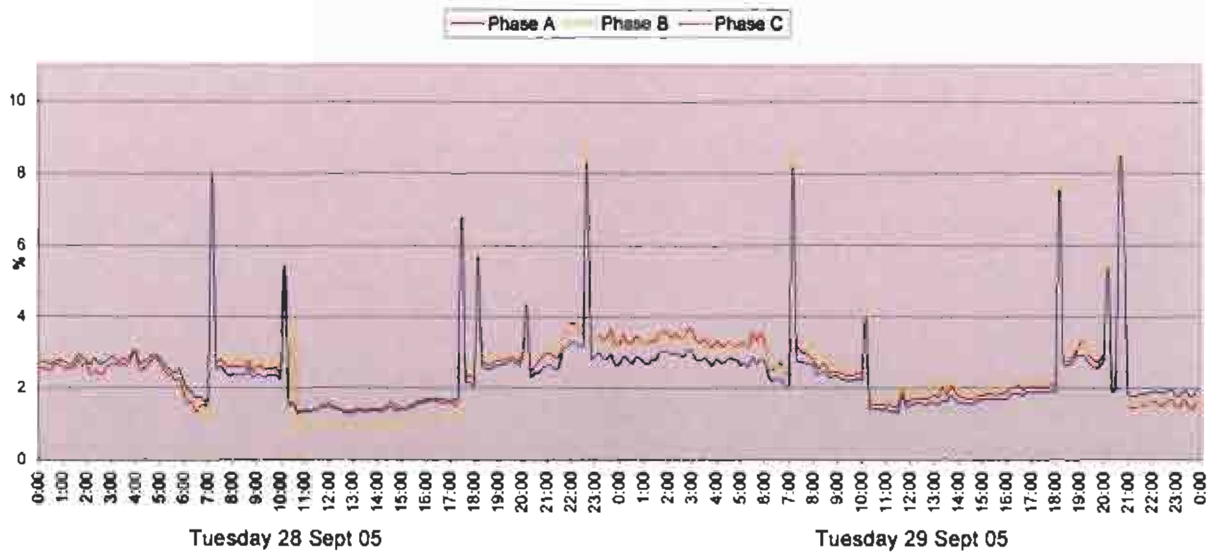


Figure 5.15: The 5th harmonic from 28 – 29 Sept 05

Figure 5.15 shows a more detailed view of the 5th harmonic over 2 days. It shows periodic appearance around 7:00, 10:00, 18:00 and 20:00 for approximately 20 minutes. The duration is not long and therefore the uncertainty arises for the cause. It could be attributed to the start up of the pump station. There is no indication of prolonged 5th harmonics at the pump station that is above the NRS 048 limit.

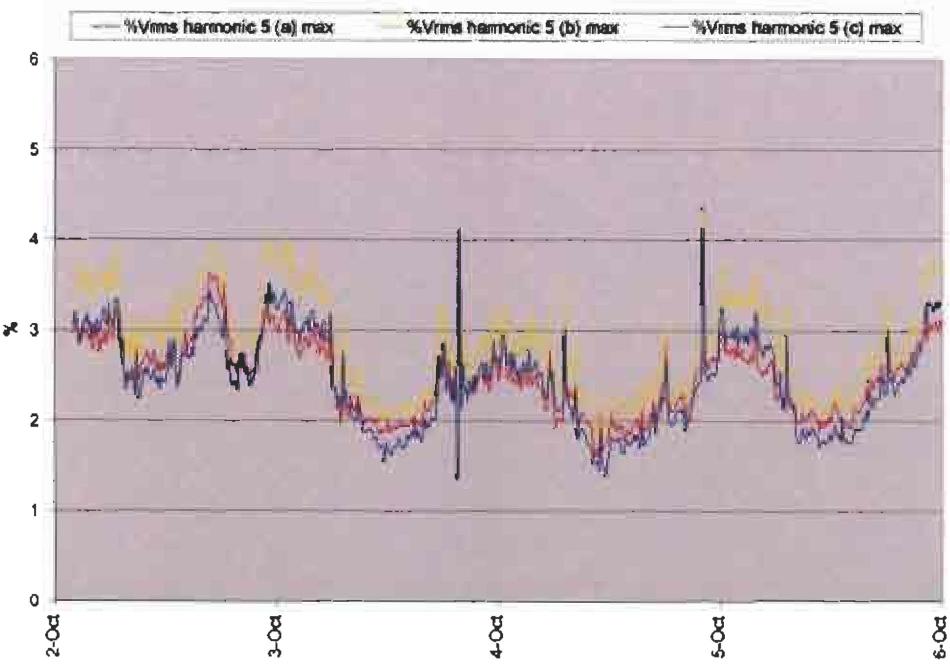


Figure 5.16: The 5th harmonic as a percentage of the fundamental voltage at the ripening plant

The total harmonic voltage distortions (THD_V) for all the sites are also below the NRS 048 limit of 8% and averages around ±3%.

