# A RELIABILITY MODEL OF A POWER DISTRIBUTION NETWORK WITH REFERENCE TO PETROCHEMICAL AND GAS-TO-LIQUID PLANTS

by

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# SUMMARY

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| Keywords: | Failure rate, mean time to repair, inherent availability, cost of loss of production, capital cost, total cost of ownership, reliability index, network topology |

## ABSTRACT

The interruption cost for one hour of a petrochemical plant is 33 times higher than that of the average interruption cost for industrial plants across all industries. In addition to the high cost of loss of production, interruptions to the operations of petrochemical and gas-to-liquid plants pose safety and environmental hazards. Thus it is necessary to better understand the reliability requirements of petrochemical and gas-to-liquid plants.

This study investigated the reliability of electrical distribution networks used in petrochemical and gas-to-liquid plants compared to those used in other industrial plants. A model was developed that can be used to establish the adequacy of the reliability of a distribution network in terms of the components and network topologies used. This model was validated against data that had been collected by the IEEE and applied to an actual petrochemical plant.

Over 19 years' worth of data regarding the trips that have occurred on the distribution network of an existing petrochemical plant was collected and manipulated in order to calculate the reliability indices associated with the equipment used to make up this distribution network. These reliability indices were compared to those given by the IEEE

Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems.

The cost of loss of production and the capital costs associated with increased reliability were calculated for a section of the existing petrochemical plant. The reliability associated with different network topologies that could possibly be used to supply power to this section of the plant were modelled using an appropriate software package. The resulting total cost of ownership over the life of the plant associated with each topology was then calculated in order to establish which network topology is the most appropriate for petrochemical and gas-to-liquid plants.

It was concluded the components that affect the reliability of an industrial distribution network are different to those that affect a utility distribution network. These components were listed and compared. It was found that the reliability indices that were calculated for the components that affect the reliability of a petrochemical plant were similar to those provided by the IEEE. 17 out of 20 of the indices that were calculated were within the required factor of deviation. Generally the failure rates of components used in petrochemical plants were very similar to those given in the IEEE Gold Book, while the MTTR’s for the components used in petrochemical plants were found to be slightly better than those given in the IEEE Gold Book.

The effect of network topology was found to be significant, with small changes in the topology of a network resulting in large variations in the reliability of the network. It was also found that the most appropriate type of network topology to use in the design of the electrical distribution network of a petrochemical plant is the dual radial network. This is the most conservative of the commonly used network topologies and is the one that is currently used in the existing plant that was studied.

Due to the high cost of loss of production in petrochemical plants it was established that any incremental improvement in the reliability of the dual radial network would be beneficial to the total cost of ownership of such a plant. Such incremental improvement of the reliability of the distribution network could be cost effectively achieved by adopting a conservative maintenance strategy and the establishment of a conservative spares inventory.

Before this study was undertaken, there was no literature around the reliability of electrical distribution networks that focused specifically on petrochemical and gas-to-liquid plants. This study produced a set of reliability indices and a model that electrical engineers can use in the reliability analysis of petrochemical and gas-to-liquid plants. Furthermore it shows that, because the cost of loss of production in petrochemical plants is so high, the most conservative distribution network design and maintenance philosophies should always be used.

# OPSOMMING

## ‘N BETROUBAARHEIDSMODEL VAN ‘N ELEKTRIESE VERSPREIDINGSNETWERK MET VERWYSING NA PETROCHEMIESE EN GAS-TOT-VLOEISTOF-AANLEGTE

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| Graad: | Magister in Ingenieurswese (ElektrieseIngenieurswese) |
| Sleutelwoorde: | Falingskoers, gemiddeldehersteltyd, inherentebeskibaarheid, koste van produksieverliese, kapitalekoste, totalekoste van eienaarskap, betroubaarheidsindeks, netwerktopologie |

## OPSOMMING

Die koste van ’n onderbreking van een uur by ’n petrochemieseaanleg is 33 keer hoër as die gemiddelde onderbrekingskoste by nywerheidsaanlegte in alle nywerhede. Bykomend tot die hoë koste van produksie verliese, veroorsaak onderbrekings in die werksaamhede van petrochemiese en gas-tot-vloeistof-aanlegte veiligheids- en omgewings gevare. Gevolglik is dit nodig om die betroubaarheidsvereistes van petrochemiese en gas-tot-vloeistof-aanlegte beter te verstaan.

Hierdie studie het die betroubaarheid ondersoek van elektriese verspreidingsnetwerke wat in petrochemiese en gas-tot-vloeistof-aanlegte gebruik word, in vergelyking met dié wat in ander nywerheidsaanlegte gebruik word. ’n Model is ontwikkel wat gebruik kan word om die toereikendheid van die betroubaarheid van ’n verspreidingsnetwerk te bepaal met betrekking tot die komponente en netwerktopologieë wat gebruik word. Hierdie model is getoets teen data wat deur die IEEE versamel is en dit is op ’n werklike petrochemiese aanleg toegepas.

Meer as 19 jaar se data oor die klinke wat plaasgevind het in die verspreidingsnetwerk van ’n bestaande petrochemiese aanleg is versamel en gemanipuleer om die

betroubaarheidsindekse te bereken wat verband hou met die toerusting waaruit hierdie verspreidingsnetwerk bestaan. Hierdie betroubaarheidsindekse is vergelyk met dié wat verskaf word deur die IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems.

Die koste van produksieverlies en die kapitale koste wat verband hou met verhoogde betroubaarheid is bereken vir ’n gedeelte van die bestaande petrochemieseaanleg. Die betroubaarheid wat in verband gebring word met verskillende netwerktopologieë wat moontlik gebruik kan word om krag te voorsien aan hierdie gedeelte van die aanleg is gemodelleer deur ’n geskikte sagtewarepakket te gebruik. Die gevolglike totale koste van eienaarskap oor die leeftyd van die aanleg wat met elke topologie geassosieer word, is daarna bereken om te bepaal watter netwerktopologie die mees geskikte topologie vir petrochemiese en gas-tot-vloeistof-aanlegte is.

Daar is bevind dat die betroubaarheidsindekse wat vir die petrochemieseaanleg bereken is, soortgelyk was aan dié wat deur die IEEE verskaf is. Daar is ook bevind dat die beste sort networktopologie om in die ontwerp van ’n elektrisiteitsverspreidingsnetwerk te gebruik, die tweeledigeradialenetwerk (dual radial network) is. Dit is die mees konserwatiewe van die algemeen gebruikte netwerktopologieë en is die topologie wat tans gebruik word in die bestaande aanleg wat ondersoek is.

Voordat hierdie studie onderneem is, was daar geen literatuur beskik baar oor die betroubaarheid van elektrisiteitsverspreidingsnetwerke wat spesifiek gefokus het op petrochemiese en gas-tot-vloeistof-aanlegte nie. Hierdie studie het ’n stel betroubaarheidsindekse opgelewer, asook ’n model wat elektrieseingenieurs kan gebruik in die betroubaarheidsanalise van petrochemiese en gas-tot-vloeistof-aanlegte. Verder toon dit ook aan dat, omdat die koste van produksieverliese in petrochemieseaanlegte so hoog is, die mees konserwatiewe netwerkontwerp- en –instandhoudingsfilosofieë deurgaans toegepas moet word.

## LIST OF ABBREVIATIONS

| | |
|---|---|
| A | ampere |
| Ai | inherent availability |
| BTU | battery-tripping unit |
| Btu | British thermal unit |
| ºC | degrees Celsius |
| CIGRE | International Council on Large Electric Systems |
| CT | current transformer |
| H | Henrys |
| hr | hour (hrs = hours) |
| IEEE | Institute of Electrical and Electronic Engineers |
| kJ | kilojoules |
| kl | kiloliter |
| kV | kilovolts |
| kW | kilowatts |
| kWh | kilowatt hours |
| m | meter |
| MTBF | mean time between failure |
| MTTF | mean time to failure |
| MTTR | mean time to repair |
| MV | medium voltage |
| MW | megawatts |
| NECR | neutral earthing compensator/resistor |
| PV | present value |
| PILC | paper-insulated lead-covered |
| PVC | polyvinylchloride |
| Rdt | repair downtime |
| s | seconds |
| $SF_6$ | sulphur hexafluoride gas |
| SWA | steel wire armour |
| V | volt |
| XLPE | cross-linked polyethylene |
| ZAR | South African Rand |
| $\lambda$ | Failure rate |
| $\mu$ | rate of repair |

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# 1 INTRODUCTION

## 1.1 BACKGROUND AND MOTIVATION

The reliability of the power distribution network of an industrial plant has a direct impact on the profitability, safety and overall operation of that plant. Reliability is often discussed in terms of cost: the cost of loss in production and damage that will result from a lack of reliability versus the cost of improved reliability. It is impossible to build a plant that has a zero percent chance of failure. The closer one approaches zero percent, the greater the capital required. The challenge of reliability studies is to find the point at which the cost of the improved reliability of a plant added to the potential cost of failure is at a minimum. This is shown in Figure 1.1.

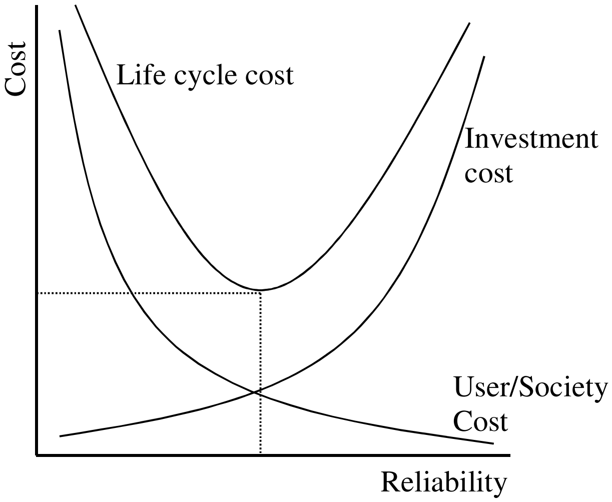

Figure 1.1 Cost of reliability and cost of failure [1]

Table 1.1 One-hour interruption costs for industrial consumers [2]

| **Industry** | **$/kW$_{peak}$** |
|---|---:|
| Logging | 2.11 |
| Mining | 3.00 |
| Crude petroleum | 276.01 |
| Quarry and sand | 5.33 |
| Services to mining | 2.13 |
| Food industries | 20.46 |
| Beverage industries | 1.55 |
| Rubber products | 1.80 |
| Plastic products | 2.91 |
| Leather products | 1.37 |
| Primary textiles | 17.29 |
| Textile products | 8.93 |
| Clothing | 8.68 |
| Wood industries | 2.93 |
| Furniture | 23.20 |
| Paper products | 7.52 |
| Printing and publishing | 6.01 |
| Primary metal | 3.54 |
| Fabricated metal | 8.41 |
| Machinery | 7.70 |
| Transportation | 42.96 |
| Electrical products | 8.78 |
| Non-metal minerals | 9.59 |
| Chemical products | 4.65 |
| Other manufacturing | 15.31 |
| **Average industrial** | **8.40** |

The cost of loss of production is significant to the profitability of a petrochemical plant. Table 1.1 shows the one-hour interruption costs for plants in various industries [2]. These values are based on a University of Saskatchewan survey and are presented in 2001 dollars. The interruption cost for one hour of a crude petroleum plant in 2001 is given as \$276.01 per kW. The interruption cost of industrial plants is \$8.40 per kW on average. Thus the cost of loss of production is almost 33 times higher in petrochemical plants as compared to the average industrial plant. Furthermore, it is 6.5 times higher than the next highest industry, namely transportation.

In petrochemical plants reliability is important in terms of cost and safety. This is due to the hazardous environment that is created by the petrochemical processes. Sudden loss of power can result in explosions or the escape of noxious gasses. Often, it is not the loss of power that causes the problem, but the uncontrolled start-up of a plant when the power is restored. At the very least, a loss in power to a small section of a plant leads to the flaring off of substandard product. This results in the gross emission of carbon dioxide and air pollutants.

It is this potentially dangerous aspect of petrochemical plants that highlights the importance of reliability. This leads to large sums of money that are spent on reliability. It is important to gain a better understanding of the levels of reliability required at petrochemical plants, and how to achieve them.

The goal of this study is to investigate the reliability of electrical distribution networks used in petrochemical and gas-to-liquid plants compared to those used in other industrial plants and to develop a model that can be used to establish the adequacy of the reliability of a distribution network in terms of the components and network topologies used.

## 1.2 OVERVIEW OF CURRENT LITERATURE

### 1.2.1 Reliability in engineering

There is a vast body of knowledge on reliability in engineering and the reliability of electrical systems. Many textbooks have been written on the subject. Mathematical tools and techniques are provided to perform reliability analyses. The most notable and widely referenced are the eight textbooks authored by Roy Billinton [1].

Most academic papers written on the subject of the reliability of electrical systems present new methods for calculating outage costs [3], calculating the risk of outages [4], different methods of performing reliability analysis [5 & 6], and suggestions on how to improve the reliability of electrical systems during their design [7].

### 1.2.2 Reliability of utility distribution networks

Significantly more work has been done on the reliability of utility distribution networks than on industrial distribution networks. Many of the principles that apply to utility distribution networks can be applied to industrial networks – but not all. For this reason, it is worthwhile to study the literature on the reliability analysis of utility distribution networks before analysing the literature on industrial distribution networks.

Again, different mathematical methods of performing reliability analyses are presented in the available literature. Examples of these methods include the use of fuzzy logic [8] and Monte Carlo simulation [9]. Another topic that has been regularly discussed in recent years is the effect of the changing economic models of utilities on the reliability of their networks [10]. [11] Presents reliability data of electrical equipment used by utility distribution networks.

### 1.2.3 Reliability of industrial power distribution networks

An important consideration when studying the reliability of industrial power distribution networks is the reliability of the utility supply to the industrial plant. If an industrial plant fails due to an outage from the utility, the plant incurs the associated costs. An industrial plant has some level of control over the reliability of the supply it obtains from the utility. The reliability depends on how much one is willing to spend. In [12] and [13] typical literature is presented on the reliability of different utility supply configurations to industrial plants. Data on power interruption costs are also presented.

The majority of literature is not published in popular journals and is not very often cited. Topics that are typically covered include the impact of cogeneration on reliability [14 &

15], methods for analysing industrial distribution network reliability [16] and power quality [17] (of which reliability is a characteristic).

The most comprehensive text available on the subject of the reliability of industrial power networks is the IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems [17], commonly referred to as the IEEE Gold Book. According to the authors, "it is a self-contained body of knowledge in which reliability analyses can be performed on industrial and commercial systems without requiring cross-references to other texts". It contains guidelines for analysing the reliability of industrial power systems and it provides reliability data on equipment commonly used in industrial power networks.

In a comprehensive literature survey using searching tools such as SCOPUS, IEEE Explore and Google Scholar no paper was found that dealt with the reliability analysis of the electrical distribution network of a petrochemical plant.

## 1.3 LITERATURE TO BE INCORPORATED INTO THIS STUDY

[11] presents a summary of the Canadian Electrical Association's Equipment Reliability Information System. This includes statistics on the forced outage performance characteristics of transmission equipment (i.e. transformers, circuit breakers, cables, etc.). It also discusses the primary causes of major equipment forced outages – whether the outages were mainly due to subcomponents of the major equipment or the terminal equipment. While the statistical information itself is not useful to this study, the way that it is sorted and presented is. Once the reliability indices for equipment in the petrochemical industry are calculated, they are sorted and presented in a way that is similar to that which is done in [11].

[12] describes a basic radial power distribution as the sole power source for an industrial plant. This is the simplest scheme and is used as a basis for exploring alternative configurations, showing increased reliability, while expanding the complexity of the design thus needed. Other schemes looked at are a radial system with cogeneration, a radial

system with two utility sources and a radial system with two utility sources and cogeneration. The method used in this paper of comparing different topologies with one another and analysing their reliability used is used in this study.

[13] summarizes the results of a survey of 210 large commercial and industrial customers to obtain detailed descriptions of the components of interruption costs they would experience under varying outage conditions. The paper discusses the items that should be taken into consideration when calculating the cost of loss of production and these are built upon in this study.

[17], the IEEE Gold book is an IEEE standard sponsored by the Power Systems Reliability Subcommittee of the Power Systems Engineering Committee of the IEEE Industry Applications Society. It lists reliability indices for electrical equipment that are have been calculated for industrial plants and discusses some common network topologies. The reliability indices given in the IEEE Gold Book are compared to those calculated in this study to assess the reasonableness of the calculated values and the network topologies described in the IEEE gold book are used to establish which is the most suitable network topology to be used in a petrochemical plant.

## 1.4 RESEARCH QUESTIONS AND OBJECTIVES

The objective of this study was to establish a model for determining the reliability of petrochemical plants. Validation of the model was done by comparing it to IEEE data. This was achieved by answering the following questions:

- What are the major reliability components that make up the electrical distribution network of a petrochemical plant? (Chapter 3)
- What are the reliability indices (failure rates [$\lambda$] and mean time to repair [MTTR]) for the electrical equipment used to make up the distribution networks in petrochemical and gas-to-liquid plants? (Chapter 4)
- How do the reliability indices that are calculated for petrochemical plants compare with the indices given by the IEEE Gold Book? (Chapter 5)
- What is the impact of network topology on the reliability of petrochemical plants? (Chapter 6)

- What are the optimal distribution network topologies that should be used in petrochemical and gas-to-liquid plants? (Chapter 6)
- What are the optimal levels of reliability for petrochemical and gas-to-liquid plants? (Chapter 6)
- Are there cheaper ways of achieving high levels of reliability in petrochemical and gas-to-liquid plants? (Chapter 6)

## 1.5 RESEARCH DESIGN

This study is quantitative in nature, relying on statistical modelling and computer simulations. The design classification of the study is as follows:

- Empirical – useful data is collected from a large body of existing data and used in a computer simulation and financial analysis
- Hybrid data – some of the data that is used is primary data (i.e. the capital cost associated with constructing distribution networks was determined specifically for this study) and some of the data is secondary data (i.e. the cost of loss of production that is associated with a particular trip was recorded by the plant maintenance personnel as part of their performance management system).
- Numeric data – the data is numeric as opposed to text.
- Medium control – no control can be exercised on the data that already exists, but the data that is selected is controlled and control is exercised over the new data that is created.

The strength of this method is the ability to model a large system and simplify the components (and relationships between the components) in order to analyse the system within a reasonable amount of accuracy.

The weakness of this method is the possibility of insufficient and poor quality of data. If the quality of the data is poor, the results of the study may not be valuable. In order to mitigate this risk, the data that was collected was compared with reliable IEEE data [18] in order to establish the credibility of the collected data.

## 1.6 RESEARCH METHODOLOGY

### 1.6.1 Data collection

The maintenance engineers of the power distribution department at Sasol in Secunda are disciplined in recording all the trips that have occurred in their area of responsibility since Sasol II started operating in 1978. This includes the 132kV supply to the factory from the utility (Eskom), the substations and transformers that convert the power to 33kV, the 33kV distribution network, the 11kV generators that generate half of the factory's required power from steam, and the 11kV critical power distribution network. They are also responsible for an 11kV non-process power distribution network that supplies power to offices and workshop facilities around the factory through ring main units and miniature substations.

Records are available detailing every trip that has occurred and the circumstances that have led to a particular trip. When a trip occurs, the engineer on duty is required to investigate the cause of the trip and record as much information as possible onto a trip report form. This form details information such as the date and time of the trip, the location of the trip, the origin of the trip, the exact cause of the trip, and the downtime associated with the trip. An example of such a form is provided in ADDENDUM C.

The relevant data on the trip report forms was recorded on a spread sheet. The fields that were captured on the spread sheet were as follows:

- Trip number
- Date
- Voltage [kV]
- Substation
- Breaker
- Feed to
- Downtime [hrs]
- Production loss
- Detail of loss
- Fault origin

- Exact cause of trip

Although the data that was available for capture dates back to the early 1980s, the power distribution department had initially operated as two separate departments: one operating in the eastern factory and the other operating in the western factory, with only one of the two departments collecting trip data. The two departments merged in the late 1980s. The newly formed department continued to collect data for the whole factory. When calculating the reliability indices of different types of equipment it is necessary to know all the failures that have occurred for a type of equipment as well as the total number of units of a particular type of equipment that are in operation in the plant where the investigation is taking place. Since there was no trip data for half of the plant prior to the merging of the power distribution departments, only the trip data that was recorded after the merge has been used for this study.

ADDENDUM D is an extract from the trip spread sheet that shows a couple of the more recent trip events and the associated data.

In total, 546 trip events have been captured. The first trip occurred in 1989 and the latest in 2008. The purpose of this study was to investigate the reliability of distribution networks in petrochemical plants, and because the 11kV network distributes power only to offices and workshops, all trips on the 11kV distribution network have been removed from the list. It is worth noting that no trip on the 11kV network has resulted in a production loss. This reduced the total number of trip events to 410. Two process distribution networks were considered, namely the critical power distribution network and the normal power distribution network.

Once the trip data was captured electronically, it was sorted and used to produce statistical values such as failure rates (per year), and actual hours of downtime per failure for different equipment. The IEEE Gold Book [18] contains reliability data collected from reliability surveys and a data-collection program over a period of 35 years. The Sasol data was validated against the IEEE Gold Book. It was expected that the Sasol data might err on the side of better performing equipment since Sasol has a reputation for conservative plant design and maintenance philosophies. If the Sasol data proved to be credible it could be used in future reliability analysis. If the Sasol data could not be validated against the IEEE Gold Book data, the primary objective of the study would not have been achieved. IEEE Gold Book data would have to be used to carry out the second component of the study, i.e. to determine the most suitable distribution network topology to be used in petrochemical plants.

By reviewing the data that had been captured regarding the cost of loss of production associated with particular trips, a section of plant was identified on which the model could be applied. The costs of loss of production for this particular section of plant were established and this data was used in the cost/benefit analysis.

The costs involved in purchasing various items of equipment associated with increased reliability were obtained by requesting quotes from the vendors of the respective equipment and repair services. These costs were used in the cost/benefit analysis.

### 1.6.2 Reliability analyses

A section of the current distribution network of Sasol Secunda was modelled in an electrical simulation software package called PALADIN DESIGNBASE 2.0. The reliability was entered for the various items of electrical equipment. The reliability of the electrical supply to a particular plant was established. Alternative distribution network topologies were then modelled and analysed. The IEEE Gold Book presents examples of common distribution network topologies. These examples were used as guidelines but not strictly adhered to. Five topologies were analysed.

### 1.6.3 Cost/benefit analysis

A cost/benefit analysis was carried out for each of the network topologies. Using information from the reliability analyses, the money that would be spent per year on loss of production was calculated for each topology. The amount of money that would be spent to achieve the reliability of each topology was calculated. The capital and annual costs of each topology were added together for a period of 50 years at an interest rate of 10% compounded interest annually. The topologies were ranked according to their present values (PV).The topology with the lowest PV was considered to be the most economically viable.

A period of fifty years was considered to be a reasonable period to use as the life of a petrochemical factory. The Sasol Secunda Factory had been in operation for over 30 years at the time of this study. The factory is expected to be in operation for at least a further 20 years.

## 1.7 CONTRIBUTION

This study establishes reliability indices (failure rates [λ] and mean time to repair [MTTR]) for the electrical equipment used to make up the distribution networks in petrochemical and gas-to-liquid plants. Prior to the execution of this study, the most authoritative reliability indices that were available were those that can be found in the IEEE Gold Book. These indices were established by using data from a very wide variety of industrial and commercial sites, and are not specifically applicable to petrochemical and gas-to-liquid plants – the types of plants that have the highest cost of loss of production in the world.

In this study, the optimal distribution network topology design that should be used in petrochemical and gas-to-liquid plants was considered. This was done by calculating the total cost of ownership of different distribution network topologies. In the design of distribution networks for new oil and gas plants, engineers either do not have enough operational data, enough time or do not know how to perform the analysis required for establishing what type of network topology to use. This study recommends the optimal network topology to use in such cases and provides evidence to support this proposal.

In summary, this study led to an improved understanding of the levels of reliability required at petrochemical and gas-to-liquid plants. It further established how to economically achieve those levels.

# 2 RELIABILITY MODELLING OF DISTRIBUTION NETWORKS

Reliability is the probability of a device or system performing its purpose adequately for the period of time intended, under the operating conditions encountered [1].

## 2.1 TYPES OF SYSTEMS

There are two types of systems: mission-orientated systems and continuously operated systems. Mission-orientated systems are required to operate without failure for the duration of a mission. If the system fails before the end of the mission, the mission has failed. An example of a mission-orientated system is an aircraft. All the subsystems on the aircraft are checked and are known to be operational before the flight takes off. If the system fails before the aircraft reaches its destination, the mission has failed. In continuously operated systems a certain number of system downtimes are tolerated, provided they do not occur too frequently or last too long. When subsystems fail, they are either repaired or replaced. It is important to record the time it takes for the failed system to be reinstated. An example of such a system is an electrical distribution network. If the power supply to a consumer in the network fails, the failure is repaired and the consumer is supplied with electricity again. The problem does have to be rectified in as short a time as possible to limit the negative consequences associated with interrupting power delivery to consumers.

In both system types, the reliability of the system is a function of the reliability of the individual components. In mission-orientated systems, the reliability of a particular component is measured in the probability of that component remaining operational for the duration of the mission, that is, what is the probability of failure or success. In continuously operated systems, the reliability of a component or subsystem is measured in the probability that a component will be operational at any point in time, that is, the availability or unavailability of a component. The availability of a component is calculated by dividing the duration in which a component was operational during a particular period of time by the duration of that period of time.

$$A = \frac{D_O}{D_T} \tag{2.1}$$

Where:

A = Availability

$D_O$ = Operational duration of period

$D_T$ = Total duration of period

## 2.2 BASIC RELIABILITY CALCULATIONS

To illustrate the methods used to model the networks, mission-orientated systems were used. They are simpler than continuously operated systems.

The reliability of a system depends not only on the reliability of the components that make up the system, but also on the way in which the components are arranged. Components are said to be in series if all of the components in the system must work in order for the system to work. Only one component needs to fail for the system to fail. Components are said to be in parallel if only one is required to work for the system to work. All of the components must fail for the system to fail.

Systems are made up of subsystems. These are made up of components that are arranged either in series or parallel or in a combination of the two. It is important to be able to recognise the different topologies and their associated reliability [1].

### 2.2.1 Series systems

A system that is made up of two components, A and B, which operate in series from a reliability point of view, is shown in Figure 2.1.

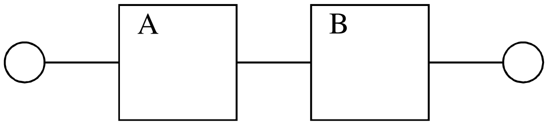

Figure 2.1 Two-component series system

$R_A$ and $R_B$ are the probability of a successful operation of components A and B respectively. $Q_A$ and $Q_B$ are the probability of an unsuccessful operation of components A and B. Since success and failure are mutually exclusive and complementary:

$$R_A + Q_A = 1 \ and \ R_B + Q_B = 1 \tag{2.2}$$

The requirement for system success is that both A and B must be working. The probability for system success is:

$$R_S = R_A \cdot R_B \tag{2.3}$$

If there are *n* components in series:

$$R_S = \prod_{i=1}^{n} R_i \tag{2.4}$$

The probability for system failure is calculated as follows:

$$Q_S = 1 - R_A \cdot R_B \tag{2.5}$$

$$= 1 - (1 - Q_A) \cdot (1 - Q_B)$$

$$= Q_A + Q_B - Q_A \cdot Q_B \tag{2.6}$$

For an *n* component system:

$$Q_S = 1 - \prod_{i=1}^{n} R_i \tag{2.7}$$

The greater the number of components that make up the series system, the greater the probability of failure of the system and the smaller the probability of success of the system.

### 2.2.2 Parallel systems

A system that is made up of two components, A and B, which operate in parallel, is shown in Figure 2.2

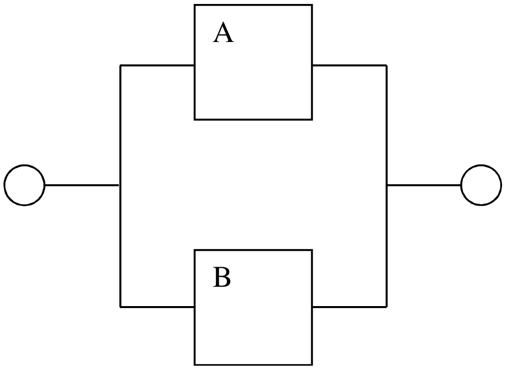

Figure 2.2 Two-component parallel system

The requirement for the system to operate successfully is that at any point in time at least one component needs to be working. Both components need to fail for the system to fail. The probability for system success is calculated as follows:

$$R_P = 1 - Q_A \cdot Q_B \tag{2.8}$$

$$= R_A + R_B - R_A \cdot R_B \tag{2.9}$$

For an *n* component system:

$$R_P = 1 - \prod_{i=1}^{n} Q_i \tag{2.10}$$

Also:

$$Q_P = Q_A \cdot Q_B \tag{2.11}$$

If there are *n* components in series:

$$Q_P = \prod_{i=1}^{n} Q_i \tag{2.12}$$

It is important note that the greater the number of components that make up the parallel system, the greater the probability of success of the system and the smaller the probability of failure of the system.

### 2.2.3 Series/parallel systems

The system that is shown in Figure 2.3 is a combination of a series and a parallel system.

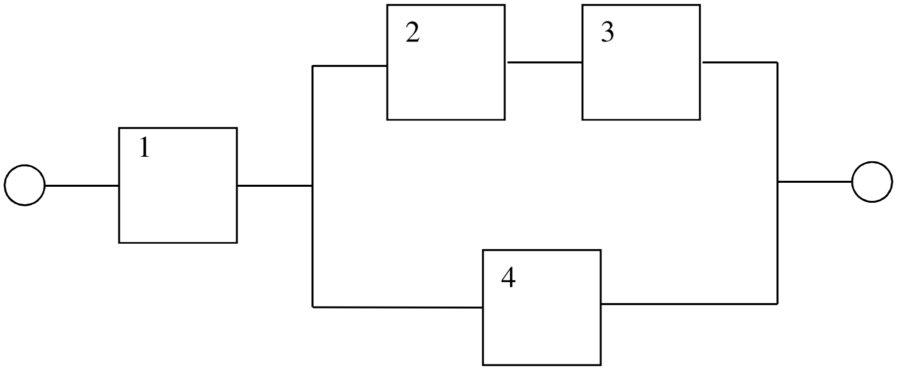

Figure 2.3 A series/parallel system

Generally, complex networks are made up of a combination of series and parallel systems. In order to calculate the reliability of the network, one reduces the complicated network sequentially by combing the appropriate series and parallel branches until a single equivalent element remains. The reliability of the remaining element is the reliability of the network. The system in Figure 2.3 is reduced as per the following description:

$$R_5 = R_2 \cdot R_3$$

$$R_6 = R_5 + R_4 - R_5 \cdot R_4$$

$$R_7 = R_1 \cdot R_6$$

By expanding $R_5$ and $R_6$:

$$R_7 = R_1 \cdot (R_2 \cdot R_3 + R_4 - R_2 \cdot R_3 \cdot R_4)$$

$R_7$ represents the equivalent probability of success of the whole system. The technique is illustrated in Figure 2.4.

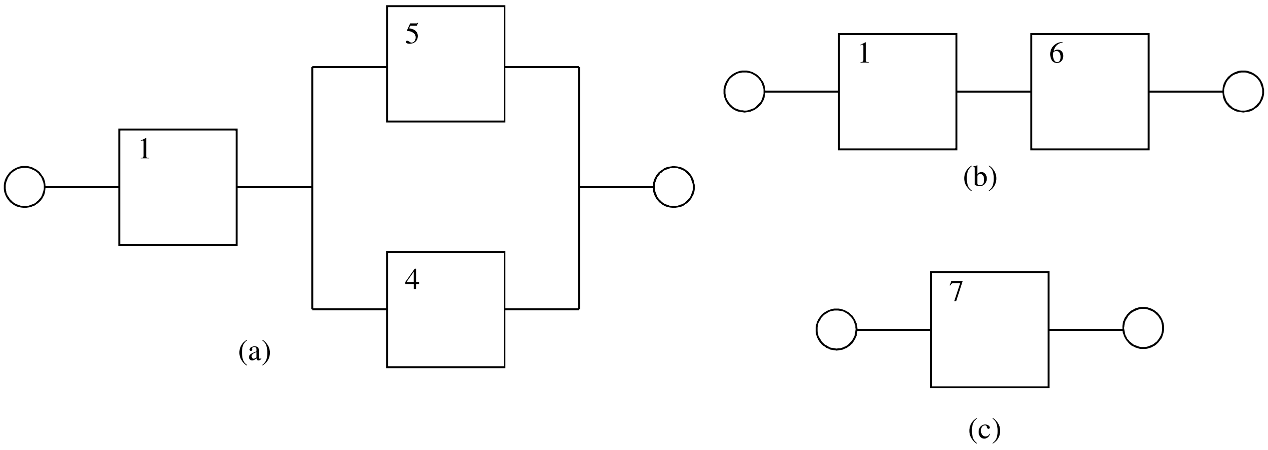

Figure 2.4 Reduction of the system illustrated in Figure 2.3. (a) First reduction. (b) Second reduction. (c) Third reduction.

An example of a non-series/parallel system is shown in Figure 2.5.

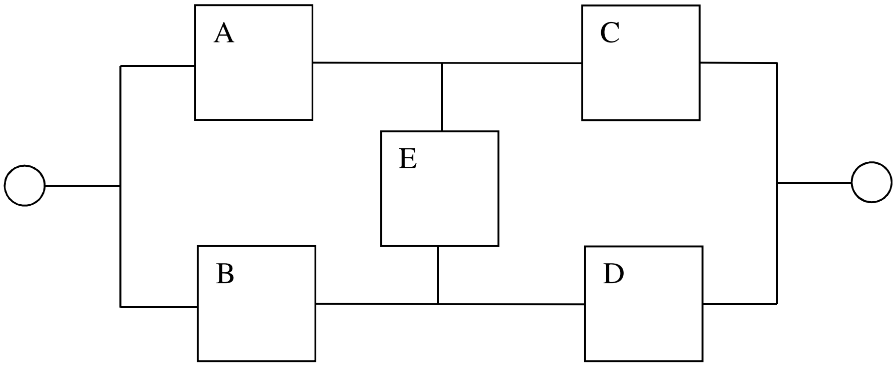

Figure 2.5 Example of a non-series/parallel system

There are a number of techniques that can be used to solve this type of network. These include the conditional probability method, cut-and-tie set analysis, tree diagrams, logic diagrams and connection matrix techniques. The conditional probability and cut-set methods are discussed in this section.

- **Conditional probability method**

This method reduces the system sequentially into subsystem structures that are connected in series/parallel and then recombines these subsystems using conditional probability. The principle is illustrated in the following formula:

$$P(system\ success\ or\ failure) =$$
$$P(system\ failure\ or\ success\ if\ component\ E\ is\ good).P(E\ is\ good) +$$
$$P(system\ success\ or\ failure\ if\ component\ E\ is\ bad).P(E\ is\ bad) \qquad (2.13)$$

According to this method, the system shown in Figure 2.5 is reduced as shown in Figure 2.6.

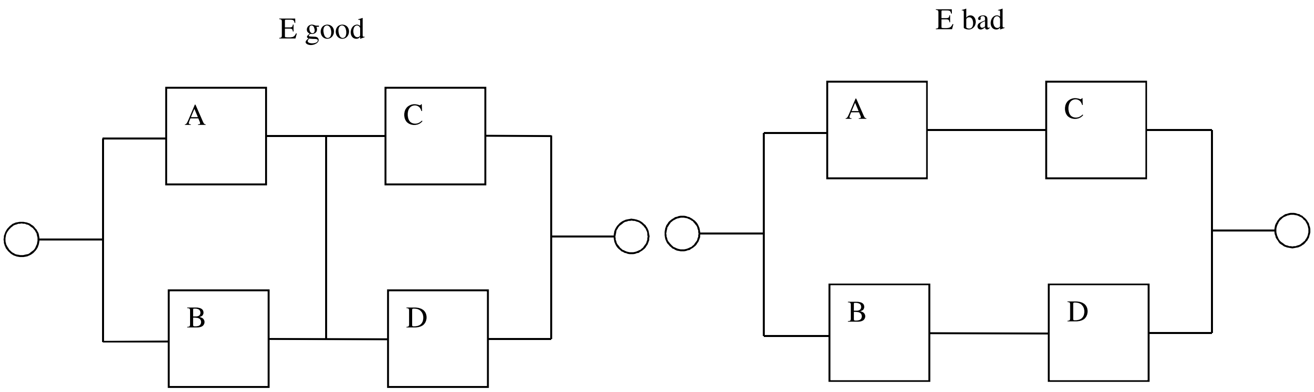

Figure 2.6 Reduction of system shown in Figure 2.5

For the condition where E is given as good:

$$R_S = (1 - Q_A \cdot Q_B)(1 - Q_C \cdot Q_D)$$

For the condition that is given as bad:

$$R_S = 1 - (1 - R_A \cdot R_C) \cdot (1 - R_B \cdot R_D)$$

The system reliability is:

$$R_S = (1 - Q_A \cdot Q_B)(1 - Q_C \cdot Q_D)R_E + (1 - (1 - R_A \cdot R_C) \cdot (1 - R_B \cdot R_D))Q_E$$

- **Cut-set method**

A cut set is a set of system components which, when failed, causes the system to fail, in other words, a cut set is a set of components which must fail in order to disrupt all the paths between the input and output of a reliability network. The cut sets of the system shown in Figure 2.5 are AB, CD, AED and BEC. These are illustrated in Figure 2.7.

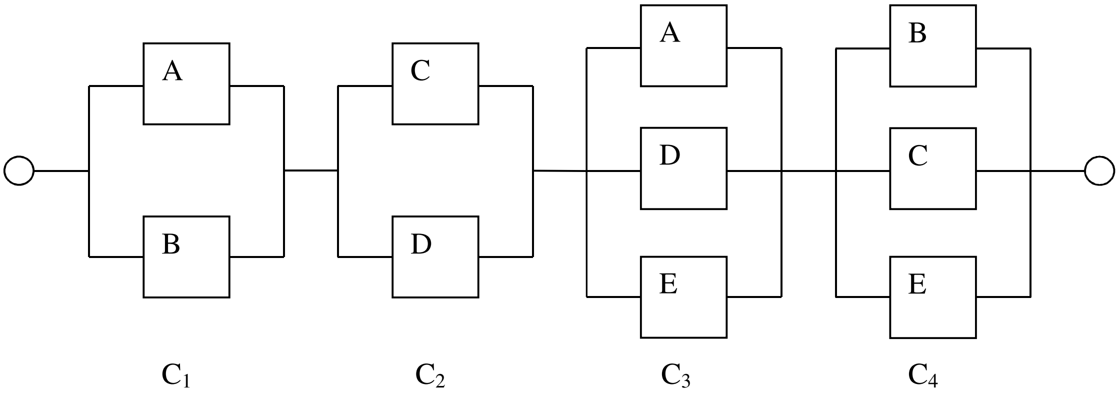

Figure 2.7 Cut sets of system shown in Figure 2.5

The unreliability of the system is the probability union of all the cut sets, namely:

$$Q_S = P(C_1 \cup C_2 \cup C_3 \cup C_4) \qquad (2.14)$$

## 2.3 CONTINUOUSLY OPERATED SYSTEMS

Most components of a continuously operated system can be represented by the simple two-state model shown in Figure 2.8 [1].

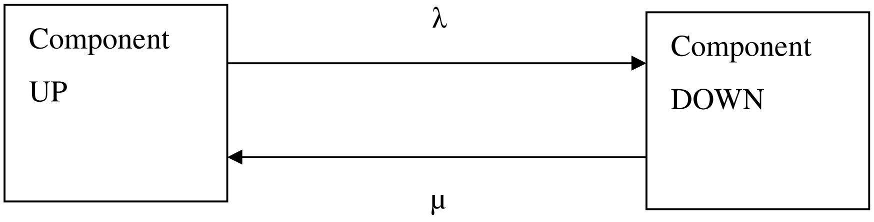

Figure 2.8 Two-state model for a repairable component

In Figure 2.8:

λ = component failure rate

μ = component repair rate

The same diagram can be used to describe the UP and DOWN states of a continuously operated repairable system. In this case the availability and unavailability are given by:

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \tag{2.15}$$

and

$$U(t) = \frac{\lambda}{\lambda+\mu} - \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \tag{2.16}$$

## 2.4 EQUIPMENT RELIABILITY INDICES

The most important equipment reliability indices of interest for each type of component are the following:

- **Failure rate** [λ], often expressed as failures per year per component or failures per unit year. It is calculated with the formula:

$$\lambda = \frac{Tf}{N \cdot Tp} \tag{2.17}$$

- **Mean time to repair** [MTTR], average time to repair, replace or maintain a component after it has failed in service, expressed in hours per failure. It is calculated with the formula:

$$MTTR = \frac{Rdt}{Tf} \tag{2.18}$$

Where:
N = total number of units of a particular type of equipment,
Tp = the total period over which reliability data has been collected,
Tf = the total number of failures of a particular component during that period, and
Rdt = the repair down time (the total downtime for unscheduled maintenance)

These indices are the indices that are used in the IEEE Gold Book [18]. Later in this dissertation, the failure rate and MTTR that are calculated for the Sasol Factory in Secunda are compared to those of the IEEE Gold Book indices. This is done to establish the credibility of the indices calculated for the Sasol Factory in Secunda. The failure rate and

MTTR are the indices that are required for each type of equipment in the PALADIN DESIGNBASE 2.0 electrical network modelling software package. This is the software that is used to compare the reliability of different distribution network topologies.

There are other reliability indices of interest for each type of equipment. These include:

- **Mean time between failures** [MTBF]: the mean exposure time between consecutive failures of a component. It is calculated with the formula:

$$MTBF = \frac{Tp}{Tf} \tag{2.19}$$

- **Mean time to failure** [MTTF]: the mean exposure time between the repair of a component and the next failure of that component. It is calculated with the formulas:

$$MTTF = MTBF \cdot \frac{Tp-Rdt}{Tp} \tag{2.20}$$

Or

$$MTTF = MTBF - MTTR \tag{2.21}$$

In some instances the MTTR is small as compared to the MTBF in which case the MTTR becomes negligible and *MTBF* = *MTTF*. Figure 2.9 shows the relationship between MTTF and MTBF.

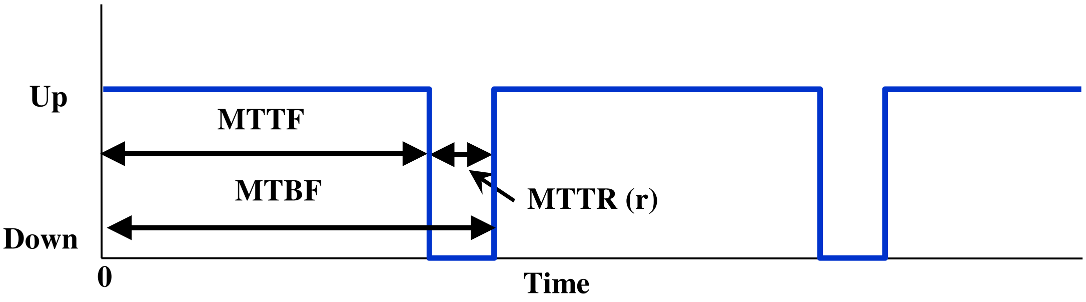

Figure 2.9 The relationship between MTTF, MTBF and MTTR [1]

- **Inherent availability** [Ai]: the instantaneous probability that a component of a system will be up or down. Ai considers only downtime for repair to failures. Ai is calculated with the formula:

$$Ai = \frac{MTTF}{MTTF+MTTR} \tag{2.22}$$

## 2.5 RELIABILITY EVALUATION OF DISTRIBUTION NETWORKS

Electrical distribution networks are usually very large and complex systems. The application of the methods described earlier in this chapter to evaluate the reliability of electrical distribution networks is extremely cumbersome and labour intensive if performed manually. For this reason, computer software is used to perform reliability evaluation of electrical distribution networks. Most computer software packages use one of two techniques to perform reliability evaluations. These are Monte Carlo Simulation and the Contingency Enumeration Method.

### 2.5.1 Monte Carlo simulation

The techniques described earlier in this chapter are analytical, that is, they are all mathematical representations of the systems they solve. A Monte Carlo simulation is a stochastic simulation. This means that it is a series of experiments that are repeated for a predefined number of times or until some statistical parameter is met. The average result of the series of experiments is similar to that obtained from an analytical technique. It will not necessarily be exactly the same.

To demonstrate this concept, consider the toss of a coin. Analytically we can calculate that the probabilities of the result being heads or tails are both 0.5. This is known because there are two possible results, each with the same probability. In a Monte Carlo simulation, a random number generator is used to generate random numbers between 0 and 1. “Heads” is defined as any number greater than zero but smaller than or equal to 0.5, while “tails” is defined as any number greater than 0.5 but smaller than or equal to 1. After 100 trials we find that 52 of the trials resulted in heads, while 48 resulted in tails. This would mean that, according to the Monte Carlo simulation, the probability of heads is 0.52 while the probability of tails is 0.48.

This concept is further demonstrated by applying it to a simple two-component engineering reliability problem. Each of the components has a reliability and unreliability of 0.8 and 0.2 respectively. Analytically, the reliability of the system can be calculated by using equation 2.2 if the components are in series or equation 2.7 if the components are in parallel. By Monte Carlo simulation, a series of trials is established for the system in which a random number between 0 and 1 is generated for each component. If the random number of a component is greater than 0 but smaller than or equal to 0.2, the component is said to have failed the trial. If the random number is greater than 0.2 but smaller than or equal to 1, the component is said to succeed in the trial. For series systems, the system is said to have failed the trial if either of the two components failed the trial. For parallel systems, the system is said to have failed if both of the components have failed the trial. The reliability of the system is established by repeating the trial for a very large number of iterations and calculating the probability of success or failure of the system by dividing the number of successes or failures by the total number of trials.

An advantage of the Monte Carlo simulation is that it can easily be used to produce frequency histograms. In the example of the two-component system this would be achieved in the flowing way: Set one series of trials equal to 100 iterations. Repeat the series 100 times (10 000 trials have been executed). Record the number of failures that have taken place in each series. Tally the frequency of each number of failures (for example, in three of the series there were no failures, in six of the series there was one failure, in 15 of the series there were two failures, and so on). The frequency of each number of failures can be graphed to form a frequency histogram. Thus Monte Carlo simulations are able to produce the average probability of a system failure as well as the standard deviation of the probability. Frequency histograms can also be converted into probability density functions or probability distribution functions.

### 2.5.2 Contingency enumeration method

The procedure for the contingency enumeration method is described in the following three steps [19]:

- Systematic selection and evaluation of contingencies
- Contingency classification according to predetermined failure criteria
- Compilation of appropriate predetermined adequacy indices

A contingency is a change in the state of the network, i.e. the failure of a component and/or the opening or closing of a circuit breaker.