From the above results the conclusion can be made that the banana farm is not severely affected by other power quality aspects such as harmonics and unbalances. However, the measurements taken were over a short period and longer duration measurements would give a much more accurate indication.

5.6 CONCLUSION

From the analysis of the recorded measurements it was clear that the farm was plagued with poor power quality in terms of voltage variations, which includes voltage dips and interruptions caused by network faults.

When comparing the two classification methods the NRS 048 and the symmetrical component algorithm it shows that the NRS 048 does not distinguish between the types of faults and the latter does. This is because the NRS 048 only uses the magnitude of the lowest phase and the longest duration to classify the dip, whether it is single, double or three-phase dips. Whereas the symmetrical component algorithm only distinguish between the type of dips and not their severity.

The results show that all the incidents recorded except for the pump start dips were externally generated by the network. The large number of incidents can be contributed to the poor network condition that was noticed during the site visit.

An algorithm used to determine the dip characteristics was successfully incorporated and the dip type was used to determine the probable cause of the fault. The results of the dip types were compared to the actual waveforms and rms values shows that Table 2.3 in Chapter 2, which was used to determine the propagation of voltage dips across transformers holds true and that a probable cause was determined.

The large number of interruptions that were experienced by the farm was related to the number of dips that were recorded. Meaning that most of the interruptions were caused by similar faults, however its duration and magnitude was more severe, which caused line protection of the substation to clear the fault. From the recorded interruptions it appears that the breakers are not auto-reclosed , which means that if an event causes a line to trip there is no automatic restoring of supply and personnel from the distribution Utility have to manually restore power to the interrupted area.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSION

The purpose of an electrical power system is to deliver energy to its consumers, which has to be done with the utmost reliability and economy. When power outages occurs the normal routine of society is disrupted. All modern industries today rely heavily on good power quality because poor power quality can cause a halt in production and in some cases even lead to a decrease in product quality. Power quality plays an import role in the efficiency and success of a business.

The analysis of the network showed promising results for improving the voltage levels at the distribution points. Seven different network configurations where studied using PSAF. These configurations varied from installing an extra substation transformer to inserting an extra distribution line. The load flow studies showed that the best way of improving the voltage levels at most of the points was to add the extra distribution line. Contrary to this the distribution Utility decided to add an extra transformer. When these two configurations were studied (as shown in Chapter 4) it was shown that the extra transformer has no significant impact on the network voltages.

Impedograph power quality recorders were used to record voltage variations, which include supply interruptions and voltage dips. These recorded voltage dips were analyzed with an algorithm as proposed by Bollen, to determine the dip type and the cause of the dip. It determined the dip type from the positive- and negative sequence components from the measured rms. voltages. From the dip type and table 2.3 in Chapter 2 the probable cause of each incident was determined. The analysis of the voltage dips showed that a large number of these incidents were caused by swinging conductors, falling trees, loose transformer connections, etc. This indicates to a poor network condition and bad maintenance.

From the results of Chapter 4 and 5 the best solution for improving the power quality on the banana farm, in terms of voltage profiles, power flow distribution, reduction of voltage dips and interruptions was to add an extra 22 kV distribution line. Not only will this help to increase voltage profiles, but it would reduce the number of voltage dips and interruptions experienced by the farm, which will lead them benefiting from these upgrades to the network.

6.2 FUTURE WORK

Although a large data set was available, not much information was known regarding the type of captured events, their location or the response of the protection system. More knowledge about the measurements would allow better understanding of the phenomena and extraction of more information.

It would be a good to incorporate knowledge of the operation characteristics of the system that is monitored (protection system, voltage control methods, and load characteristics) into the knowledge base for classification and the analysis of power system events.

It is difficult and sometimes very time consuming to try and pin point where a fault in the network originates. Therefore, it would be advised to develop an algorithm in the future that could be implemented to determine the location (distance from measuring point) and cause of the fault.