The total number of contingencies chosen in the first step can be decided by using cut-off criteria such as fixed levels or probability or frequency values. The number can be further reduced by using ranking techniques or selection procedures. Contingency classification may involve a load flow analysis of a model of the system. There are a large number of possible indices that can be calculated at each load point and for the overall system. These indices are listed in Table 2.1 and Table 2.2.

Table 2.1 Load point indices for contigency enumeration method

| **Basic values** |
|---|
| Probability of failure |
| Expected frequency of failure |
| Expected number of voltage violations |
| Expected number of load curtailments |
| Expected load curtailed |
| Expected energy not supplied |
| Expected duration of load curtailment |
| **Maximum values** |
| Maximum load curtailed |
| Maximum energy curtailed |
| Maximum duration of load curtailment |
| **Average values** |
| Average load curtailed |
| Average energy not supplied |
| Average duration of curtailment |
| **Bus isolation values** |
| Expected number of curtailments |
| Expected load curtailed |
| Expected energy not supplied |
| Expected duration of load curtailment |

Table 2.2 System indices for contingency enumeration method

| **Basic values** |
|---|
| Bulk power interruption index |
| Bulk power supply average MW curtailment per disturbance |
| Bulk power energy curtailment index |
| Modified bulk power energy curtailment index |
| **Average values** |
| Average number of curtailments per load point |
| Average load curtailed per load point |
| Average energy curtailed per load point |
| Average duration of load curtailed per load point |
| Average number of voltage violations per load point |
| **Maximum values** |
| Maximum system load curtailed under any contingency condition |
| Maximum system energy not supplied under any contingency condition |

The basic structure of the contingency enumeration method is shown in detail in Figure 2.10.

It is important to note that PALADIN DESIGNBASE 2.0 uses the contingency enumeration method to assess the reliability of distribution networks [20]. It enumerates and examines a list of contingencies that cause the outage of distribution network components. For each contingency, the power system state is examined using power flow analysis to identify the system deficiencies and assess the effects of remedial actions.

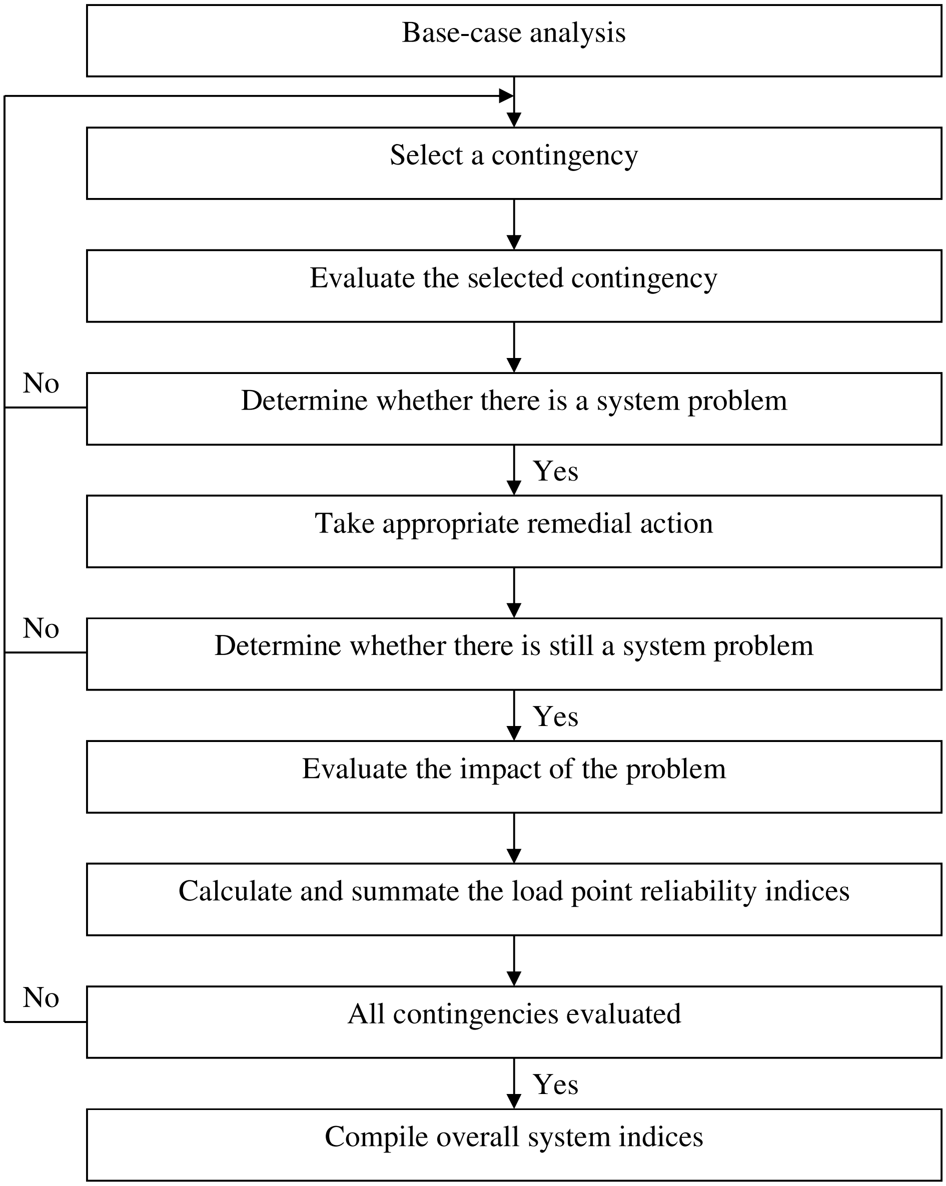

Figure 2.10 Basic structure of the contingency enumeration method

## 2.6 RELIABILITY EVALUATION OF UTILITY DISTRIBUTION NETWORKS

It is important for utilities to measure the past reliability performance of distribution networks for the following reasons:

- Provide management with performance data regarding the quality of customer service on the electrical system
- Provide data for engineering comparisons of electrical system performance in different companies
- Provide a basis for companies to establish service continuity criteria
- Provide data for analysis to determine how factors like design differences, environment, maintenance methods and operating practices affect performance
- Provide reliability history of individual circuits for discussion with customers or prospective customers
- Identify substations and circuits with substandard performance and ascertain the causes
- Obtain optimum improvement in reliability for the total cost of ownership
- Provide performance data needed for probabilistic reliability studies

There are a wide range of indices used to assess past performance. Among these are:

- **System average interruption frequency index** [SAIFI]: the average number of interruptions per customer served per year. A customer interruption is considered to be a single interruption of one customer.

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customers\ served} \tag{2.23}$$

- **Customer average interruption frequency index** [CAIFI]: the average number of interruptions per customer per year. The customers affected should be counted only once, regardless of the number of interruptions they may have experienced during the year.

$$CAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customers\ affected} \tag{2.24}$$

- **System average interruption duration index** [SAIDI]: the average interruption duration for customers served during a year.

$$SAIDI = \frac{Sum\ of\ customer\ interruption\ durations}{Total\ number\ of\ customers\ served} \tag{2.25}$$

- **Customer average interruption duration index** [CAIDI]: the average interruption duration for customers interrupted during a year.

$$CAIDI = \frac{Sum\ of\ customer\ interruption\ durations}{Total\ number\ of\ customers\ interrupted} \tag{2.26}$$

- **Average service availability index** [ASAI]: the ratio of the total number of customer hours that service was available during a year to the total customer hours demanded. Customer hours demanded is the 12-month average number of customers multiplied by 8760 hours.

$$ASAI = \frac{Customer\ hours\ of\ available\ service}{Customer\ hours\ demanded} \tag{2.27}$$

## 2.7 DIFFERENCES BETWEEN UTILITIES AND INDUSTRIAL PLANTS

A very large industrial plant can have the same load as a large town or city. For this reason, most large industrial plants have a power distribution network that operates at the same medium voltages as the utility distribution network. While there are a few similarities in the distribution networks of utilities and industrial plants, there are some fundamental differences that require the use of different models to evaluate the reliability of distribution networks used in industrial plants.

Of all the large industrial plants, the cost of loss of production is the highest in petrochemical plants (Table 1.1). Hence, reliability modelling in petrochemical plants is especially critical. This study focuses specifically on petrochemical plants.

### 2.7.1 Equipment

The equipment that affects the reliability of a distribution network in a petrochemical plant is different from the equipment that affects the reliability of a utility distribution network. A comparison is made in Table 2.3.

Table 2.3 A comparison between the equipment that affects the reliability of the distribution network of a petrochemical plant and of a utility

| **Equipment that affects the reliability of the distribution network of a utility [21]** | **Equipment that affects the reliability of the distribution network in a petrochemical plant [18]** |
|---|---|
| Overhead power lines | Bus ducts |
| Transformers | Cables |
| Circuit breakers | Cable joints |
| Cables | Cable terminations |
| Synchronous compensators | Circuit breakers |
| Static compensators | Generators |
| Shunt reactors | Motors |
| Shunt capacitor banks | Motor starters |
| Series capacitor banks | NECRs |
|  | Current-limiting reactors |
|  | Switchgear buses |
|  | Transformers |
|  | Utility networks |

### 2.7.2 Reliability indices

Utilities have service level agreements with clients on the reliability of the power supplied. Regulatory bodies ensure adherence. The performance of the utilities in relation to these service level agreements is measured according to the indices that were discussed in section 2.6.

There are 3 reasons why the indices in section 2.6 are not used to measure the reliability of distribution networks in petrochemical plants:

- In petrochemical plants, the company operating and maintaining the distribution network is the final user of the power. There are no service level agreements between the end users and the operators or maintainers of the distribution network. Furthermore, there is no regulatory body that enforces rules regarding the quality of supply.

- In some companies the performance of individual employees or departments is measured in terms of key performance areas. One of the key performance areas for the power distribution department and/or its management may be to achieve a certain level of reliability. The availability (or unavailability) of the distribution network or cost of loss of production would be used for this purpose.
- In the calculation of the indices in section 2.6, the denominator is the number of customers affected, interrupted or served. In petrochemical plants, there is only one customer. The denominator is always 1. This is not practical for implementation.

In petrochemical plants the reliability of the distribution network is evaluated by the availability or unavailability of the distribution network at a particular point in that distribution network. From the unavailability, the expected downtime per year and cost of loss of production can be calculated.

# 3 RELIABILITY MODELLING OF A PETROCHEMICAL PLANT

## 3.1 COMPONENTS THAT ARE USED TO MAKE UP THE MODEL

The components that are used to make up the model of the distribution network of a petrochemical plant were discussed in paragraph 2.7.1. The details of the reliability and failure of these components are discussed in this section.

### 3.1.1 Bus ducts

The most common cause of bus duct failure is the presence of vermin. They form a conductive path between the phases or between a phase and earth, resulting in a flashover. Another common cause of failure is the buildup of dust, often containing carbon. If air is used as the insulation medium, the gap between phases and/or earth is reduced and arcing could occur. If any solid material is used as the insulation medium, a buildup of dust on top of the insulation, between phases or earth can form a conductive path for current to flow along. Other causes of bus duct failure are the misalignment of busbars during fabrication or installation of equipment, inadequate space between conductors by design, or the presence of moisture.

During short circuits downstream of the bus duct, the mechanical forces that are exerted on the busbars as a result of the electromagnetic forces are powerful. If the busbars have not been fastened well enough with insulators that have sufficient strength to withstand the electromagnetic forces of a short circuit, the busbars could move, bend or even be blown apart. When the power is restored after the fault, arcing may occur between the phases and/or earth. This is as a result of the reduced gaps between them.

The electromagnetic force between conductors is calculated as follows [22]:

$$F_m = \frac{\mu_0}{2\pi} \cdot i_p^2 \cdot \frac{1}{a} \tag{3.1}$$

Where:

$F_m$= electromagnetic force between conductors

$\mu_0$ = magnetic field constant ($4\pi \cdot 10^{-7}$ H/m)

$i_p$= peak short circuit current

a = conductor centre line spacing

### 3.1.2 Cables

Cables fail under thermal stress. They are designed to withstand temperatures that are slightly higher than their specified thresholds for long times and temperatures that are much higher than their specified thresholds for short times. Cables with PVC insulation can typically withstand continuous conductor temperatures of up to 70ºC,and, under short-circuit conditions, a conductor temperature of 160ºC for one second. Cables heat up proportionally to the amount of current they are carrying. The conditions that cables are able to withstand are specified in the cable data sheets that are supplied by the cable manufacturers. The most significant of these cable characteristics is the current-carrying capacity of the cables, their fault-current capacity and the derating factors that are associated with their method of installation.

The current-carrying capacity of a cable is specified in a table that is supplied by the manufacturer. Typically, a 25mm$^2$three-core PVC-insulated, PVC-bedded, steel wire armoured, PVC-sheathed 600/1000V cable can carry 119A if it is buried underground, 96A if it is installed in a duct and 110A if it is installed in open air [23]. If a cable is required to carry more than its rated capacity for an extended time, the insulation becomes damaged and could fail.

The derating factors are multiplied with the current-carrying capacities of the cables. They are associated with the distance between cables, air temperature, ground temperature, etc. The current-carrying capacity of XLPE cable is multiplied by 0.95 if it installed in open air when the air temperature is 35ºC and by 0.89 if the air temperature is 40ºC.

The short-circuit rating of a cable is calculated with the following formula:

$$I = \frac{K \cdot A_c}{\sqrt{t}} \tag{3.2}$$

Where:

I = short circuit rating in Ampere

K = constant combining temperature limits and conductor material properties

$A_c$ = Area of conductor

t = duration of short circuit in seconds

The value of K for copper and aluminium conductors of XLPE cables is 143 and 92 A/mm$^2$ respectively. The value of K for copper and aluminum conductors of PVC cables is 115 and 76 A/mm$^2$ respectively.

A common cause of failure in cables is mechanical damage, especially during any form of excavation. Another cause of damage is the seepage of water into XLPE and PILC cables. The water compromises the dielectric withstand capability of the insulation. This results in the eventual deterioration of the insulation until the cable fails.

### 3.1.3 Cable joints

Cable joints fail if they are not constructed in a manner that gives them the same electrical and mechanical properties as the cables they are joining. The five most important aspects are the following [24]:

- **Connectors (ferrules) -**conductors of the cables to be jointed must be connected in a manner that will ensure electrical and mechanical integrity.
- **Insulation –**the insulation between phases and between phases and earth must be reinstated to satisfy the same design criteria as the cable.
- **Stress control–**some form of stress control is necessary in order to ease the electrical stresses caused by the discontinuation of the core screening as well as the dimensional change between the cable and cable joint components.
- **Earth continuity–**as is the case with the cable, all joints are required by specification to include some form of overall metallic earth continuity as a safety measure. This metallic earth continuity device must also be capable of carrying through fault currents.
- **Overall protection–**the joint design must include some form of overall protection from mechanical damage as well as the influx of unwanted substances such as moisture and industrial contaminants.

### 3.1.4 Cable terminations

In MV cables many terminations fail as a result of inadequate stress control. A high stress concentration occurs at the point where cable insulation is cut back in order to expose the conductor for the attachment of a lug. Approximately 30% of the line voltage is concentrated on the insulation surface in a small area around the circumference of the screening material cutback. The object of stress control is to apply a material or combination of materials in order to obtain a symmetrical radial distribution of voltage stress within the insulation material, particularly at the edge of the screening material cutback [24].

Cable terminations also fail as a result of external flashovers such as voltage surges or lightning. These are particularly common when the space and insulation between the lugs (which are at line potential) and the insulation screening material (at earth potential) are inadequate.

Finally, cable terminations fail as a result of tracking. Tracking is caused by small local arcing that occurs between drying water films on the insulation surface. This arcing causes carbonisation of the surface of organic materials and eventually conductive carbon tracks along the insulation surface.

### 3.1.5 Circuit breakers

According to international surveys conducted by CIGRE (International Council on Large Electric Systems), the mechanisms and electrical control circuits in circuit breakers are the primary sources of serious faults. The most common sources of these faults are mechanically actuated parts such as relays and signalling contacts in electrical control circuits and the primary components in operating mechanisms [22].

The reliability of circuit breakers is improved by decreasing the number of moving parts.The most durable circuit breakers have an operational life expectancy of around 100,000 switching cycles.

In [25] a functional relationship between the failure rate of circuit breakers and time is proposed. This relationship is based on the data collected in the surveys by CIGRE and is expressed as follows:

$$\lambda(t) = \begin{cases} 0 & t < 1 \\ f(t) & 1 \le t \le 10 \\ f(10) & t \ge 10 \end{cases} \tag{3.3}$$

Where f(t) is the four degree polynomial function shown below:

$$f(t) = 0.0032t^4 - 0.0055t^3 + 0.0342t^2 - 0.0113t + 2.8667 \tag{3.4}$$

Factors that influence the failure rate of circuit breakers are:

- Weather conditions (storms, lightning, snow, ice, temperature and air humidity)
- Contamination
- Vegetation
- Animals
- Humans
- High ambient temperature
- Moisture
- Excessive load
- Lack of maintenance
- Ageing

### 3.1.6 Generators

The performance of generators or power plants can be expressed through some common performance factors as [26]:

- Heat rate (energy efficiency)
- Thermal efficiency
- Capacity factor
- Load factor
- Economic efficiency
- Operational efficiency

### Heat rate (energy efficiency)

Overall thermal performance or energy efficiency for a power plant for a period can be defined as:

$$\varphi_{hr} = \frac{H}{E} \tag{3.5}$$

Where:

$\varphi_{hr}$= Heat rate (Btu/kW, kJ/kW)

H = Heat supplied to the power plant for a period (Btu, kJ)

E = Energy output from the power plant in the period (kWh)

### Thermal efficiency

Thermal efficiency of a power plant can be expressed as:

$$\mu_{te} = \frac{(100)\cdot(3412.75)}{\varphi} \tag{3.6}$$

Where:

$\mu_{te}$ = thermal efficiency (%)

### Capacity factor

The capacity factor for a power plant is the ratio between average load and rated load for a period of time and can be expressed as:

$$\mu_{cf} = \frac{100\cdot P_{al}}{P_{rl}} \tag{3.7}$$

Where:

$\mu_{cf}$ = Capacity factor (%)

$P_{al}$ = Average load for the power plant for a period (kW)

$P_{rl}$ = Rated capacity for the power plant (kW)

### Load factor

Load factor for a power plant is the ratio between average load and peak load and can be expressed as:

$$\mu_{lf} = \frac{100\cdot P_{al}}{P_{pl}} \tag{3.8}$$

Where:

$\mu_{lf}$ = Load factor (%)

$P_{pl}$ = Peak load for the power plant in the period (kW)

**Economic efficiency**

Economic efficiency is the ratio between production costs (including fuel, labour, materials and services) and energy output from the power plant for a period of time. Economic efficiency can be expressed as:

$$\varphi_{ee} = \frac{C}{E} \tag{3.9}$$

Where:

$\varphi_{ee}$ = Economic efficiency (cents/kW)

C = Production costs for a period (cents)

E = Energy output from the power plant in the period (kWh)

**Operational efficiency**

Operational efficiency is the ratio of the total electricity produced by the plant during a period of time compared to the total potential electricity that could have been produced if the plant had operated at 100 percent in the period. Operational efficiency can be expressed as:

$$\mu_{oe} = \frac{100 \cdot E}{E_{100\%}} \tag{3.10}$$

Where:

$\mu_{oe}$ = Operational efficiency (%)

E = Energy output from the power plant in the period (kWh)

$E_{100\%}$ = Potential energy output from the power plant operated at 100% in the period (kWh)

### 3.1.7 Motors

Motor failures can be broadly classified into four categories [27]. These are:

- Insulation failures
- Rotor bar failures
- Mechanical failures
- Auxiliary failures

### Insulation failures

These are the most common types of failures in electric motors and account for more than 50% of all motor failures. They occur due to the stresses that result from the thermal, electrical, mechanical and environmental processes that deviate from the designed values or from the specifications originally envisaged during detail engineering. These failures manifest in various forms, such as winding shorts and insulation to ground faults.

Thermal processes that harm insulation systems are usually the result of overheating of the windings due to factors such as overloading, frequent starting, a higher ambient temperature than what was designed for, inadequate ventilation, and high inertia loads. Motor ventilation issues are mainly due to congestion of fan covers and improper spacing at the end of the motor.

### Rotor bar failures

These are particularly common in large motors and are the result of manufacturing defects or improper operational and maintenance practices. Design factors that can create this problem are casting defects, loose laminations, and improper protection provided for operation in harsh environments. Operational factors that contribute to this type of failure are frequent starts and inadequate cooling of the motor. Maintenance factors are incorrect fitting or alignment that causes excessive vibration and heat in the rotor.

### Mechanical failures

These are primarily caused by misaligned couplings or sheaves, poorly shimmed feet, soft feet, dynamically imbalanced loads or internally imbalanced motor rotors. The most common failure under this category is bearings-related. This can be due to excessive loading (resulting in bearing clearance problems), improper lubrication, general wear out, improper engineering of the system, non-suitability of the bearing for the application and corrosion.

### Auxiliary failures

These are failures related to the power supply, electrical circuits and cable terminations. In some extreme cases of voltage imbalance or negative sequence currents motor insulation failure can result and vibrations can be seen.

### 3.1.8 Motor starters

Motor starters are circuits that control the operation of motors. They are made up of various combinations of the following components: wire conductors, switches, push buttons, fuses, relays, contactors, isolators, circuit breakers, soft starters and variable speed drives. If one of the components in a motor starter circuit fails, it is quite likely that the motor will fail to operate correctly. Some typical component failures are discussed in the following paragraphs [27].

Contact chattering is caused by the inability of contacts to make proper contact because they are dirty or because of corrosion. It is also a sign that the component to which the contacts belong (contactor or relay) has failed.

Welding or freezing of contacts is caused by ingress of foreign matter preventing the contacts from closing, by abnormally high inrush currents or a short circuit/ground fault. Abnormally high inrush currents could be caused by using an incorrectly rated fuse or circuit breaker.

Incorrect contact pressure or worn contacts or springs could lead to arcing between the tips of the contacts. This decreases the lifespan of the contact tips. Contact tips are also damaged by persistent overloading or high current interruption. In both cases the contactor could be underrated for its application. Short circuits and ground faults cause damage to contactor tips.

Relay coils fail as a result of high control voltages, gaps in the magnetic circuit and high ambient temperatures. Relay coils are rated for application in particular ambient temperatures and if a particular component is not compatible with its environment, it will not work properly.

### 3.1.9 NECRs

On HV/MV supply transformers that have delta-connected MV windings, theMV neutral point is derived using a neutral earthing compensator (NEC), with zig-zagconnected windings, and with an internal neutral earthing resistor (NER). The value of the NER is chosen so as to limit the current under an earth fault condition to less than a particular value (such as 300A).

The live parts of an NER are in the form of wire, cast elements or corrugated sheet steel lattices [22]. These components are made up into assemblies with ceramic insulators and can take the form of banks mounted on a frame. In a resistor unit, electrical energy is converted into heat. The body of the resistor can absorb this partly and only for a very short time. It must always be dissipated to the ambient air. Resistor units are usually air cooled. Natural ventilation is generally sufficient. Separate ventilation or oil cooling is advisable in special cases.

Resistors are often not designed for a 100% load factor, and only to operate for a limited period. If, during this period, the load duration $t_B < T_\vartheta$, a higher loading is permissible. The maximum load duration $t_{Bmax}$ during which the resistor element heats up to the permitted temperature with an overload of $I_a = a.I_r$, is:

$$t_{Bmax} = T_\vartheta \cdot ln\left(\frac{a^2}{a^2-1}\right) \tag{3.11}$$

Where:

$t_{Bmax}$ = Maximum load duration (s)

$T_\vartheta$ = Thermal time constant of material (s)

$I_r$= Continuous load current capacity (A)

$I_a$ = Overload current capacity (A)

A sufficiently long interval must then follow to complete cooling.

### 3.1.10 Current-limiting reactors

Current limiting reactors (series reactors) are reactances employed to limit short circuit currents [22]. They are used to reduce the short circuit power of networks or installations to a value which is acceptable for the short circuit rating of the equipment or the breaking capacity of the circuit breaker.

For the reactance of a series reactor to remain constant during short circuit currents, air core type of construction is suitable. If iron cores were used, saturation of the iron could cause a drop in the inductance of the coil. This reduces the protection against short circuits.

The rated impedance is the impedance per phase at a rated frequency. The resistance of a current-limiting reactor is negligible and amounts to no more than 3% of the reactance $X_L$. The rated voltage drop $\Delta U_r$ is the voltage induced in the reactor when operating with rated current and rated reactance:

$$\Delta U_r = I_r \cdot X_{\mathrm{L}} \tag{3.12}$$

At the nominal referred voltage of the system, the rated voltage drop is denoted $\Delta u_r$ and is usually stated in %:

$$\Delta u_r = \frac{\Delta \mathrm{U}_r \cdot \sqrt{3}}{\mathrm{U}_n} \cdot 100\% \tag{3.13}$$

The throughput of a reactor is the product of the line to earth voltage $U_n$ /√3 and the rated current $I_r$:

$$S_D = \sqrt{3} \cdot I_r \cdot U_{\mathrm{n}} \tag{3.14}$$

If the short circuit power $S_{k1}$ of a network is to be reduced to a value of $S_{k2}$using a limiting reactor, the required percentage voltage drop is:

$$\Delta u_r = 1.1 \cdot 100\% \cdot S_{\mathrm{D}} \cdot \left(\frac{S_{K1} - S_{K2}}{S_{K1} \cdot S_{K2}}\right) \tag{3.15}$$

Where:

$X_L$ = Reactance of the current-limiting reactor (H)

$\Delta U_r$ = Rated voltage drop (V)

$I_r$ = Rated current (A)

$\Delta u_r$= Rated voltage drop when referred to the nominal voltage of the system (%)

$U_n$ = Line to earth voltage (V)

$S_D$ = Throughput power (KVA)

### 3.1.11 Switchgear busses

Switchgear busses are busbars that are located inside switchgear. The factors that influence the reliability of switchgear busbars are the same as those that affect busbars in bus ducts. These are discussed in paragraph 3.1.1.

### 3.1.12 Transformers

Transformer failures are generally expensive and result in long downtimes. For this reason, transformers are fitted with protective devices that cause alarms or trips to occur, depending on the severity of the faults. An alarm makes maintenance staff aware of a problem so that they may take corrective action before the problem becomes too severe. A trip causes a transformer to be de-energised in an attempt to prevent any severe permanent damage. The fault must be cleared before the transformer is re-energised.

Typical protective devices for transformers are the following [22]:

- Overcurrent time relays respond to short circuits; they trip the circuit breakers
- Thermal relays respond to unacceptable temperature rises in the transformer, and signal overloads
- Make-proof percentage differential relays detect internal short circuits and faults, including those on lines between the current transformers: they trip the appropriate transformer breakers, but do not respond to the inrush current of a healthy transformer
- Buchholz relays detect internal damage due to gassing or oil flow: they signal minor disturbances and trip the breaker if the trouble is serious
- Temperature monitors signal when a set temperature is reached, or trips circuit breakers
- Dial-type telethermometers indicate the temperature in the transformers topmost oil layer with the maximum and minimum signal contacts
- Oil level alarms respond if the oil level is too low
- Oil flow indicators detect any disruption in the circulation in closed-circuit cooling and trigger an alarm
- Airflow indicators detect any break in the flow of forced-circulation air, and trigger an alarm.

### 3.1.13 Utility networks

The reliability of utility networks is discussed in Section 2.6.

## 3.2 RELIABILITY INDICES FOR DISTRIBUTION NETWORK EQUIPMENT

### 3.2.1 Data collection and sorting

In order to evaluate the reliability of the distribution network in a petrochemical plant, data is required on past failures. The accuracy of the reliability study depends on the reliability of the data and the period over which the data was collected.

The purpose of collecting the trip data is to calculate the reliability indices of the different kinds of equipment that makes up the power distribution network of a petrochemical plant. This includes the mean time to failure (MTTF) and mean time to repair (MTTR) [18]. Every trip is an indication that some component on the distribution network has failed. It is important to establish and record the component that has failed and resulted in the trip. An example of a trip data spread sheet is shown in ADDENDUM D.

Over a number of years, changes occur in staff that capture the trip data and the format of trip report forms on which the data is captured. The definition of the fault origin for each type of trip is not consistent. For this reason it is necessary to set rules that define the component of the distribution network that is responsible for each trip, in other words, to establish which component has failed. Once these rules are established, each trip event is analysed as per the information that has been captured on its trip report and reclassified in terms of its fault origin. ADDENDUM D illustrates the fault origins as they were before they were changed according to the rules.

The rules that are used for the reclassification of the fault origins are as follows:

- There are 13 key components relating to failures. The fault origins recorded on the trip report forms need to be changed as per the rules to become one of these 13 components. These components are the following:

1. Bus duct
2. Cable
3. Cable joint
4. Cable termination
5. Circuit breaker
6. Generator
7. Motor
8. Motor starter
9. NECR
10. Current-limiting reactor
11. Switchgear bus
12. Transformer
13. Utility

- When the reason for a circuit breaker trip cannot be found, it is assumed that the circuit breaker operated in error. Thus the circuit breaker failed. An example of this is trip number 32/2006 of ADDENDUM D. The fault origin changes from “Unknown” to “Circuit breaker”.
- If a circuit breaker operated incorrectly (or failed to operate when it was supposed to) due to faulty protection, the failure is recorded as a circuit breaker failure. An example of such a situation would be if a circuit breaker failed to close because its battery tripping unit (BTU) was faulty. The bottom line is that the circuit breaker failed to operate when it should have and the protection system that is supposed to control the circuit breaker is seen as a set of components of the circuit breaker. Another such example would be if a circuit breaker failed to operate because the incorrect polarity of a current transformer (CT) that is wired to a relay that controls the circuit breaker.
- In contrast to the previous point, if a circuit breaker operates correctly because the protection has picked up a fault in a particular unit of equipment and it is found in the investigation afterward that the unit of equipment did fail, the failure is ascribed to the piece of equipment. An example would be if the feeder to a transformer trips on winding temperature and the transformer is found to be hot.
- When human error is the cause of the failure of an item, the failure is still recorded as a failure of that item. An example of such a situation is when a cable is damaged

during an excavation. Despite the fact that it is not the cable's fault that it failed, it is still necessary to count this failure in calculating the MTTF of cables because the ultimate goal of reliability analysis is to achieve the design of plants with better reliability. When deciding whether or not to feed a substation with two cables, each from a different source, the calculated MTTF for cables takes into consideration the fact that cables are often damaged as a result of human error during excavation activities.

- There are some instances where large motors have failed and the motor protection has either operated too slowly or not at all. The upstream protection operates, thereby causing an entire distribution board to lose power. Figure 3.1 is a typical single line diagram that illustrates this. The fault origin is the motor, but the protection on the motor feeder has not operated fast enough and the circuit breaker feeding the entire board has operated. The fault has been classified as "Motor", but the only motor failures that are recorded are the few that affect the distribution network. Thus these failures do not give any indication to the reliability of motors, but they do give an indication of the impact that motors have on the reliability of the distribution network. The parts of the distribution network that they impact upon are the distribution boards they feed from. For this reason, when calculating the reliability indices for switchgear busses the "Motor" and "Motor starter" failures recorded are added to the failures of "Switchgear bus" failures and no indices for motors or motor starters are calculated.
- It is very difficult to determine exactly the number of cable joints that have been installed throughout the factory. For this reason, all faults that have occurred as a result of failing cable joints are added to the faults that are as a result of cable failures when calculating reliability indices for cables. Thus the reliability indices for cables include the effects of cable joint failures.
- Neutral earthing compensators/resistors [NECRs] are installed on most transformers to limit the fault current that flows through a transformer that has its neutral earthed. An NECR can therefore be seen as a component of a transformer because if an NECR fails it becomes unsafe to operate the transformer and a trip should occur. For this reason, when calculating the reliability indices of transformers, the trips that occur as a result of NECR failures are added to the trips that result from transformer failures. Thus, the transformer reliability indices

include the effects of the reliability of the NECRs that are attached to them. If one considers the number of transformers that are installed on the distribution network and the fact that there have only been seven NECR failures in 19 years, the effect of the NECR reliability on transformer reliability is very small.

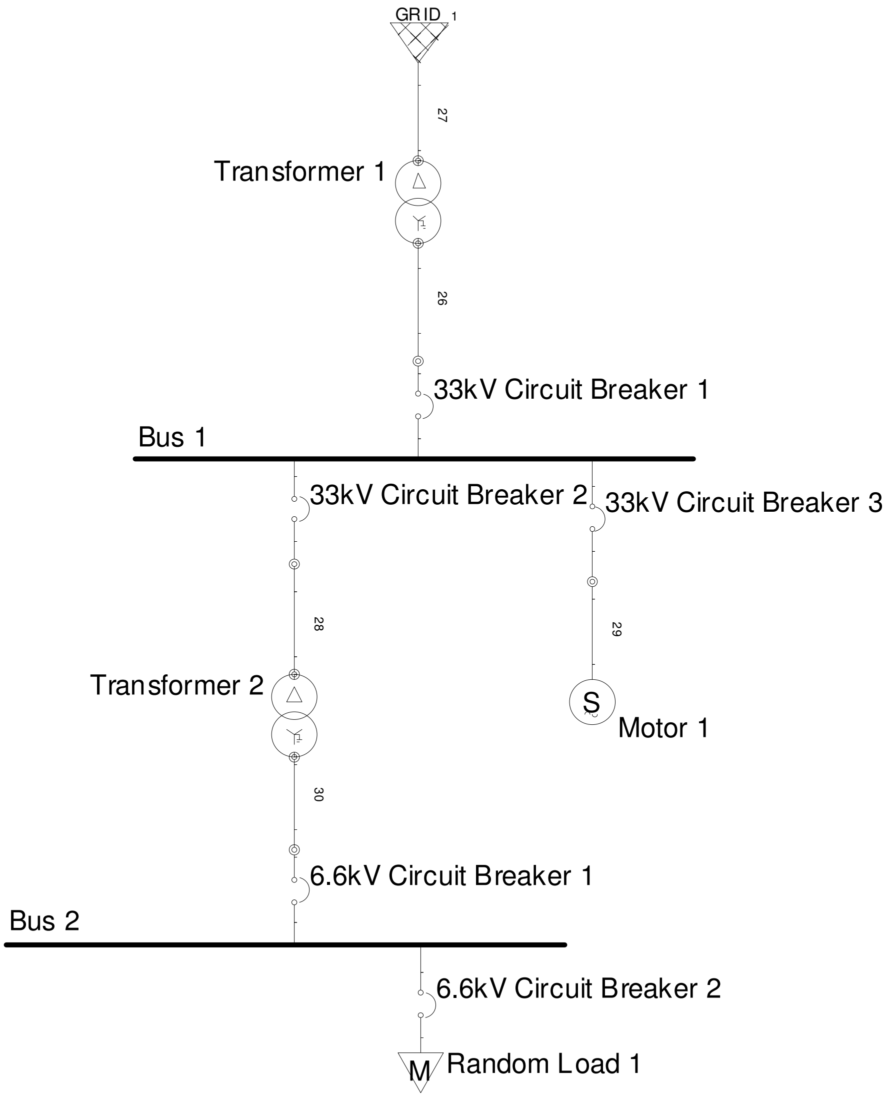

Figure 3.1 Typical single line diagram of a large MV motor that is fed from a distribution busbar

### 3.2.2 Calculation of reliability indices

In order to calculate the failure rate of all the various types of equipment it is necessary to know exactly how many items of each type of equipment are installed in the distribution network. This is achieved by adding all the units of each type of equipment that are shown on the single line diagrams of the distribution network.

Once one has established:

- N = total number of units of a particular type of equipment,
- Tp = the total period over which reliability data has been collected,
- Tf = the total number of failures of a particular component during that period, and
- Rdt = the repair downtime(the total downtime for unscheduled maintenance),

the following indices are then calculated:

- **Failure rate** [λ], using (2.16)
- **Mean time to repair** [MTTR], using (2.17)
- **Mean time between failures** [MTBF], using (2.18)
- **Mean time to failure** [MTTF], using (2.19) or (2.20)
- **Inherent availability** [Ai], using (2.21)

These indices are used as inputs into a software-based reliability model. If the petrochemical plant to be modelled does not have sufficient reliability data that can be used to compile the equipment reliability indices, the equipment reliability indices given in the IEEE Gold Book can be used. In any case, it would be prudent to compare the equipment reliability indices calculated for a particular plant with those given in the IEEE Gold Book. This is to confirm the credibility of the calculated indices. It should be noted that the IEEE Gold Book data is general and may not hold true for petrochemical plants.

## 3.3 COSTS ASSOCIATED WITH RELIABILITY

In order to carry out a reliability analysis using the reliability indices discussed in the previous paragraph, a particular plant in the factory whose cost of loss of production is well understood was selected. Further on in this model the portion of the factory's distribution network that supplies this plant with power is modelled using a software package with said reliability indices in order to establish the reliability of the existing topology. The economic value of this level of reliability was compared with other distribution topologies that had varying levels of reliability.

In this section, the average cost of loss of production for the chosen plant was established as well as the capital costs that are associated with increasing the reliability of the power supply to this plant and the savings that would have been associated with a lower level of reliability.

### 3.3.1 Cost of loss of production

As with most petrochemical and gas-to-liquid plants, the Sasol Secunda Factory is made up of a number of plants that convert feed stocks into products by means of chemical and mechanical processes. The plants follow one after the other in terms of a process flow whereby the products of one plant form the feedstock of the next plant. A description of Sasol Secunda's process flow [28] has been adapted and simplified into a flow chart shown in Figure 3.2.

It is not very often that a whole plant fails, especially since plants are designed to be able to continue operating even if a few of the components in the plant have failed. However, if the entire electricity supply to a plant is cut off the plant will not continue to operate. This is typically what happens if there is a failure in the distribution network that feeds power to the plant and usually such a failure results in a loss of production.

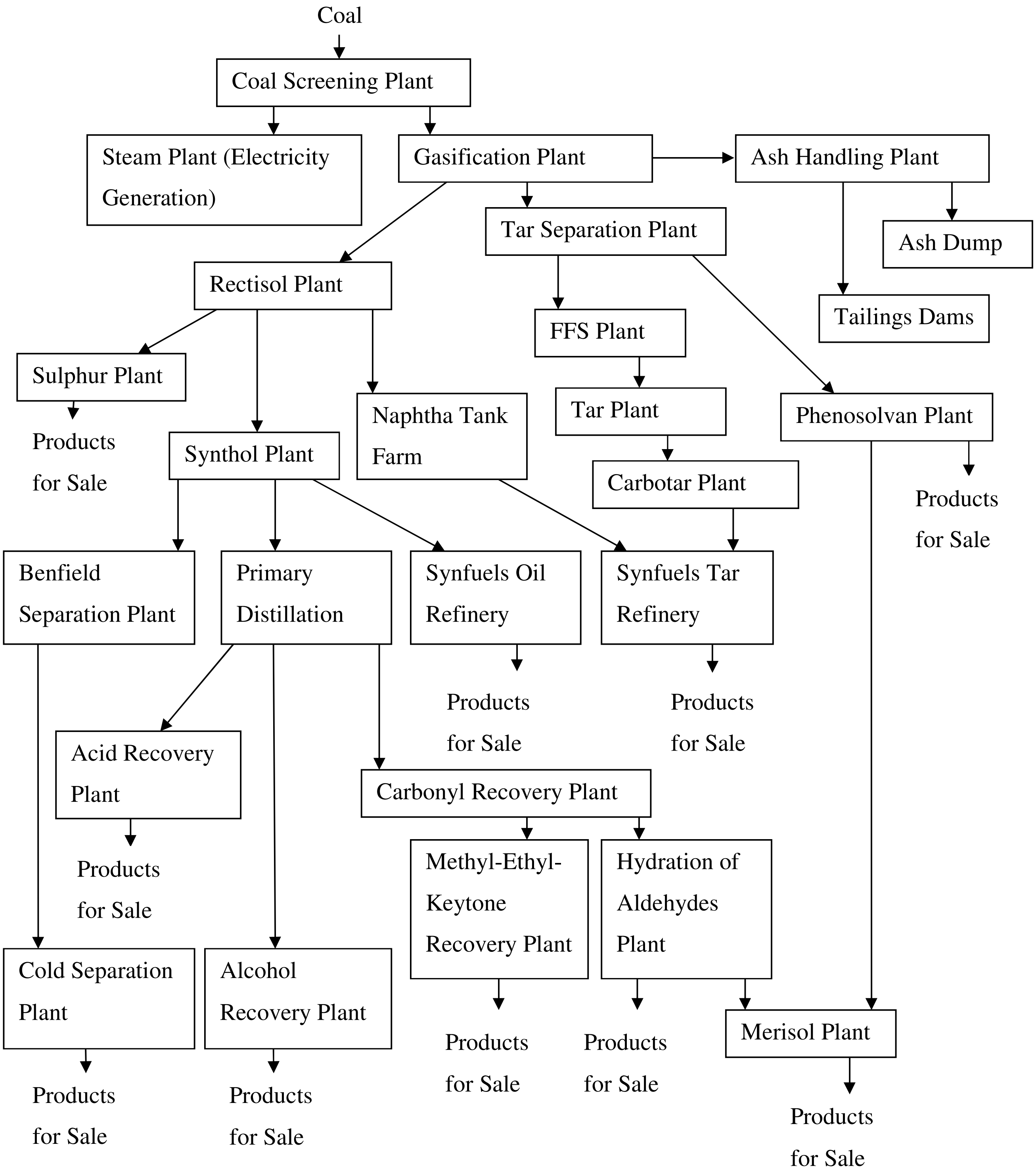

Figure 3.2 Simplified representation of process flow at Sasol Secunda

The cost of loss of production is different everywhere within the factory. The reason for this is that the different plants produce products in different quantities that have different economic values. Also, the plants that are downstream in the process rely on the plants upstream for their feed stocks. If an upstream plant fails, the impact of its failure is cascaded downstream.

To illustrate the point above, consider the failure of the Alcohol Recovery Plant in Figure 3.2. The cost of loss of production is the quantity of whatever products the Alcohol Recovery Plant produces that would have been produced during the time that the plant was down, multiplied by the sale prices of those products.

*Cost of loss of production* = *Downtime* × *Production rate of Alcohol Recovery Plant* × *Sale price of Alcohol Recovery Plant products* (3.16)

In contrast to the previous paragraph, if the Synthol Plant were to fail, the cost of loss of production would be the quantities of the products that would have been produced by the Synfuels Oil Refinery; Acid Recovery Plant; Cold Separation Plant; Alcohol Recovery Plant; Methyl-Ethyl-Keytone Recovery Plant; Hydration of Aldehydes Plant and Merisol Plant during the downtime multiplied by the respective sale prices of each product.

*Cost of Loss of Production* = *Downtime* × *[(Production Rate of Synfuels Oil Refinery* × *Sale Price of Synfuels Oil Refinery Products)* + *(Production Rate of Acid Recovery Plant* × *Sale Price of Acid Recovery Plant Products )* + *(Production Rate of Cold Separation Plant* × *Sale Price of Cold Separation Plant Products)*+ *(Production Rate of Alcohol Recovery Plant* × *Sale Price of Alcohol Recovery Plant Products)*+ *(Production Rate of Methyl-Ethyl-Keytone Recovery Plant* × *Sale Price of Methyl-Ethyl-Keytone Recovery Plant Products)*+ *(Production Rate of Hydration of Aldehydes Plant* × *Sale Price of Hydration of Aldehydes Plant Products)*+ *(Production Rate of Merisol Plant* × *Sale Price of Merisol Plant Products)]* (3.17)

A generic formula for calculating the cost of loss of production associated with a plant failure is the following:

$$CLP = DT \cdot \sum_{i=0}^{n} (PR_i \cdot SP_i) \qquad (3.18)$$

Where:

CLP = Cost of loss of production per failure (ZAR)
DT = Down time (hr)
n = Number of plants affected by failure
i = 0: Plant in which failure occurred
i = 1 to n: Plants that are downstream of plant in which failure occurred
$PR_i$ = Production rate of particular plant (kl/hr)
$SP_i$ = Sale price of product of particular plant (ZAR/kl)

The cascading effects of the failure of upstream plants are somewhat mitigated by the fact that many plants have a storage buffer of either their feed stocks or their products. This means that if an upstream plant only fails for a short time, it is possible that the downstream plants may still have enough feedstock to ride through the failure of the upstream plant. But if the upstream plant is not brought online quickly enough, the downstream plants will stop producing product too.

The amount of the storage buffer that is used up during the failure of an upstream plant does offset the production loss of that plant. However, when the system returns to normal again there will be a portion of production that will be used to fill the storage buffer instead of being sold. Thus, the advantage of a storage buffer is a delay to the interruption of production of a plant that is downstream of the plant in which the failure occurred. This causes the downtimes of all the plants that are downstream of the plant in which the failure occurred to be unique.

To show the effect of the storage buffer, (3.18) should be amended as follows:

$$CLP = \sum_{i=0}^{n} (DT_i \cdot PR_i \cdot SP_i) \tag{3.19}$$

Where:
$DT_i$ = Down time for a particular plant (hr)

It is important to note that the cost of loss of production that results from a power failure must include the financial savings that result from electrical energy not being consumed by the failed plant during its downtime. The cost of loss of production also includes any costs that may be associated with damage that may result from a loss of power. An example of such a situation would be solidification of heated liquid wax in a pipeline if it is allowed to cool in the pipeline due to a loss of power. The cost of loss of production does take into account the cost of cleaning out the pipe, as well as the cost of the production time that is lost while the pipe is unclogged. Finally, the cost of loss of production also includes the on-going costs that accrue to the plant even when the plant is shut down, such as the salaries of the employees.

The effect of savings in electricity costs, the costs associated with repairs and the on-going costs can be included in (3.19) as follows:

$$CLP = \sum_{i=0}^{n} [DT_i \cdot (PR_i \cdot SP_i + OC_i - P_i \cdot EC_i) + RC_i] \tag{3.20}$$

Where:

$P_i$ = Load not supplied during failure of particular plant (kW)

$EC_i$ = Cost of electrical energy of particular plant (ZAR/kWh)

$RC_i$ = Cost to repair damage resulting from failure of a particular plant (ZAR)

$OC_i$ = Ongoing costs of a particular plant when it is shut down (ZAR)

A further point that is worth noting is that in a case such as the one in which there is a possibility that liquid wax may solidify in a pipeline if it is allowed to cool as a result of a loss of normal power, the critical power will be used to shut the plant down in such a way that this is prevented from happening. It could mean that once normal power is lost, a pump that is supplied from the critical power network would pump all the liquid wax out of the pipeline into a vessel where it would take longer to solidify and/or a vessel that has heating capabilities.