The dip classification method can have several implications for a variety of power quality standards as it is quite proficient in presenting voltage dip measurements for power quality surveys. This depiction can assist in further development of standards for monitoring voltage dips and for the exchange of important information between utilities, clients, and equipment manufacturers. Three-phase equipment immunity tests against voltage dips is another application of the dip classification, where it becomes essential to understand the magnitude and phase-angle shift relation of the unbalanced voltage dips. When equipment immunity test procedures are developed, the test range of characteristic voltage, PN-factor and zero-sequence need to be further explored with consideration to statistics taken from various field measurements.

REFFERENCES

[1] L.D. Zhang, M.H.J. Bollen, "Characteristic of voltage dips (sags) in power systems", *IEEE Transactions on Power Delivery*, vol. 15, no. 2, pp. 827-832, April 2000.

[2] M.H.J. Bollen, "Algorithms for characterizing measured three phase unbalanced voltage dips", *IEEE Transactions on Power Delivery*, vol.18, no.3, pp. 937-944, July 2003.

[3] M.H.J. Bollen, P. Goossens, A. Robert, "Assessment of voltage dips in HV-networks: deduction of complex voltages from the measured rms voltages", *IEEE Transactions on Power Delivery*, vol. 19, no. 2, pp. 783-790, April 2004.

[4] M.H.J. Bollen, E. Styvaktakis, "Signatures of voltage dips: transformer saturation and multistage dips," *IEEE Transactions on Power Delivery*, vol. 18, no. 1, pp. 265-270, January 2003.

[5] M.H.J. Bollen, "Characterisation of voltage sags experienced by three-phase adjustable-speed drives", *IEEE Transactions on Power Delivery*, vol. 12, no. 4, pp. 1666-1671, October 1997.

[6] Myo Thu Aung, J.V. Milanovic, "The influence of transformer winding connections on the propagation of voltage sags", IEEE Transactions on Power Delivery, vol. 21, no. 1, pp. 262-269, January 2006.

[7] M.H.J. Bollen, L.D. Zang, "Different methods for classification of three-phase unbalanced voltage dips due to faults", Chalmers University of technology, Göteborg, Sweden, 2003.

[8] ANON, Chapter 5: Voltage sag analysis, Unknown (Included on CD)

[9] R.C. Leborgne, "Voltage sags characterization and estimation", Chalmers University of technology, Göteborg, Sweden, 2005, [Online]. Available: http://www.elteknik.chalmers.se/Publikationer/newpub/theses/robertoLic.pdf

[10] M.H.J. Bollen, L.D. Zhang, "A method for characterization of three-phase unbalanced dips from recorded voltage wave shapes", Chalmers University of technology, Göteborg, Sweden, [Online]. Available:

http://grouper.ieee.org/groups/sag/IEEEP1564_00_08.doc

[11] M.H.J. Bollen, E. Styvaktakis, "Characterization of three-phase unbalanced dips (as easy as one-two-three?)", *9th International IEEE Conference on Harmonics and Quality of Power*, Orlando, Florida USA, vol. 1, pp. 81-86, October 1-4, 2000.

[12] Prepared by experts from Eskom Holdings Ltd and the Endangered Wildlife Trust under the direction of Thavanthiran Pillay and Sanjeev Bisnath, "The Fundamentals and Practice of Overhead Line Maintenance", Crown Publications, March 2004.

[13] NRS 048-2: 2003, "Voltage characteristics, compatibility levels, limits and assessment methods", 2nd edition.

[14] R.C. Leborgne, G. Olguin, M.H.J. Bollen, "The influence of PQ-monitor connection on voltage dip measurements", Chalmers University of technology, Göteborg, Sweden, [Online]. Available:

http://www.elteknik.chalmers.se/Publikationer/EKS.publ/Abstract/2004/LeborgneOlguinBollenMedPower.PDF

[15] M. Didden, "Techno-economic analysis of methods to reduce damage due to voltage dips", Katholieke Universiteit Leuven, Faculteit Toegepaste Wetenschappen, Leuven, December 2003.

[16] J.A. de Kock, "The effects of voltage dips on induction motors", Elektron, June 1993, pp. 23-26.

[17] G. G. Karady, S. Saksena, B. Shi, N. Senroy, "Effects of Voltage Sags on Loads in a Distribution System", Power Systems Engineering Research Centre, Cornell University, PSERC Publication, October 2005.

[18] Banana farm claim documents (included on CD).

[19] W. van Wyk, CTLab, Impedograph power quality recorder software.

http://www.ctlab.com

[20] IEC 61000-4-30