The cost of loss of production of a plant is most useful when it is presented as a cost per hour. This way it can be used in reliability analyses. It is calculated by dividing the total cost of loss of production incurred by a particular plant in a particular period by the total downtime of that plant in said period.

$$Clh = \frac{CLP_{total}}{DT_{total}} \tag{3.21}$$

Where:

$CLP_{total}$ = Total cost of loss of production in a particular period (ZAR)

$DT_{total}$ = Total downtime in particular period (hr)

Clh = Cost of loss of production per hour (ZAR/hr)

### 3.3.2 Capital costs of increased reliability

Increasing reliability through design is usually associated with installing more equipment, thereby increasing the number of possible paths for electric current to flow through. The capital cost of increased reliability is established by obtaining quotes from vendors for the supply and installation of power distribution equipment.

## 3.4 RELIABILITY ANALYSIS

The availability of the point of interest in the distribution network (possibly the reticulation substation of a particular plant) is established by modelling the distribution network up to that point. This value for the availability of the point of interest is converted into a number of hours of downtime per year and multiplied by the average cost of loss of production per hour in order to arrive at an expected cost of loss of production per year.

$$U = 1 - A \tag{3.22}$$

$$E = U \cdot 8760 \tag{3.23}$$

$$Cly = Clh \cdot E \tag{3.24}$$

Where:

A = Availability of reticulation substation of a particular plant (p.u.)
U = Unavailability of reticulation substation of a particular plant (p.u.)
E = Expected downtime of reticulation substation of a particular plant (hr/year)
Clh = Cost of loss of production per hour (ZAR/hr)
Cly = Cost of loss of production per year (ZAR/year)

Once this cost of loss of production per year has been established, the PV of this calculated annual loss of production over the life of the plant is added to the capital cost of building a particular network topology. The resulting value is the cost of ownership of the plant only with regard to the reliability of the design of the distribution network.

$$CP = L \cdot Cly \tag{3.25}$$

$$CO = CP + CC \tag{3.26}$$

Where:

L = Expected life of plant (years)
CP = Expected cost of loss of production for life of plant (ZAR)

CC = Cost to build distribution network (ZAR)
CO = Expected cost of ownership of plant (ZAR)

When comparing the cost of ownership of alternative topologies the best method is to compare the total cost of each alternative topology. Another common method is to find the incremental cost in all alternatives over a base, or least expensive, topology. Using the incremental cost method may introduce a slight error into the economic comparisons, thus the total cost method is used.

One more point that is worth noting is the fact that the distribution network that feeds the point of interest is only a very small portion of a very large distribution network. When calculating the capital cost of a network topology, only the components that make up the distribution network that feed the point of interest are included. This is to prevent the capital cost of building the entire network from skewing the results of the economic analysis. The capital costs associated with building the whole network would be disproportionately greater than the cost of loss of production at the point of interest.

# 4 APPLICATION OF MODEL TO SASOL PLANT DATA

The first objective of this study is to calculate the reliability indices of all the types of equipment used in the distribution network using formulas 2.17 to 2.21. In order to do this the total number of units of each type of equipment that is used in the distribution network needs to be established. In addition, the total number of failures of each type of equipment needs to be determined.

## 4.1 EQUIPMENT DATA

There are essentially two distribution networks that supply the power that drives the processes in the Sasol Secunda Factory. There is the normal power distribution network that operates at 132kV and 33kV. This network feeds the bulk of the load in the factory and forms the link between the power supply from the utility, the generation plants in the factory and the 6.6kV reticulation networks. The second network is the critical power distribution network that operates at 11kV and 6.6kV. It is also fed by the generation plants in the factory as well as from the utility. However, if there is a failure in the supply from the utility, an island condition arises whereby all the loads that are fed by the normal power network are shed and only the loads on the critical power network are fed by the generation plants. In addition, there is more redundancy in the topology of the critical power network so that if the power supply to a particular plant in the factory fails, it is likely that the critical power will still be available. In this case, all the loads fed from the normal power network are shed while the loads on the critical power network will still be powered. The purpose of the critical supply network is to allow a particular plant to shut down safely in the event that its normal power supply is lost. Thus the reliability of the critical power network is much higher than that of the normal power network, but the cost of failure is much higher in the critical power network than in the normal power network. For this reason, the reliability data for equipment on the critical power network will be calculated separately from that of the normal power network. In order to achieve this, the equipment making up the critical power network is counted separately from that of the normal power network.

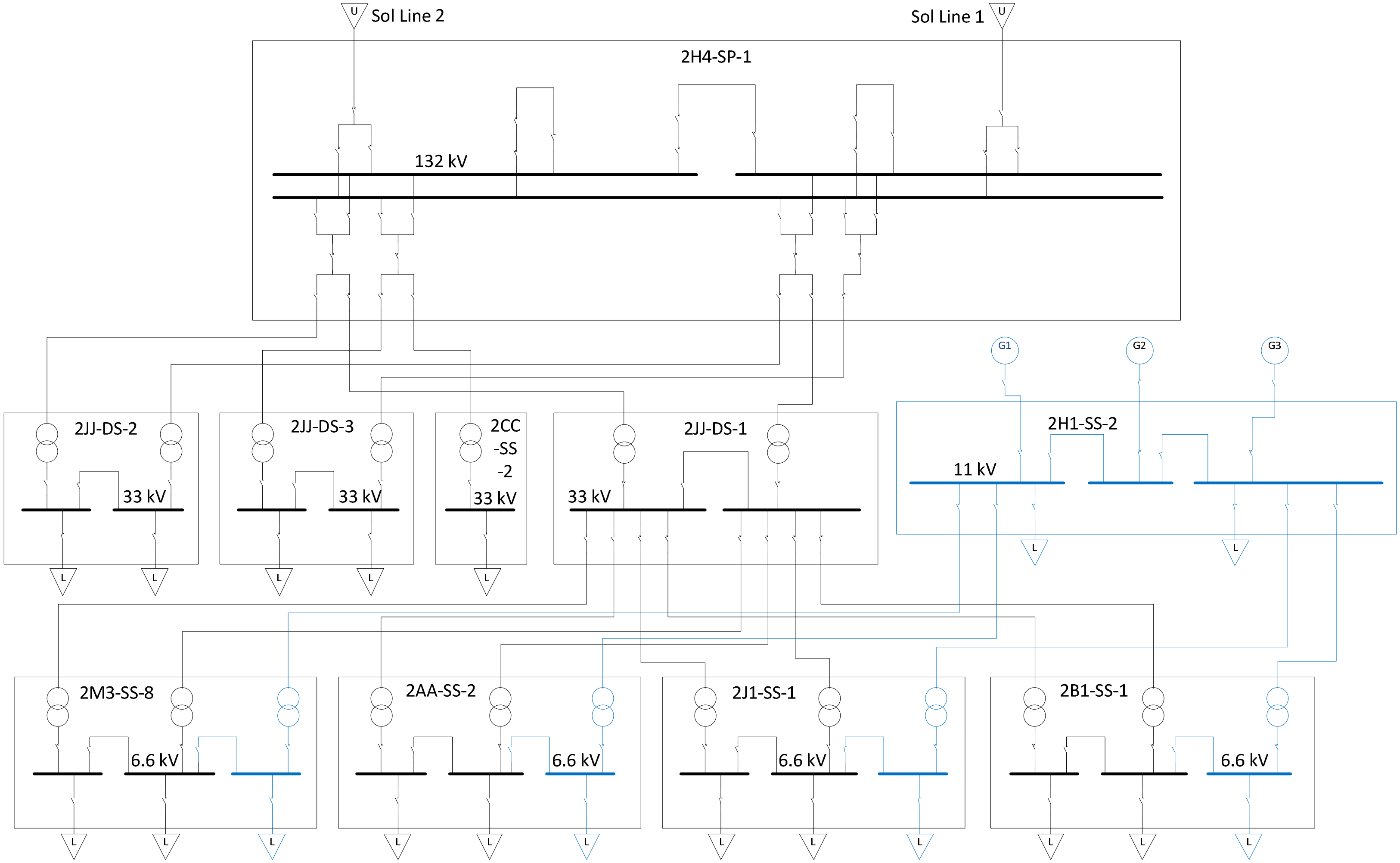

Figure 4.1 Simplified diagram of normal and critical power networks

Figure 4.1 illustrates the normal power distribution network in black and the critical power distribution network in blue.

### 4.1.1 Bus ducting

In Sasol, bus ducting is used to connect the secondary sides of transformers to the switchgear panels that the transformers are feeding. Thus, on the single-line diagrams, the lines between the secondary sides of transformers and the incoming circuit breakers of switchgear panels represent bus ducts. This is illustrated in Figure 4.2.

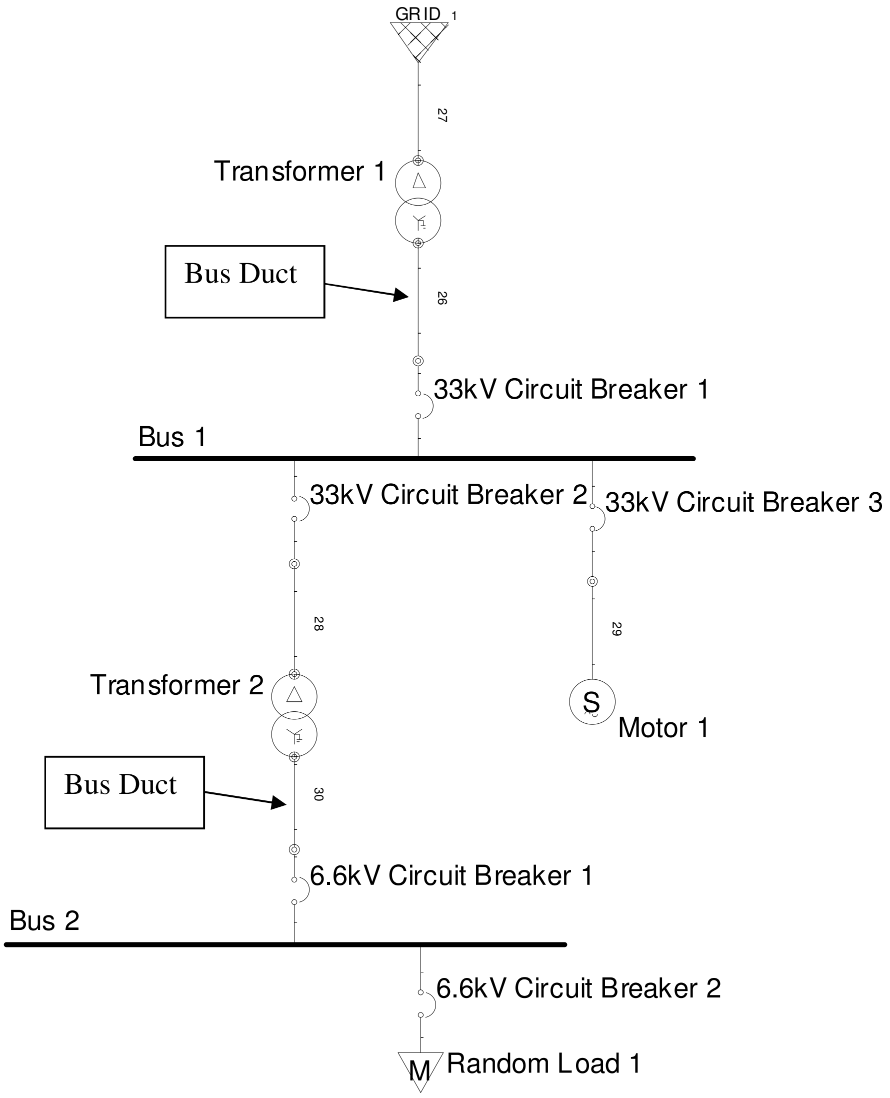

Figure 4.2 Example of how bus ducting is illustrated on a single-line diagram

It is not possible to tell from the single-line diagrams what the length of each bus duct is. Therefore a length of 20m for every bus duct is assumed because the average length of bus duct in the factory is about 20m. Thus the total length of bus ducting installed is the number of bus ducts installed x 20m.

The results of counting all the bus ducts shown on the single-line diagrams and the application of the formula described above are as follows:

- 6.6kV and 11kV critical power: 2620m
- 33kV and 132kV normal power: 1560m

### 4.1.2 Cables

All the substations in the factory have been identified and labelled on Google Earth. By establishing from the single-line diagrams which substations are connected to each other and routing the most likely cable runs along cable racks, cable trenches and pipe gantries, the amount of cable used to make up the two process distribution networks in the factory can be measured by using the “Ruler” function in Google Earth.

An example of such a cable length measurement is shown in Figure 4.3. This particular example shows the length of cable between substations 2H4-SP-1 and 2GG-DS-1. According to the “Ruler” function, this length is 1147.96m. A length of 1150m will be captured for this particular run of cable in the calculation of the total length of cable used in the factory. The total length of cable used in the distribution network of the factory is calculated by adding up all the lengths of cable run between the substations in the factory.

It is worth noting that we are interested only in the length of the cable runs, and not in the actual length of cable used in each run. Many of the cable runs are made up of multiple core cables run in parallel or trefoils of single-core cable. These details are not taken into consideration as it is assumed that if any of the cables making up a cable run is damaged the entire run fails or will fail shortly. Cables are usually installed in parallel to meet current-carrying capacity requirements, volt drop constraints and fault level withstand capability, and never for the purpose of redundancy. In order to achieve redundancy there are two runs of cable between 2H4-SP-1 and 2GG-DS-1, each running along a different route between the two substations, each fed from a different busbar in 2H4-SP-1 and feeding a different busbar in 2GG-DS-1.

Figure 4.3 Illustration of cable length measurement

The results of adding all the cable runs in the factory together as per the method described above are as follows:

- 6.6kV and 11kV critical power: 41 750m
- 33kV and 132kV normal power: 97 770m

### 4.1.3 Cable terminations

The total number of cable terminations that are used in the two process distribution networks throughout the factory is calculated by counting all the cable runs that were used to calculate the total length of cable used in the factory and multiplying the total by two. Once again, the effect of using cables in parallel is not taken into consideration. This is because if one termination should fail, a fault condition would arise and result in a trip.

The number of cable terminations per distribution network is as follows:

- 6.6kV and 11kV critical power: 324
- 33kV and 132kV normal power: 282

### 4.1.4 Circuit breakers

The number of circuit breakers used in the two process distribution networks is established by counting all the relevant circuit breakers shown on the single-line diagrams. No distinction is made between $SF_6$ circuit breakers, air circuit breakers, vacuum circuit breakers, fused isolator-contactor combinations or fuse-isolator-contactor combinations. In this sense, the term "circuit breaker" is used to describe the switching system in a switchgear panel that forms part of a feeder to a transformer or substation or an incomer from a transformer or other substation.

The number of circuit breakers per distribution network is as follows:

- 6.6kV and 11kV critical power: 342
- 33kV and 132kV normal power: 323

### 4.1.5 Generators

The term "generator" refers to internal combustion engine driven generator sets as well as steam turbines and open or closed-cycle gas turbines. The number of generators used in the distribution network is established by counting all the generators that are shown in the single-line diagrams that show the distribution network of the factory. Since the generators feed both the critical power distribution network and the normal power distribution network, no distinction is made between generators that are part of the one distribution network and those that are part of the other distribution network. It is, however, required that a generator be permanently installed and be generating onto the distribution network for it to be counted in this census.

The number of generators found in the distribution network totals 40.

### 4.1.6 Current-limiting reactors

A few series current-limiting reactors are installed in the distribution network. They are all associated with the generators and are therefore not allocated to either the critical power or normal power distribution network. The number of series current-limiting reactors installed is established by counting all the series current-limiting reactors on the factory single-line diagrams.

The number of series current-limiting reactors found in the distribution network totals 12.

### 4.1.7 Switchgear busses

The units in which the number of switchgear busses is measured in are the number of circuit breakers inside a switchgear board [18]. The number of switchgear bus units is established by counting the number of circuit breakers per relevant distribution board shown on the single-line diagrams for the factory.

The number of switchgear bus units per distribution network is as follows:

- 6.6kV and 11kV critical power: 361
- 33kV and 132kV normal power: 288

### 4.1.8 Transformers

Transformers are classified according to their primary voltages. If the primary side of a transformer is connected to the normal power distribution network, the transformer is seen to be part of the normal power distribution network, and if the primary side is connected to the critical power distribution network, the transformer is seen to be part of the critical power distribution network. Also, if a transformer is feeding a reticulation substation, the transformer is seen to be the last point of the distribution network before the reticulation network begins. The numbers of transformers used in the process power distribution networks are established by counting the relevant transformers shown on the single-line diagrams for the factory.

The number of transformers per distribution network is as follows:

- 6.6kV and 11kV critical power: 131
- 33kV and 132kV normal power: 142

### 4.1.9 Utilities

Sasol buys all of its electricity from Eskom, that is, it is supplied with electricity from one utility only. However, there are numerous incomers that enter the Sasol consumer substations. The units in which the utility supply is counted is the number of incomers from the utility at Sasol's two consumer substations. The number of units is established by counting all the incomers into the consumer substation that are shown on the single-line diagrams of the consumer substations.

The number of utility incomers is 4, namely two per substation.

## 4.2 CALCULATION OF EQUIPMENT RELIABILITY INDICES

Once the total number of units of a particular type of equipment has been established, the reliability indices of that particular type of equipment can be calculated.

The equipment reliability indices for the Sasol Secunda Factory are calculated using formulas 2.17 to 2.21 and the results are shown in Table 4.1.

As described in paragraph 3.2.1, the fault origins of certain trips have been reclassified as follows:

- In trips where the fault origins are found to be “Motor” or “Motor starter”, the trips are counted as “Switchgear bus” failures.
- In trips where the fault origins are found to be “NECR”, the trips are counted as “Transformer” failures.
- In trips where the fault origins are found to be “Cable joint”, the trips are counted as “Cable” failures.

In the trip data sheets that are described in paragraph 1.6.1, the downtimes associated with the trips were recorded for most of the trips, but not for all of the trips. Therefore, in order to calculate the MTTR for each type of equipment, the downtimes associated with each trip where the downtimes *were* recorded are added together and divided by the number of trips where the down times were recorded. For certain types of equipment, absolutely no downtimes were ever recorded. In these cases “Not captured” is shown in the MTTR field of Table 4.1.

According to the IEEE Gold Book [18], a minimum of eight field failures is necessary to have a reasonable chance of estimating the failure rate or average downtime per failure to within a factor of 2. Thus, it is expected that for all types of equipment that have experienced fewer than eight failures, the reliability indices calculated in Table 4.1 are not very reliable, that is, for bus ducts and cable terminations on the critical power network and all for current-limiting reactors.

In Table 4.1 the bus ducts are presented in units of one circuit meter while the cables are presented in units of one circuit kilometer.

Table 4.1 Results of calculation of reliability indices for equipment used in the distribution network of Sasol in Secunda

| **Equipment** | **Equipment Subclass** | **Unit Years** | **Failures** | **Failure Rate [λ]** | **MTTR [hrs]** | **MTBF [years]** | **MTTF [years]** | **Ai** |
|---|---|---|---|---|---|---|---|---|
| Bus Ducts | 6.6 & 11kV Critical | 49780 | 3 | 0.000060 | Not Captured | 16593.3333 | - | - |
| | 33 & 132kV Normal | 29640 | 8 | 0.000270 | Not Captured | 3705.0000 | - | - |
| | Combined | 79420 | 11 | 0.000139 | Not Captured | 7220.0000 | - | - |
| Cables | 6.6 & 11kV Critical | 793.25 | 13 | 0.016388 | 4 | 61.0192 | 61.0188 | 0.999992517 |
| | 33 & 132kV Normal | 1857.63 | 52 | 0.027993 | 29.4 | 35.7237 | 35.7203 | 0.999906052 |
| | Combined | 2650.88 | 65 | 0.024520 | 26.4 | 40.7828 | 40.7798 | 0.999926104 |
| Cable Terminations | 6.6 & 11kV Critical | 6156 | 4 | 0.000650 | Not Captured | 1539.0000 | - | - |
| | 33 & 132kV Normal | 5358 | 11 | 0.002053 | 6.75 | 487.0909 | 487.0901 | 0.999998418 |
| | Combined | 11514 | 15 | 0.001303 | 6.75 | 767.6000 | 767.5992 | 0.999998996 |
| Circuit Breakers | 6.6 & 11kV Critical | 6498 | 19 | 0.002924 | 8.2 | 342.0000 | 341.9991 | 0.999997263 |
| | 33 & 132kV Normal | 6137 | 88 | 0.014339 | 11.3 | 69.7386 | 69.7373 | 0.999981503 |
| | Combined | 12635 | 107 | 0.008469 | 11 | 118.0841 | 118.0829 | 0.999989366 |
| Generators | All | 760 | 12 | 0.015789 | 29.1 | 63.3333 | 63.3300 | 0.999947549 |
| Current-limiting Reactors | All | 228 | 1 | 0.004386 | 3 | 228.0000 | 227.9997 | 0.999998498 |
| Switchgear Busses | 6.6 & 11kV Critical | 6859 | 8 | 0.001166 | 8 | 857.3750 | 857.3741 | 0.999998935 |
| | 33 & 132kV Normal | 5472 | 32 | 0.005848 | 6.3 | 171.0000 | 170.9993 | 0.999995794 |
| | Combined | 12331 | 40 | 0.003244 | 6.6 | 308.2750 | 308.2742 | 0.999997556 |
| Transformers | 6.6 & 11kV Critical | 2489 | 50 | 0.020088 | 4.3 | 49.7800 | 49.7795 | 0.999990 |
| | 33 & 132kV Normal | 2698 | 85 | 0.031505 | 7.1 | 31.7412 | 31.7404 | 0.999974465 |
| | Combined | 5187 | 135 | 0.026027 | 6.7 | 38.4222 | 38.4215 | 0.999980 |
| Utilities | 132kV Normal | 76 | 19 | 0.25 | 2.5 | 4.0000 | 3.9997 | 0.999928653 |

# 5 VALIDATION OF STUDY WITH IEEE DATA

## 5.1 EQUIPMENT RELIABILITY INDICES FROM THE IEEE GOLD BOOK

The equipment reliability indices given in the IEEE Gold Book were normalised in certain instances before they could be compared to the equipment reliability indices that have been calculated for the Sasol Secunda Factory. That is because in these instances the units upon which the reliability indices are calculated are different, since in the IEEE Gold Book length is measured in feet as opposed to meters. Thus Table 5.1 shows the equipment reliability indices that are given by the IEEE Gold Book in imperial units as well are the same indices that are recalculated in metric units.

Table 5.1 Equipment reliability indices given by IEEE Gold Book

| **Equipment** | **Equipment Subclass** | **Failure Rate[λ](Imperial Units)** | **Failure Rate[λ](Metric Units)** | **MTTR [hrs]** |
|---|---|---|---|---|
| Bus Ducts | All Voltages | 0.000125 | 0.000410 | 9.5 |
| Cables | 601V to 15 000V | 0.006170 | 0.020243 | 35 |
| | Above 15000V | 0.003360 | 0.011024 | 16 |
| Cable Terminations | All Voltages | 0.000303 | 0.000303 | 23.4 |
| Circuit Breakers | Above 600V | 0.003600 | 0.003600 | 168 |
| Generators | All | 0.169100 | 0.169100 | 32.7 |
| Current-limiting Reactors | All | 0.015300 | 0.015300 | 1664 |
| Switchgear Busses | Above 600V | 0.001917 | 0.001917 | 36 |
| Transformers | Liquid Filled | 0.015300 | 0.015300 | 1178.5 |
| Utilities | None | - | - | - |

It is assumed that the IEEE Gold Book does not give reliability indices for utilities because of the vast range of possibilities regarding the reliability of utility supplies. More specifically, the reliability of a utility supply is directly in accordance with what a plant or factory is prepared to pay for, which is determined to a large extent by the value that the plant or factory management places on a reliable utility supply.

## 5.2 CRITICAL EVALUATION

The reliability indices that were calculated for the Sasol Secunda Factory were compared to the reliability indices that are given in the IEEE Gold Book in Table 5.2.

A factor of 10 was chosen to be the acceptable limit of deviation for the calculated equipment reliability indices to deviate from the equipment reliability indices that are given by the IEEE Gold Book. This is in line with the common practise to describe high levels of reliability by the number of nines appearing at the left of availability values [2]. If a manufacturing plant has “six nines” of availability this implies that the availability of the plant is 99.9999% (equivalent to 31.5 seconds of down time per year). A reliability of “seven nines”, or 99.99999% is equivalent to 3.2 seconds of down time per year. Thus, in reliability analysis, a factor of 10 is considered a significant step change.

The indices given in the IEEE Gold Book represent the industry average and it is quite possible that Sasol’s reliability performance is well above, or even well below the industry average. Thus, the comparison between the reliability indices that were calculated for Sasol Secunda and the indices given in the IEEE Gold Book can more accurately be described as a sanity check to see that the calculated values are probable.

In the rest of this section, the comparison between the equipment reliability indices that were calculated for the Sasol Secunda Factory and those that are given by the IEEE Gold Book is discussed for each type of equipment.

### 5.2.1 Bus ducts

The factor of deviation of the calculated failure rate from the failure rate given in the IEEE Gold Book is 2.96, which is within the acceptable limit of deviation. From this comparison it appears that the failure rate for bus ducts in the Sasol Secunda Factory is almost three times better than the industry average.

There was not sufficient information captured in the trip data sheets to calculate a MTTR for bus ducts in the Sasol Secunda Factory.

### 5.2.2 Cables

The indices given by the IEEE Gold Book are separated into cables rated from 601V to 15000V and cables rated 15000V and above. The indices given for the cables rated from 601V to 15000V were compared to those calculated for the 6.6kV and 11kV critical power distribution network and the indices given for the cables rated 15kV and higher were compared to those calculated for the cables used in the 33kV and 132kV normal power distribution network.

The factor of deviation of the failure rate for the cables rated between 601V and 15kV is 1.24, which is within the acceptable limit. This also shows that the failure rate for cables used in the critical power network is 24% better than the industry average. The MTTR for these cables is almost nine times better in the Sasol Secunda Factory than the industry average.

For the cables rated 15kV and above, the failure rate for cables used in the normal power network of the Sasol Secunda Factory is almost 2.6 times more than the industry average and the MTTR is almost twice as long.

It is interesting to note that the reliability performance of cables used in the critical network is better than the industry average while that of the cables used in the normal power network is worse than the industry average. The higher failure rate in the normal power distribution network could be ascribed to a more lenient attitude toward overloading cables and less preventative maintenance. The shorter MTTR for cables used in the critical network could be ascribed to the high priority that is given to critical power cable failures by maintenance crews.

Table 5.2 Comparison between equipment reliability indices calculated for the Sasol Secunda Factory and those given by the IEEE Gold Book

| **Equipment** | **Equipment Subclass** | **Failure Rate IEEE Gold Book** | **Failure Rate Sasol Calculated** | **Factor of Deviation** | **MTTR [hrs] IEEE Gold Book** | **MTTR [hrs] Sasol Calculated** | **Factor of Deviation** |
|---|---|---|---|---|---|---|---|
| Bus Ducts | All Voltages | 0.000410 | 0.000139 | 2.96 | 9.5 | - | - |
| Cables | 601V to 15000V | 0.020243 | 0.016388 | 1.24 | 35 | 4 | 8.75 |
|  | Above 15000V | 0.011024 | 0.027993 | 0.39 | 16 | 29.4 | 0.54 |
| Cable Terminations | All Voltages | 0.000303 | 0.001303 | 0.23 | 23.4 | 6.75 | 3.47 |
| Circuit Breakers | Above 600V | 0.003600 | 0.008469 | 0.43 | 168 | 11 | *15.27 |
| Generators | All | 0.169100 | 0.015789 | 10.71 | 32.7 | 29.1 | 1.12 |
| Current-limiting Reactors | All | 0.015300 | 0.004386 | 3.49 | 1664 | 3 | *554.67 |
| Switchgear Busses | Above 600V | 0.001917 | 0.003244 | 0.59 | 36 | 6.6 | 5.45 |
| Transformers | Liquid Filled | 0.015300 | 0.026027 | 0.59 | 1178.5 | 6.7 | *175.90 |
| Utilities | - | - | 0.25 | - | - | 2.5 | - |

* Deviates significantly from IEEE Gold Book data

### 5.2.3 Cable terminations

The failure rate for cable terminations in the Sasol Secunda Factory is just over four times worse than the industry average while the MTTR is almost 3.5 times better.

### 5.2.4 Circuit breakers

The calculated failure rate of circuit breakers for the Sasol Secunda plant is 2.3 times worse than the industry average that is given by the IEEE Gold Book.

The calculated MTTR for the Sasol Secunda Plant is 11 hours while the industry average that is given by the IEEE Gold Book is 168. Thus the MTTR that was calculated for Sasol Secunda deviates by a factor of 15.27 from the IEEE Gold Book MTTR, which is too great a deviation.

The IEEE Gold Book gives reliability indices for 10 different types of circuit breaker. These are shown in Table 5.3.

Table 5.3 Reliability indices given by IEEE Gold Book for circuit breakers

| **Equipment Subclass** | **Failure Rate** | **MTTR [Hours]** |
|---|---|---|
| Fixed (including molded case) - All | 0.0052 | 4.0 |
| 0 to 600V – All sizes | 0.0042 | 4.0 |
| 0 to 600A | 0.0035 | 1.0 |
| Above 600A | 0.0096 | 8.0 |
| Above 600V | 0.0176 | 3.8 |
| Metal-clad draw-out type – All | 0.0030 | 7.6 |
| 0 to 600V – All sizes | 0.0027 | 4.0 |
| 0 to 600A | 0.0023 | 1.0 |
| Above 600A | 0.0030 | 5.0 |
| Above 600V | 0.0036 | 168.0 |

The type of circuit breakers that are used in the process power distribution networks of the Sasol Secunda Factory are metal-clad draw-out type rated above 600V and that is why the

MTTR of 168 hours from the IEEE Gold Book was compared to the 11 hours that were calculated for the Sasol Secunda Factory. However, this value of 168 hours is more than 16 times higher than the values for all the other types of circuit breaker. It is not clear why the MTTR for metal-clad draw-out type circuit breakers rated above 600V is so high. It could be that a small sample size was used that included some abnormally long downtimes.

The MTTR of 11 hours that was calculated for the Sasol Secunda Factory is very close to the MTTR values for all the other types of circuit breaker. In particular, it is very close to the 7.6 hours that is given for all the metal-clad draw-out type circuit breakers combined. Thus, the MTTR value of 11 hours is seen to be reasonable.

### 5.2.5 Generators

The failure rate of generators that was calculated for the Sasol Secunda Factory is 10.71 times better than the industry average that was given by the IEEE Gold Book. This seems a little unlikely. It is worth noting, though, that most of these generators that operate at Sasol Secunda are gas turbines that are rated at 60MW, while those used to calculate the IEEE Gold Book values are all 7MW and smaller. It may be possible that the reliability requirements on such big steam turbines are that much greater than on smaller ones, in which case the failure rate that has been calculated for Sasol Secunda cannot be dismissed.

The MTTR calculated for Sasol Secunda differs from the IEEE Gold Book MTTR by 12%. This is a very small difference.

### 5.2.6 Current-limiting reactors

Only one failure of a current-limiting reactor was recorded in the entire sample period. This is a very small sample size and can thus not be trusted as being representative. That being said, the calculated value of the failure rate for Sasol Secunda is well within the acceptable limits of deviation from the values given in the IEEE Gold Book.

The time that it took to repair the one current-limiting reactor failure was three hours. This is because the temperature device on the transformer was filled with water due to heavy rain – a relatively quick fix.  However, the MTTR given by the IEEE Gold Book is 1664 hours. It should be noted that these 1664 hours are the average time it takes to repair a current-limiting reactor. The industry average time it takes to replace a current-limiting reactor is 38.7 hours. The decision to repair or replace a current-limiting reactor would certainly depend on the availability of a suitable spare unit. Due to the fact that the current-limiting reactors are on the critical power distribution network, it is assumed that the distribution department does have a spare or at the very least has access to a spare, and that, should a fault occur, the MTTR would be 38.7 hours.

### 5.2.7 Switchgear busses

The failure rate calculated for switchgear busses used in the Sasol Secunda Factory is 41% worse than the industry average given by the IEEE Gold Book, while the MTTR for the Sasol Secunda plant is 5.45 times faster. With a relatively large sample size, these values are quite probable.

### 5.2.8 Transformers

The failure rate calculated for transformers used in the Sasol Secunda Factory is 41% worse than the industry average given by the IEEE Gold Book.

The MTTR calculated for the Sasol Secunda Factory is 6.7 hours, while the industry average given by the IEEE Gold Book is 1178.5. That is a factor of deviation of 175.9, which is beyond of the bounds of what has been defined as an acceptable limit of deviation. It is worth noting, though, that this MTTR of 1,178.5 hours is the average time it takes to repair a transformer, while the average time it takes to replace a transformer is 192 hours. Compared to the Sasol Secunda MTTR of 6.7 hours there is still a factor of deviation of 28.7, which is still beyond the acceptable limit.

Despite the fact that the MTTR calculated for the Sasol Secunda plant is so different from that given by the IEEE Gold Book, 135 trips have been recorded in the Sasol Secunda Factory that are associated with transformer failures. That is the largest sample size for failures of any type of equipment in this study. Also, the longest downtime for a transformer failure in the Sasol Secunda plant was 72 hours, the second longest was 36 hours and the third longest was 18 hours (far less than 192 hours). Most transformer faults are associated with oil leaks and water ingress, which are quickly repaired, and the failures that are serious enough to lead to transformer replacements are resolved quickly because there are always suitable spare transformers on site.

Therefore, despite the fact that the calculated MTTR for transformers used in the Secunda factory is 28.7 times lower than that given in the IEEE Gold Book, it is still quite probable.

### 5.2.9 Utilities

As was discussed in Chapter5.1, the IEEE Gold Book does not give reliability indices for utilities. However, the failure rate for the utility supply to Sasol Secunda is 0.25 failures per year and the average downtime is 2.5 hours.

### 5.2.10 Overall comparison

Seventeen out of 20 reliability indices that have been calculated using the Sasol Secunda data are within the required factor of deviation. This is an 85% success rate, which indicates that the data collection and establishment of reliability indices for petrochemical plants has been successful.

Generally, the failure rate of equipment at Sasol in Secunda is similar to that of the industry average represented by the IEEE Gold Book data. The failure rates of five out of ten types of equipment were better at Sasol Secunda while the other five out of ten were worse.

In terms of MTTR, Sasol performed a lot better than the industry average given by the IEEE Gold Book data. Seven out of ten types of equipment had better MTTRs at Sasol in Secunda than the industry average. In two cases, the Sasol Secunda calculated indices were more than a factor of ten times better than the industry average given by the IEEE Gold Book data and it was proved that these high factors of deviation were acceptable because of the strong likelihood of the Sasol Secunda data being correct. This can be ascribed to the high cost of loss of production associated with a failure in a petrochemical plant and the high priority that is given to repairing failures that stop production.

## 5.3 RELIABILITY INDICES TO BE USED IN RELAIBILITY ANALYSIS

In view of the comparison that was made in the previous chapter between the indices that were calculated for the Sasol Secunda Factory and the indices that are given by the IEEE Gold Book, the indices that should be used in the reliability analysis of the Sasol Secunda Factory are given in Table 5.4.

Table 5.4 Reliability indices that should be used for reliability analysis of Sasol Secunda

| **Equipment** | **Equipment Subclass** | **Failure Rate [Failures per unit-year]** | **Source of Failure Rate** | **MTTR [hrs]** | **Source of MTTR** |
|---|---|---|---|---|---|
| Bus Ducts | All | 0.000139 | Sasol Secunda | 9.5 | IEEE Gold |
| Cables | Critical Power | 0.016388 | Sasol Secunda | 4 | Sasol Secunda |
| | Normal Power | 0.027993 | Sasol Secunda | 29.4 | Sasol Secunda |
| Cable Terminations | All | 0.001303 | Sasol Secunda | 6.75 | Sasol Secunda |
| Circuit Breakers | All | 0.008469 | Sasol Secunda | 11 | Sasol Secunda |
| Generators | All | 0.169100 | IEEE Gold | 29.1 | Sasol Secunda |
| Current-limiting Reactors | All | 0.004386 | Sasol Secunda | 38.7 | IEEE Gold |
| Switchgear Busses | All | 0.003244 | Sasol Secunda | 6.6 | Sasol Secunda |
| Transformers | All | 0.026027 | Sasol Secunda | 6.7 | Sasol Secunda |
| Utilities | All | 0.25 | Sasol Secunda | 2.5 | Sasol Secunda |

# 6 APPLICATION OF MODEL TO SASOL RELIABILITY EVALUATION

## 6.1 COSTS ASSOCIATED WITH RELIABILITY

### 6.1.1 Cost of loss of production

Table 6.1 lists the failures of the Ash Handling Plant that have occurred in the 19-year period over which data has been collected. Actually, Table 6.1 only lists the failures in the portion of the distribution network between distribution substation 2JJ-DS-1 and the reticulation substation for the Ash Handling Plant, 2M3-SS-8. There have been other instances where the whole Ash Handling Plant has been down due to mechanical failures in the ash plant that have been significant enough to cause the shutdown of the whole plant. In addition, there have been instances where all the loads feeding from distribution substation 2JJ-DS-1 have been lost due to a fault in the network feeding 2JJ-DS-1 and there have even been instances where the utility supply has failed and the whole factory has been down.

The reasons why we are only interested in the failures that are listed in Table 6.1 are:

- The engineers of the electrical distribution department were not interested in the downtimes of the Ash Handling Plant that were not as a result of failures in the electrical distribution network and thus did not record them.
- This study is concerned only with the recorded cost loss of production for downtime of the Ash Handling Plant.

The cost of loss of production that is recorded when the whole of distribution substation 2JJ-DS-1 loses power includes the cost of loss of production of all the plants that are fed from 2JJ-DS-1 and it is impossible to know from the data that has been captured by the engineers of the distribution department what portion of that total cost can be ascribed to the Ash Handling Plant. Thus, the data in Table 6.1 gives us only the information regarding the downtimes of the Ash Handling Plant when it is as a result of a failure of the electrical distribution network – the normal power distribution network, to be exact.

Table 6.1 Failures that have been recorded in distribution network that feeds Ash Handling Plant

| Trip No | Date | Voltage [kV] | Substation | Breaker | Feed to | Down Time [hrs] | Production loss | Detail of loss | Fault Origin | Exact cause of trip |
|---|---|---|---|---|---|---|---|---|---|---|
| 36/2007 | 11/4/2007 | 33 | 2JJ-DS-1 | 52-8 | 2M3-SS-8 | 50 | No | Not Recorded | Cable | Cable fault on cable from Brk 52-8 in 2JJ-DS-1 to 2M3-SS-8 Brk 52-2 |
| 31/2007 | 10/30/2007 | 33 | 2JJ-DS-1 | 52-7 | 2M3-EE-814A | 1 | Yes | R 1800000.00 | Cable | 33kV cable fault on Brk 52-7 feed to 2M3-EE-814 (2M3-SS8 Brk 52-1) |
| 27/2007 | 10/7/2007 | 33 | 2JJ-DS-1 | 52-8 | 2M3-SS-8 | 30 | No | Not Recorded | Cable | Cable fault on cable from brk 52-8 in 2JJ-DS-1 to 2M3-SS-1 Brk 52-2(Faults started occurring on this line after a tank was installed nearby. Construction of tank was associated with excavation) |
| 24/2007 | 7/23/2007 | 33 | 2JJ-DS-1 | 52-7 | 2M3-SS-8 |  | No | Not Recorded | Cable | Cable fault on cable from 2JJ-DS-1 Brk 52-7 to 2M3-SS-8 Brk 52-1 |
| 28/2006 | 10/19/2006 | 33 | 2JJ-DS-1 | 52-7 & 8 | 2M3-SS-8 | 12 | Yes | R 52000000.00 | Cable | During Excavation work two 33kV cables were damaged. One on each of the feeders to 2M3-SS-8 |

From the information given in Table 6.1 it can be seen that only two out of the five failures resulted in production losses. The reason for this is that there are two incomers into 2M3-SS-8, as shown in Figure 6.1. It can also be seen in Figure 6.1 that the 6.6kV switchboard in 3M3-SS-8 is made up of two busses with a bus coupler in between. The load on this board is then distributed over the two busses. If there is a fault on one of the incomers or transformers, the bus coupler closes so that the feeder that is still operational takes up the load of the entire board. The feeders and transformers are sized in such a way that one transformer has enough capacity to take up the load of the whole board. Thus it is possible for a feeder or transformer to fail without the whole plant losing power.

It is interesting to note that in trip no. 28/2006 both of the cable runs that feed 2M3-SS-8 were damaged in one excavation accident. Part of the point of feeding this reticulation substation with two cable runs is to avoid the whole plant going down in the event of something like cables being damaged during an excavation. The cable runs are supposed to be laid along different routes in order to benefit from this philosophy. Clearly, if both cable runs were damaged in one excavation accident, the cables were laid right next to each other and the benefit was lost.

In order to calculate the average cost of loss of production for the Ash Handling Plant, the first step is to convert the cost of loss of production values into present values [PVs]. This is because the failures that have resulted in losses in production have occurred in different years, and, due to the time value of money, these values are not comparable. The formula used to calculate PV is as follows:

$$PV = Val \times (1 + r)^n \tag{6.1}$$

Where:

$Val$ = the value of the cost of loss of production in the year that it occurred

$r$ = the rate of return or inflation rate (chosen to be 10%), and

$n$ = the number of periods (years) that have passed since the failure

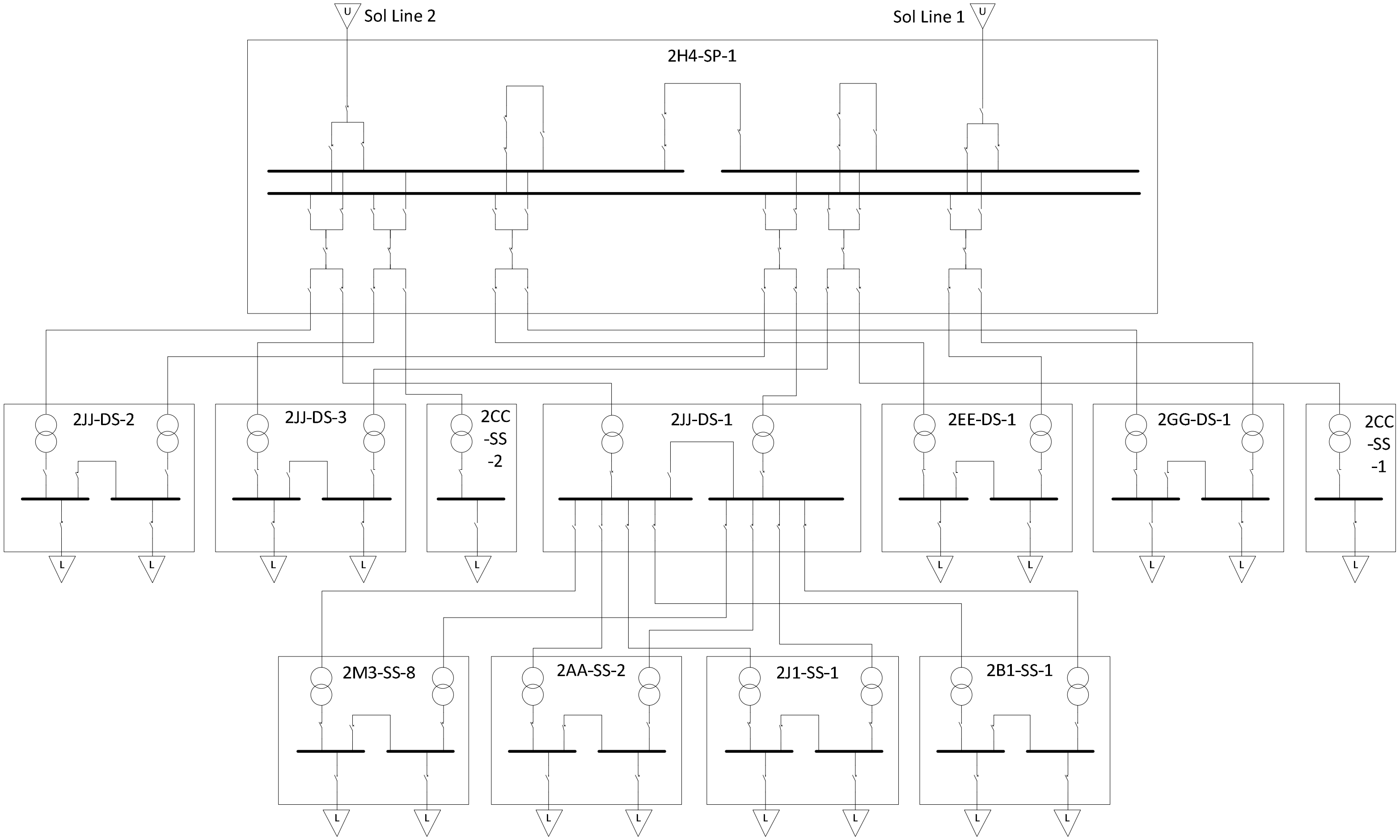

Figure 6.1 Single-line diagram of distribtion network that feeds Ash Handling Plant Substation

Thus the PV for trip no. 31/2007 was R2,395,800 and the PV for trip no. 28/2006 was R76,133,200 in 2010. These values were recorded by the engineers who investigated the trips and not calculated in this study.

In order to calculate the average cost of loss of production, the following formula is used:

$$C_{ave} = \frac{\sum C_{trip}}{\sum P_{trip}} \tag{6.2}$$

Where:

$C_{ave}$ = the average cost of loss of production,

$C_{trip}$ = the cost of loss of production for each trip, and

$P_{trip}$ = the total period of downtime for each trip

Thus, for the Ash Handling Plant, the average cost of loss of production in 2010 was R6,040,692.30 per hour.

It is important to note that in the Ash Handling Plant, as with most plants, the relationship between the cost of loss of production and the duration of downtime is not linear. If there had been more trip events that have resulted in a cost of loss of production, a table would have been drawn up that assigned different cost of loss of production values for different durations of downtime.

In Table 1.1, the one-hour interruption costs for plants in various industries are shown. These values are based on a University of Saskatchewan survey and are presented in 2001 dollars [2]. The interruption cost for one hour of a crude petroleum plant in 2001 is given as $276.01 per kW and the interruption cost for industrial plants on average is $8.40 per kW. For a plant that draws about 14MW of power (such as the Ash Handling Plant) these values are translated to R68.34million and R2.1million respectively in 2010 equivalent values using an exchange rate of R7.50 to the US dollar. Since the average cost of loss of production of R6,040,692.30 per hour that has been calculated for the Ash Handling Plant falls within this range, it is considered to be a probable value.

### 6.1.2 Capital costs associated with increased reliability

The costs of the equipment that would be required to increase the reliability of a distribution network in 2010 equivalent prices are estimated in Table 6.2. An attempt has been made to include the costs of installation and peripheral materials such as plinths and cable racking associated with each item of equipment.

## 6.2 RELIABILITY ANALYSIS CALCULATIONS

In this section, five different network topologies are analysed and compared with one another. They are the following:

- Existing Topology (dual radial)
- Alternative Topology 1 (simple radial)
- Alternative Topology 2 (primary selective)
- Alternative Topology 3 (primary selective with hospital bus)
- Alternative Topology 4 (secondary selective)

The alternative topologies are based on the topologies that are described in the IEEE Gold Book [18] as being commonly used distribution network topologies.

### 6.2.1 Existing 2M3-SS-8 topology (dual radial)

The existing distribution network that feeds 2M3-SS-8 (the reticulation substation for the Ash Handling Plant) is shown in Figure 6.2.

The reliability analysis report for the existing 2M3-SS-8 topology is shown in Table 6.3. The report shows that the availability of substation 2M3-SS-8 is 99.99252%.

The cost of building the existing distribution network that feeds 2M3-SS-8 is calculated in Table 6.4.

Table 6.2 Spread sheet indicating costs of equipment associated with increased reliability

| NO. | MATERIAL AND LABOUR DESCRIPTION | Unit | Unit Cost | Quantity | SUB-TOTAL COST | TOTAL COST |
|---|---|---|---|---|---|---|
| 1 | ***SWITCHGEAR*** | | | | | R0.00 |
| | 132kV Incomers, Feeders and Bus Couplers in Consumer Substation (including protection panels) | | R2160000.00 | | R0.00 | |
| | 33kV Incomers, Feeders and Bus Couplers in Distribution Stations (including protection panels) | ea | R1440000.00 | | R0.00 | |
| | 6.6kV Switchgear panels in Reticulation Substations | ea | R1008000.00 | | R0.00 | |
| 2 | ***TRANSFORMERS*** | | | | | R0.00 |
| | 132/33kV 48/80 MVA Transformers | ea | R12960000.00 | | R0.00 | |
| | 33/6,6kV 12.5/15.63 MVA Transformers | ea | R8640000.00 | | R0.00 | |
| 3 | ***CABLING*** | | | | | R0.00 |
| | 132kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R6048.00 | | R0.00 | |
| | 33kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R5040.00 | | R0.00 | |
| 4 | ***BUSDUCTING*** | | | | | R0.00 |
| | Busducting (All Voltages) | m | R72000.00 | | R0.00 | |
| 6 | ***SUBSTATION SURFACE AREA*** | | | | | R0.00 |
| | 132kV Consumer Substation | m² | R11520.00 | 0 | R0.00 | |
| | 33kV Distribution Substation | m² | R11520.00 | 0 | R0.00 | |
| | 6.6kV Reticulation Substation | m² | R11520.00 | 0 | R0.00 | |
| | ***TOTAL MATERIAL AND LABOUR*** | | | | | ***R0.00*** |
| | ***TOTAL ENGINEERING*** | | | | | ***R0.00*** |
| | ***GRAND TOTAL*** | | | | | ***R0.00*** |

The cost of ownership in terms of reliability for substation 2M3-SS-8 is shown in Table 6.5.

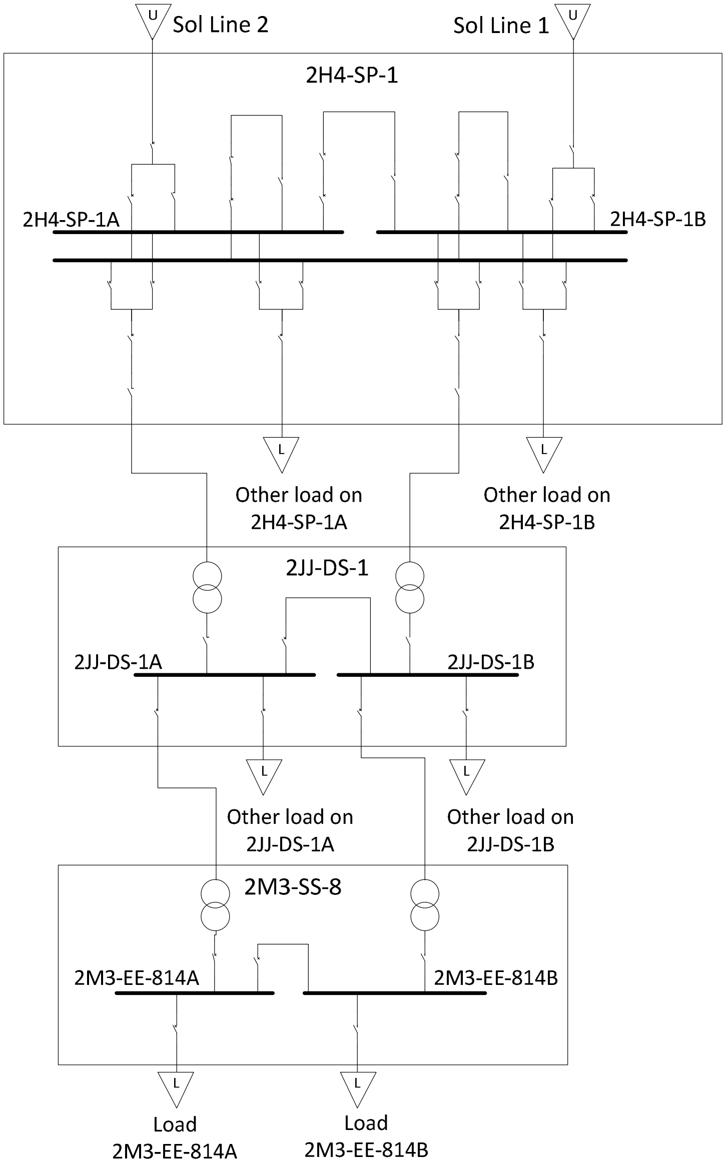

Figure 6.2 Single-line diagram of existing distribution network that feeds 2M3-SS-8

Table 6.3 Reliability analysis results of existing 2M3-SS-8 topology

| **Bus Name** | **Calculated Availability [%]** |
|---|---|
| Other Load on 2H4-SP-1A | 99.99892 |
| Other Load on 2H4-SP-1B | 99.99892 |
| Other Load on 2JJ-DS-1A | 99.99678 |
| Other Load on 2JJ-DS-1B | 99.99678 |
| Load 2M3-EE-814A | 99.99252 |
| Load 2M3-EE-814B | 99.99252 |

Table 6.4 Cost to build existing 2M3-SS-8 topology

| NO. | MATERIAL AND LABOUR DESCRIPTION | Unit | Unit Cost | Quantity | SUBTOTAL COST | TOTAL COST |
|---|---|---|---|---|---|---|
| 1 | ***SWITCHGEAR*** | | | | | R 77,760,000.00 |
| | 132kV Incomers, Feeders and Bus Couplers in Consumer Substation (including protection panels) | | R2160000.00 | 29 | R62640000.00 | |
| | 33kV Incomers, Feeders and Bus Couplers in Distribution Stations (including protection panels) | ea | R1440000.00 | 7 | R10080000.00 | |
| | 6.6kV Switchgear panels in Reticulation Substations | ea | R1008000.00 | 5 | R5040000.00 | |
| 2 | ***TRANSFORMERS*** | | | | | R43200000.00 |
| | 132/33kV 48/80 MVA Transformers | ea | R12960000.00 | 2 | R25920000.00 | |
| | 33/6,6kV 12.5/15.63 MVA Transformers | ea | R8640000.00 | 2 | R17280000.00 | |
| 3 | ***CABLING*** | | | | | R22196160.00 |
| | 132kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R6048.00 | 2820 | R17055360.00 | |
| | 33kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R5040.00 | 1020 | R5140800.00 | |
| 4 | ***BUSDUCTING*** | | | | | R23040000.00 |
| | Busducting (All Voltages) | m | R72000.00 | 320 | R23040000.00 | |
| 6 | ***SUBSTATION SURFACE AREA*** | | | | | R6105600.00 |
| | 132kV Consumer Substation | m² | R11520.00 | 435 | R5011200.00 | |
| | 33kV Distribution Substation | m² | R11520.00 | 70 | R806400.00 | |
| | 6.6kV Reticulation Substation | m² | R11520.00 | 25 | R288000.00 | |
| | ***TOTAL MATERIAL AND LABOUR*** | | | | | ***R172301760.00*** |
| | ***TOTAL ENGINEERING*** | | | | | ***R17230176.00*** |
| | ***GRAND TOTAL*** | | | | | ***R189531936.00*** |

Table 6.5 Calculation of cost of ownership for existing distribution topology

| Description | | Value | Units | Equation |
|---|---|---|---|---|
| **Cost to build distribution network [CC] =** | | R189531936.00 | | |
| **Availability of substation 2M3-SS-8 [A] =** | | 99.99252 | % | |
| | or | 0.9999252 | | |
| Unavailability of substation 2M3-SS-8 [U] = | | 7.48E-05 | | *U = 1 - A* |
| Expected downtime per year of 2M3-SS-8 [E] = | | 0.655248 | hours/year | *E = U x 8760* |
| **Average cost of loss of production per hour [Clh] =** | | R6040692.30 | /hour | |
| Expected cost of loss of production per year [Cly] = | | R3958151.55 | /year | *Cly = Clh x E* |
| **Expected life of plant [L] =** | | 50 | years | |
| Expected cost of loss of production for life of plant [CP] = | | R197907577.41 | | *CP = L x Cly* |
| **Expected cost of ownership [CO]** | | **R387439513.41** | | *CO = CP + CC* |

### 6.2.2 Alternative Topology 1 (simple radial)

In Alternative Topology 1, only the bare minimum is installed in terms of equipment. The single-line diagram for this topology is shown in Figure 6.3.

The reliability analysis report for Alternative Topology 1 is shown in Table 6.6and the availability of 2M3-SS-8 was found to be 99.95431%.

The capital cost for building Alternative Topology 1 is calculated in Table 6.7.

The total cost of ownership in terms of reliability for Alternative Topology 1 is calculated in Table 6.8.

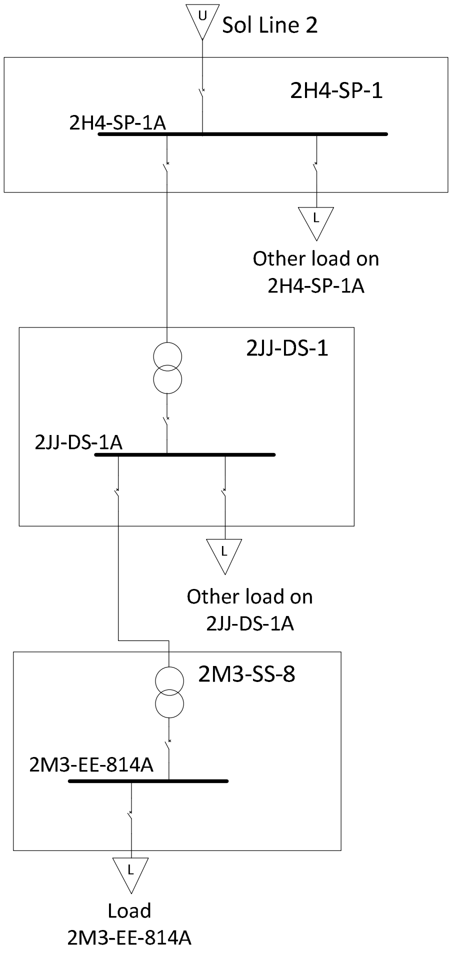

Figure 6.3 Single-line diagram of Alternative Topology 1

Table 6.6 Reliability analysis report for Alternative Topology 1

| **Bus Name** | **Calculated Availability [%]** |
|---|---|
| Other Load on 2H4-SP-1A | 99.98134 |
| Other Load on 2JJ-DS-1A | 99.96782 |
| Load 2M3-EE-814A | 99.95431 |

Table 6.7Capital cost of building Alternative Topology 1

| NO. | MATERIAL AND LABOUR DESCRIPTION | Unit | Unit Cost | Quantity | SUBTOTAL COST | TOTAL COST |
|---|---|---|---|---|---|---|
| 1 | ***SWITCHGEAR*** | | | | | R12816000.00 |
| | 132kV Incomers, Feeders and Bus Couplers in Consumer Substation (including protection panels) | | R2160000.00 | 3 | R6480000.00 | |
| | 33kV Incomers, Feeders and Bus Couplers in Distribution Stations (including protection panels) | ea | R1440000.00 | 3 | R4320000.00 | |
| | 6.6kV Switchgear panels in Reticulation Substations | ea | R1008000.00 | 2 | R2016000.00 | |
| 2 | ***TRANSFORMERS*** | | | | | R21600000.00 |
| | 132/33kV 48/80 MVA Transformers | ea | R12960000.00 | 1 | R12960000.00 | |
| | 33/6,6kV 12.5/15.63 MVA Transformers | ea | R8640000.00 | 1 | R8640000.00 | |
| 3 | ***CABLING*** | | | | | R11098080.00 |
| | 132kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R6048.00 | 1410 | R8527680.00 | |
| | 33kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R5040.00 | 510 | R2570400.00 | |
| 4 | ***BUSDUCTING*** | | | | | R2880000.00 |
| | Busducting (All Voltages) | m | R72000.00 | 40 | R2880000.00 | |
| 6 | ***SUBSTATION SURFACE AREA*** | | | | | R979200.00 |
| | 132kV Consumer Substation | m² | R11520.00 | 45 | R518400.00 | |
| | 33kV Distribution Substation | m² | R11520.00 | 30 | R345600.00 | |
| | 6.6kV Reticulation Substation | m² | R11520.00 | 10 | R115200.00 | |
| | ***TOTAL MATERIAL AND LABOUR*** | | | | | ***R49373280.00*** |
| | ***TOTAL ENGINEERING*** | | | | | ***R4937328.00*** |
| | ***GRAND TOTAL*** | | | | | ***R54310608.00*** |

Table 6.8 Total cost of ownership in terms of reliability for Alternative Topology 1

| Description | Value | Units | Equation |
|---|---|---|---|
| **Cost to build distribution network [CC] =** | R54310608.00 | | |
| **Availability of substation 2M3-SS-8 [A] =** | 99.95431 | % | |
| or | 0.9995431 | | |
| Unavailability of substation 2M3-SS-8 [U] = | 0.0004569 | | *U = 1 - A* |
| Expected downtime per year of 2M3-SS-8 [E] = | 4.002444 | hours/year | *E = U x 8760* |
| **Average cost of loss of production per hour [Clh] =** | R6040692.30 | /hour | |
| Expected cost of loss of production per year [Cly] = | R24177532.65 | /year | *Cly = Clh x E* |
| **Expected life of plant [L] =** | 50 | years | |
| Expected cost of loss of production for life of plant [CP] = | R1208876632.60 | | *CP = L x Cly* |
| **Expected cost of ownership [CO]** | **R1263187240.60** | | *CO = CP + CC* |

### 6.2.3 Alternative Topology 2 (primary selective)

In Alternative Topology 2, a second utility feeder is added to Alternative Topology 1. The single-line diagram for this topology is shown in Figure 6.4.

The reliability analysis report for Alternative Topology 2 is shown in Table 6.9and the availability of 2M3-SS-8 was found to be 99.97819%.

The capital cost for building Alternative Topology 2 is calculated in Table 6.10.

The total cost of ownership in terms of reliability for Alternative Topology 2 is calculated in Table 6.11.

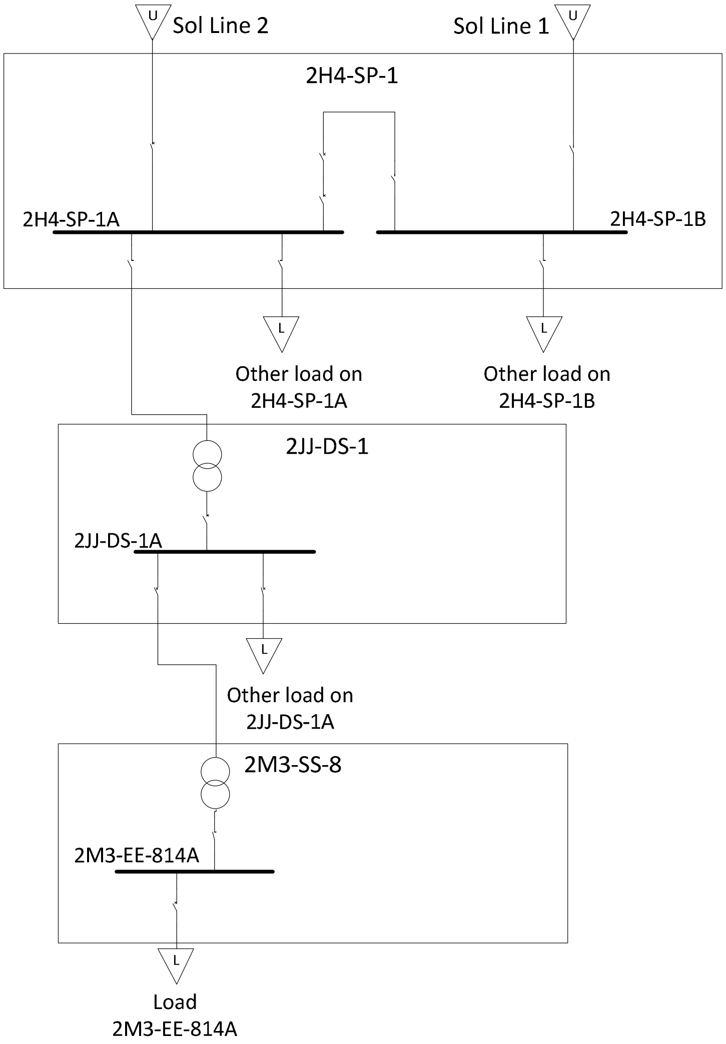

Figure 6.4 Single-line diagram of Alternative Topology 2

Table 6.9 Reliability analysis report for Alternative Topology 2

| **Bus Name** | **Calculated Availability [%]** |
|---|---|
| Other Load on 2H4-SP-1A | 99.99892 |
| Other Load on 2H4-SP-1B | 99.99892 |
| Other Load on 2JJ-DS-1A | 99.98540 |
| Load 2M3-EE-814A | 99.97189 |

Table 6.10 Capital cost of building Alternative Topology 2

| NO. | MATERIAL AND LABOUR DESCRIPTION | Unit | Unit Cost | Quantity | SUB-TOTAL COST | TOTAL COST |
|---|---|---|---|---|---|---|
| 1 | ***SWITCHGEAR*** | | | | | R23616000.00 |
| | 132kV Incomers, Feeders and Bus Couplers in Consumer Substation (including protection panels) | | R2160000.00 | 8 | R17280000.00 | |
| | 33kV Incomers, Feeders and Bus Couplers in Distribution Stations (including protection panels) | ea | R1440000.00 | 3 | R4320000.00 | |
| | 6.6kV Switchgear panels in Reticulation Substations | ea | R1008000.00 | 2 | R2016000.00 | |
| 2 | ***TRANSFORMERS*** | | | | | R21600000.00 |
| | 132/33kV 48/80 MVA Transformers | ea | R12960000.00 | 1 | R12960000.00 | |
| | 33/6,6kV 12.5/15.63 MVA Transformers | ea | R8640000.00 | 1 | R8640000.00 | |
| 3 | ***CABLING*** | | | | | R11098080.00 |
| | 132kV. Supply, installation, trenching and racking of SWA XLPE + KwenaEarthing cable | m | R6048.00 | 1410 | R8527680.00 | |
| | 33kV. Supply, installation, trenching and racking of SWA XLPE + KwenaEarthing cable | m | R5040.00 | 510 | R2570400.00 | |
| 4 | ***BUSDUCTING*** | | | | | R7200000.00 |
| | Busducting (All Voltages) | m | R72000.00 | 100 | R7200000.00 | |
| 6 | ***SUBSTATION SURFACE AREA*** | | | | | R1843200.00 |
| | 132kV Consumer Substation | m² | R11520.00 | 120 | R1382400.00 | |
| | 33kV Distribution Substation | m² | R11520.00 | 30 | R345600.00 | |
| | 6.6kV Reticulation Substation | m² | R11520.00 | 10 | R115200.00 | |
| | ***TOTAL MATERIAL AND LABOUR*** | | | | | ***R65357280.00*** |
| | ***TOTAL ENGINEERING*** | | | | | ***R6535728.00*** |
| | ***GRAND TOTAL*** | | | | | ***R71893008.00*** |

Table 6.11 Total cost of ownership in terms of reliability for Alternative Topology 2

| Description | | Value | Units | Equation |
|---|---|---|---|---|
| **Cost to build distribution network [CC] =** | | R71893008.00 | | |
| **Availability of substation 2M3-SS-8 [A] =** | | 99.97189 | % | |
| | or | 0.9997189 | | |
| Unavailability of substation 2M3-SS-8 [U] = | | 0.0002811 | | *U = 1 - A* |
| Expected downtime per year of 2M3-SS-8 [E] = | | 2.462436 | hours/year | *E = U x 8760* |
| **Average cost of loss of production per hour [Clh] =** | | R6040692.30 | /hour | |
| Expected cost of loss of production per year [Cly] = | | R14874818.18 | /year | *Cly = Clh x E* |
| **Expected life of plant [L] =** | | 50 | years | |
| Expected cost of loss of production for life of plant [CP] = | | R743740909.22 | | *CP = L x Cly* |
| **Expected cost of ownership [CO]** | | **R815633917.22** | | *CO = CP + CC* |

### 6.2.4 Alternative Topology 3 (primary selective with hospital bus)

In Alternative Topology 3, a hospital bus is added to the consumer substation 2H4-SP-1 of Alternative Topology 2. The single-line diagram for this topology is shown in Figure 6.5.

The reliability analysis report for Alternative Topology 3 is shown in Table 6.12and the availability of 2M3-SS-8 was found to be 99.97083%.

The capital cost for building Alternative Topology 3 is calculated in Table 6.13

The total cost of ownership in terms of reliability for Alternative Topology 3 is calculated in Table 6.14.

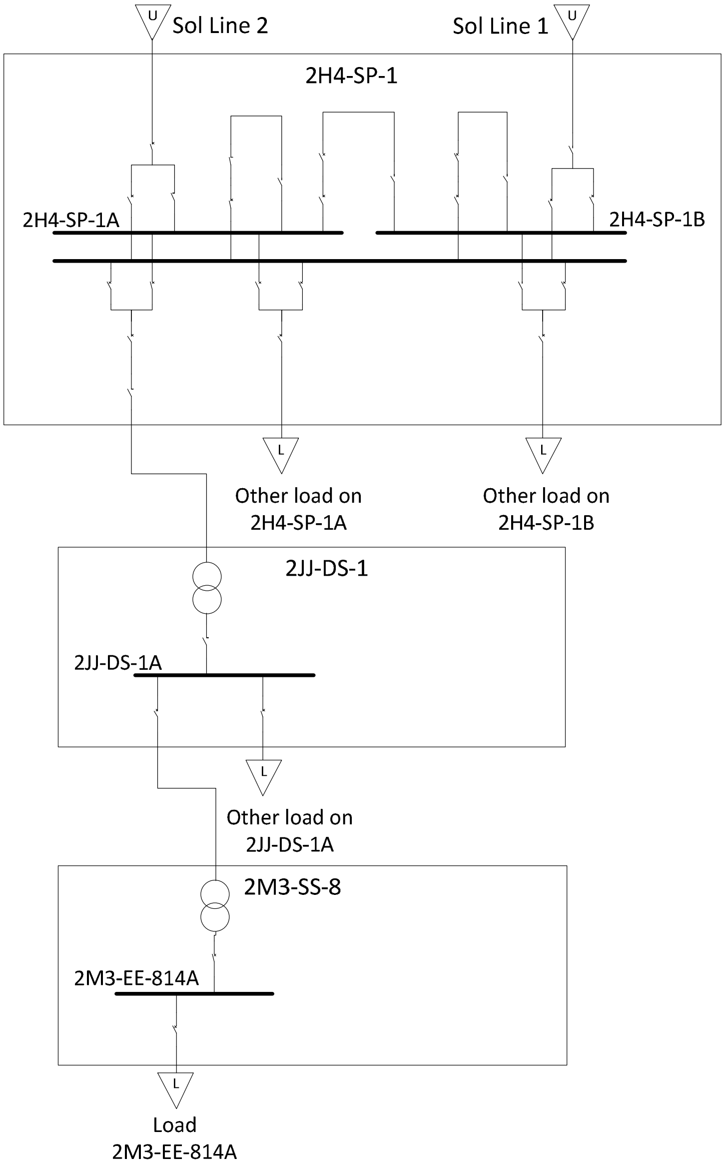

Figure 6.5 Single-line diagram of Alternative Topology 3

Table 6.12 Reliability analysis report for Alternative Topology 3

| **Bus Name** | **Calculated Availability [%]** |
|---|---|
| Other Load on 2H4-SP-1A | 99.99892 |
| Other Load on 2H4-SP-1B | 99.99892 |
| Other Load on 2JJ-DS-1A | 99.98434 |
| Load 2M3-EE-814A | 99.97083 |

Table 6.13 Capital cost of building Alternative Topology 3

| NO. | MATERIAL AND LABOUR DESCRIPTION | Unit | Unit Cost | Quantity | SUBTOTAL COST | TOTAL COST |
|---|---|---|---|---|---|---|
| 1 | ***SWITCHGEAR*** | | | | | R68,976,000.00 |
| | 132kV Incomers, Feeders and Bus Couplers in Consumer Substation (including protection panels) | | R2160000.00 | 29 | R62640000.00 | |
| | 33kV Incomers, Feeders and Bus Couplers in Distribution Stations (including protection panels) | ea | R1440000.00 | 3 | R4320000.00 | |
| | 6.6kV Switchgear panels in Reticulation Substations | ea | R1008000.00 | 2 | R2016000.00 | |
| 2 | ***TRANSFORMERS*** | | | | | R21600000.00 |
| | 132/33kV 48/80 MVA Transformers | ea | R12960000.00 | 1 | R12960000.00 | |
| | 33/6,6kV 12.5/15.63 MVA Transformers | ea | R8640000.00 | 1 | R8640000.00 | |
| 3 | ***CABLING*** | | | | | R11098080.00 |
| | 132kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R6048.00 | 1410 | R8527680.00 | |
| | 33kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R5040.00 | 510 | R2570400.00 | |
| 4 | ***BUSDUCTING*** | | | | | R20160000.00 |
| | Busducting (All Voltages) | m | R72000.00 | 280 | R20160000.00 | |
| 6 | ***SUBSTATION SURFACE AREA*** | | | | | R5472000.00 |
| | 132kV Consumer Substation | m² | R11520.00 | 435 | R5011200.00 | |
| | 33kV Distribution Substation | m² | R11520.00 | 30 | R345600.00 | |
| | 6.6kV Reticulation Substation | m² | R11520.00 | 10 | R115,200.00 | |
| | ***TOTAL MATERIAL AND LABOUR*** | | | | | ***R127306080.00*** |
| | ***TOTAL ENGINEERING*** | | | | | ***R12730608.00*** |
| | ***GRAND TOTAL*** | | | | | ***R140036688.00*** |

Table 6.14 Total cost of ownership in terms of reliability for Alternative Topology 3

| Description | | Value | Units | Equation |
|---|---|---|---|---|
| **Cost to build distribution network [CC] =** | | R140036688.00 | | |
| **Availability of substation 2M3-SS-8 [A] =** | | 99.97083 | % | |
| | or | 0.9997083 | | |
| Unavailability of substation 2M3-SS-8 [U] = | | 0.0002917 | | *U = 1 - A* |
| Expected downtime per year of 2M3-SS-8 [E] = | | 2.555292 | hours/year | *E = U x 8760* |
| **Average cost of loss of production per hour [Clh] =** | | R6040692.30 | /hour | |
| Expected cost of loss of production per year [Cly] = | | R15435732.71 | /year | *Cly = Clh x E* |
| **Expected life of plant [L] =** | | 50 | years | |
| Expected cost of loss of production for life of plant [CP] = | | R771786635.43 | | *CP = L x Cly* |
| **Expected cost of ownership [CO]** | | **R911823323.43** | | *CO = CP + CC* |

### 6.2.5 Alternative Topology 4 (secondary selective)

In Alternative Topology 4, a second feeder is added between consumer substation 2H4-SP-1 and distribution substation JJ-DS-1 and the bus in JJ-DS-1 is split in two with a bus coupler. The single-line diagram for this topology is shown in Figure 6.6.

The reliability analysis report for Alternative Topology 4 is shown in Table 6.15and the availability of 2M3-SS-8 was found to be 99.98220%.

The capital cost for building Alternative Topology 4 is calculated in Table 6.16.

The total cost of ownership in terms of reliability for Alternative Topology 4 is calculated in Table 6.17.

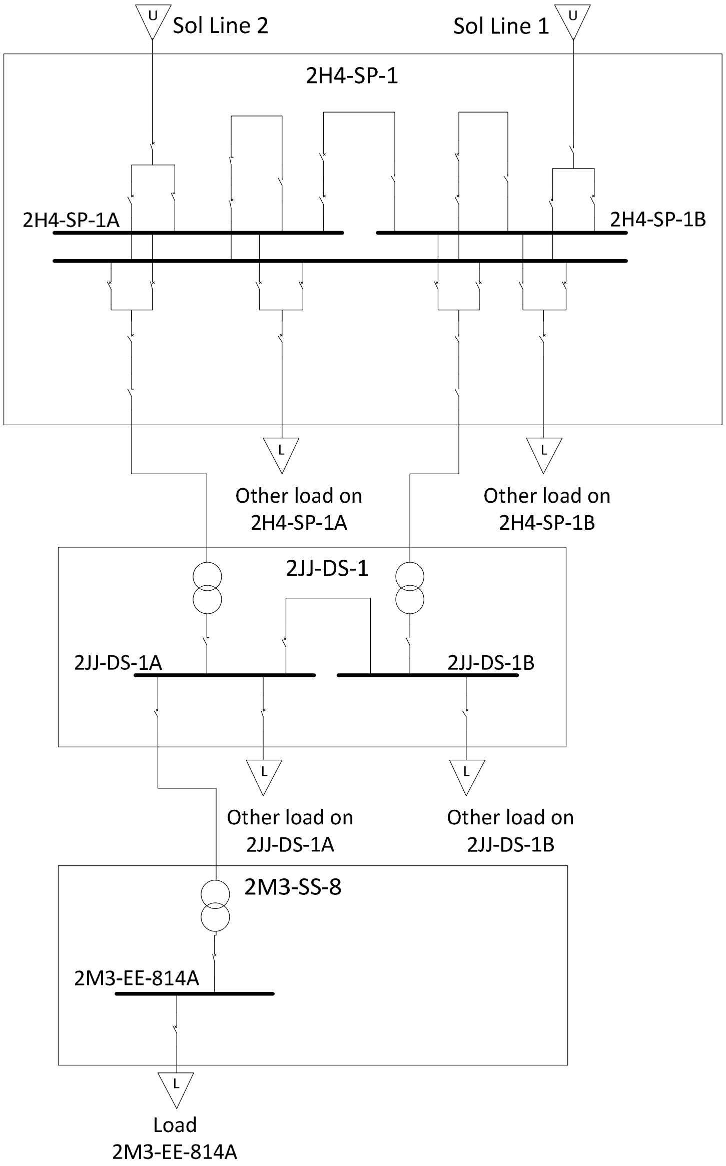

Figure 6.6 Single-line diagram of Alternative Topology 4

Table 6.15 Reliability analysis report for Alternative Topology 4

| **Bus Name** | **Calculated Availability [%]** |
|---|---|
| Other Load on 2H4-SP-1A | 99.99892 |
| Other Load on 2H4-SP-1B | 99.99892 |
| Other Load on 2JJ-DS-1A | 99.99572 |
| Other Load on 2JJ-DS-1B | 99.99572 |
| Load 2M3-EE-814A | 99.98220 |

Table 6.16 Capital cost of building Alternative Topology 4

| NO. | MATERIAL AND LABOUR DESCRIPTION | Unit | Unit Cost | Quantity | SUB-TOTAL COST | TOTAL COST |
|---|---|---|---|---|---|---|
| 1 | ***SWITCHGEAR*** | | | | | R 74,736,000.00 |
| | 132kV Incomers, Feeders and Bus Couplers in Consumer Substation (including protection panels) | | R2160000.00 | 29 | R62640000.00 | |
| | 33kV Incomers, Feeders and Bus Couplers in Distribution Stations (including protection panels) | ea | R1440000.00 | 7 | R10080000.00 | |
| | 6.6kV Switchgear panels in Reticulation Substations | ea | R1008000.00 | 2 | R2016000.00 | |
| 2 | ***TRANSFORMERS*** | | | | | R34560000.00 |
| | 132/33kV 48/80 MVA Transformers | ea | R12960000.00 | 2 | R25920000.00 | |
| | 33/6,6kV 12.5/15.63 MVA Transformers | ea | R8640000.00 | 1 | R8640000.00 | |
| 3 | ***CABLING*** | | | | | R19 625760.00 |
| | 132kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R6048.00 | 2820 | R17055360.00 | |
| | 33kV. Supply, installation, trenching and racking of SWA XLPE + Kwena Earthing cable | m | R5040.00 | 510 | R2570400.00 | |
| 4 | ***BUSDUCTING*** | | | | | R21600000.00 |
| | Busducting (All Voltages) | m | R72000.00 | 300 | R21600000.00 | |
| 6 | ***SUBSTATION SURFACE AREA*** | | | | | R5932800.00 |
| | 132kV Consumer Substation | m² | R11520.00 | 435 | R5011200.00 | |
| | 33kV Distribution Substation | m² | R11520.00 | 70 | R806400.00 | |
| | 6.6kV Reticulation Substation | m² | R11520.00 | 10 | R115200.00 | |
| | ***TOTAL MATERIAL AND LABOUR*** | | | | | ***R156454560.00*** |
| | ***TOTAL ENGINEERING*** | | | | | ***R15645456.00*** |
| | ***GRAND TOTAL*** | | | | | ***R172100016.00*** |

Table 6.17 Total cost of ownership in terms of reliability for Alternative Topology 4

| Description | Value | Units | Equation |
|---|---|---|---|
| **Cost to build distribution network [CC] =** | R172100016.00 | | |
| **Availability of substation 2M3-SS-8 [A] =** | 99.9822 | % | |
| or | 0.999822 | | |
| Unavailability of substation 2M3-SS-8 [U] = | 0.000178 | | *U = 1 - A* |
| Expected downtime per year of 2M3-SS-8 [E] = | 1.55928 | hours/year | *E = U x 8760* |
| **Average cost of loss of production per hour [Clh] =** | R6040692.30 | /hour | |
| Expected cost of loss of production per year [Cly] = | R9419130.69 | /year | *Cly = Clh x E* |
| **Expected life of plant [L] =** | 50 | years | |
| Expected cost of loss of production for life of plant [CP] = | R470956534.48 | | *CP = L x Cly* |
| **Expected cost of ownership [CO]** | **R643056550.48** | | *CO = CP + CC* |

## 6.3 DISCUSSION OF RESULTS

The results from the reliability analyses and cost calculations are summarised in Table 6.18 and illustrated on a graph in Figure 6.7.

Table 6.18 Results from reliability analysis and cost calculations

| Distribution Network Topology | Availability [%] | Capital Cost | Cost of Loss of Production | Cost of Ownership | Cost of Ownership [p.u.] |
|---|---|---|---|---|---|
| Alternative Topology 1 | 99.95431 | R54310608.00 | R1208876632.60 | R1263187240.60 | 3.26 |
| Alternative Topology 2 | 99.97189 | R71893008.00 | R743740909.22 | R815633917.22 | 2.11 |
| Alternative Topology 3 | 99.97083 | R140036688.00 | R771786635.43 | R911823323.43 | 2.35 |
| Alternative Topology 4 | 99.98220 | R172100016.00 | R470956534.48 | R643056550.48 | 1.66 |
| Existing feed to 2M3-SS-8 | 99.99252 | R189531936.00 | R197907577.41 | R387439513.41 | 1.00 |

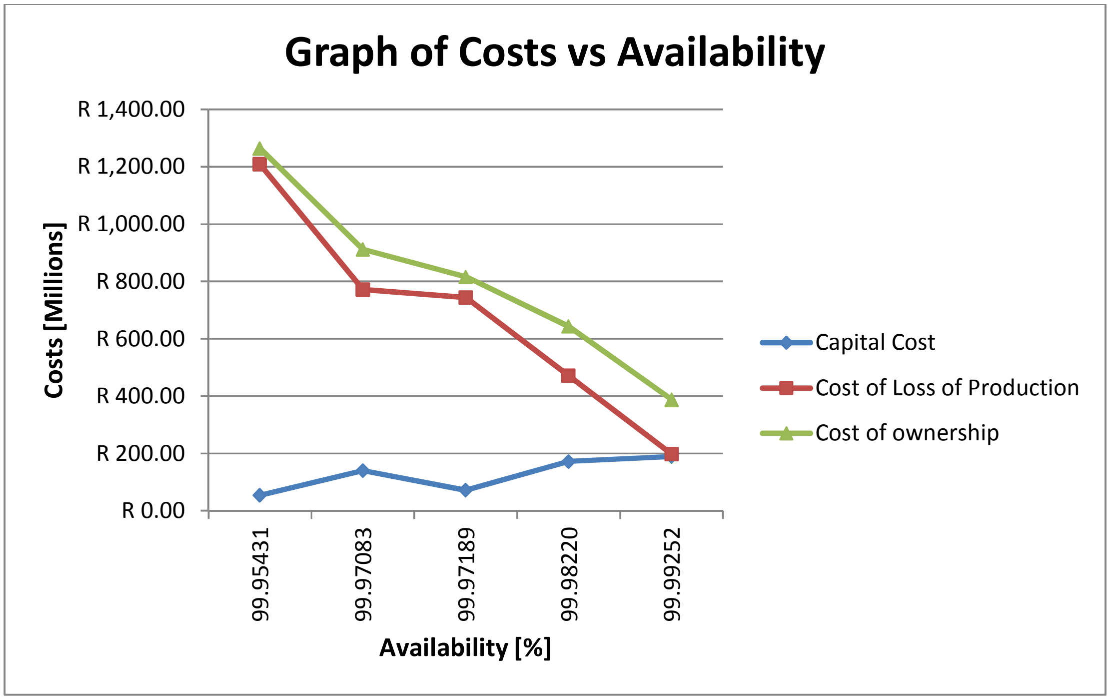

Figure 6.7 Graph of costs associated with reliability as a function of availability

Alternative Topology 1 is the most basic topology with the minimum amount of equipment required to supply power to reticulation substation 2M3-SS-8. As would be expected, it is also the topology with the lowest capital cost and greatest cost of loss of production over the life of the plant.

In Alternative Topology 2, an additional utility supply is added to the consumer substation 2H4-SP-1. This results in a significant increase in availability compared to Alternative Topology 1 with an increase in capital cost of only R17.6 million (although the additional capital cost does not consider the cost to the utility for creating the additional power supply). The increase in availability results in a decrease in loss of production costs of R465 million over the lifetime of the plant which, in turn, results in a decrease in cost of ownership to the value of R447 million. Thus, the investment in a second utility power supply is extremely good value for money.

In Alternative Topology 3 a hospital bus is added to consumer substation 2H4-SP-1 along with a complicated system of switches and circuit breakers to allow the hospital bus to be utilised when it is required and to allow the protection system to operate correctly in the event of a fault. While the addition of the hospital bus does allow for more pathways that current can flow along to reach the distribution substations, each of these new pathways includes a number of extra circuit breakers and switches in series. Since the reliability of these circuit breakers is not perfect, the resulting system has a slightly lower availability than Alternative Topology 2 and a higher cost of loss of production. In addition to this, Alternative Topology 3 costs almost twice the price of Alternative Topology 2 to build. Thus the total cost of ownership for Alternative Topology 3 is R96.2 million more than Alternative Topology 2. This means that unless the hospital bus is installed to allow work to be done to certain parts of the substation without shutting the whole substation down, there is no benefit associated with the addition of a hospital bus and it is a very expensive thing to do.

In Alternative Topology 4 an additional cable is installed between consumer substation 2H4-SP-1 and distribution substation 2JJ-DS-1 along with an associated additional transformer and incomer into the distribution board in 2JJ-DS-1. The board in 2JJ-DS-1 is also split into two with a bus coupler. This results in a moderate improvement in availability over both Alternative Topologies 2 and 3. The cost of Alternative Topology 4 is R32 million more than that of Alternative Topology 3 and the associated cost of loss of production is R373 million less than that associated with Alternative Topology 2. The result is a total cost of ownership that is R269 million less than that of Alternative Topology 3 and R173 million less than that associated with Alternative Topology 2. Thus, the addition of the second path from the consumer substation to the distribution substation is a good investment.

The existing topology of the feed to 2M3-SS-8 is very similar to Alternative Topology 4, except for the addition of a second path from distribution substation 2JJ-SS-1 to reticulation substation 2M3-SS-8. This results in a moderate improvement in reliability over Alternative Topology 4 and is just over R17 million more expensive to build.
The result is a R273 million saving in the cost of loss of production and a R256 million saving in the total cost of ownership over the lifetime of the plant. Thus the addition of the second path from distribution substation 2JJ-DS-1 to reticulation substation 2M3-SS-8 is also a good investment.

It is clear from the discussion above that the existing topology is the most economically viable one with the lowest total cost of ownership in terms of reliability over the lifetime of the plant. The single improvement that is the most valuable in attempting to increase the reliability of the distribution network is the addition of a second utility supply.

The fact that at an availability of 99.99252% (which is achieved by the existing topology), the graph of cost of ownership versus availability is still trending downwards tells us there is still room for improving the reliability of the plant by increased capital expenditure. However, since the existing topology is already representative of the most conservative distribution topology commonly used (the double radial network topology), it is unlikely that any incremental improvement to the design of the topology would be practical. Further improvements in the availability should be achieved by buying better quality equipment that has lower failure rates per year and/or equipment that requires shorter repair times. It is important to note that this study considered only the impact of design on the reliability of distribution networks. Availability could be greatly increased by adopting conservative maintenance plans and keeping a conservative inventory of spares.

# 7 SENSITIVITY ANALYSIS

## 7.1 EFFECT OF COST OF LOSS OF PRODUCTION

The reason why none of the topologies modelled in this study have resulted in a situation where an increase in availability does not result in a decrease in total cost of ownership is that the cost of loss of production of the plant that has been studied is so high. According to Table 1.1, one hour's interruption cost for a primary metals plant is \$3.54 per kW. Using the method described at the end of paragraph 6.1.1 this translates into R876449.16 per hour for a plant with a load of 14MW in South Africa in 2010 assuming an inflation rate of 10% per annum. If the cost of loss of production for the plant that was used in this study was R876449.16, the results of the reliability analysis and cost calculations would be as per Table 7.1 and Figure 7.1.

Table 7.1 Results of reliability analysis and cost calculations for plant with lower cost of loss of production

| **Distribution Network Topology** | **Availability [%]** | **Capital Cost** | **Cost of Loss of Production** | **Cost of Ownership** | **Cost of Ownership [p.u.]** |
|---|---:|---:|---:|---:|---:|
| Alternative Topology 1 | 99.95431 | R54310608.00 | R175396933.44 | R229707541.44 | 1.05 |
| Alternative Topology 2 | 99.97189 | R71893008.00 | R107909997.79 | R179803005.79 | 0.82 |
| Alternative Topology 3 | 99.97083 | R140036688.00 | R111979175.93 | R252015863.93 | 1.15 |
| Alternative Topology 4 | 99.98220 | R172100016.00 | R68331482.06 | R240431498.06 | 1.10 |
| Existing feed to 2M3-SS-8 | 99.99252 | R189531936.00 | R28714577.85 | R218246513.85 | 1.00 |

From Figure 7.1 it can be seen that Alternative Topology 2 is the optimal solution in terms of total cost of ownership. The capital cost that is associated with increasing the availability of the plant above 99.97189% is not justified by the associated saving in terms of the decreased cost of loss of production over the life of the plant for any of the other alternatives.

It is also worth noting that for a primary metals plant, a dual radial network topology is not the ideal network topology to use. The ideal network topology to use in a primary metals plant is the primary selective simple radial network.

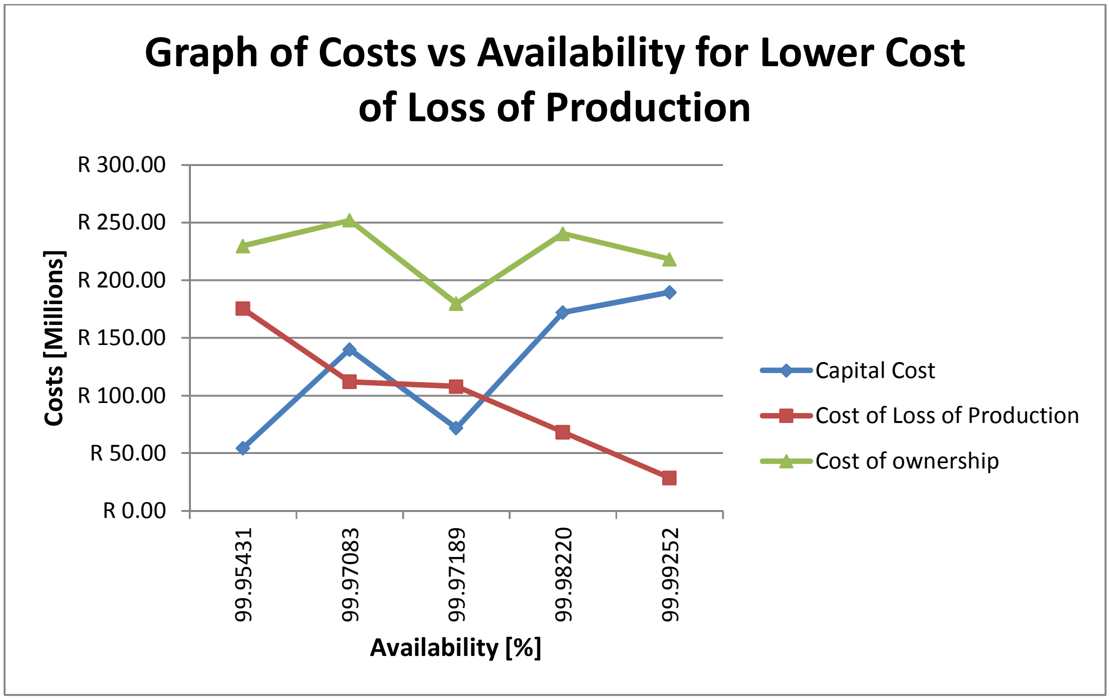

Figure 7.1 Graph of the costs associated with reliability of a plant that has a lower cost of loss of production

## 7.2 EFFECT OF LIFE OF PLANT

Table 7.1 and Figure 7.1 illustrate how changing the average cost of loss of production changes the result of the cost comparison. While the average cost of loss of production has been calculated from data that has been collected regarding the trips that have occurred in the Ash Handling Plant over the past 19 years, there are some values on which this study is based that have been assumed.

One such value that has been assumed is the life of the plant. The cost comparisons that are discussed in Chapter 6.3 are based on a life of plant of 50 years. If a life of plant of 10 years had been assumed, the results of the cost comparison would be as per Table 7.2 and Figure 7.2.

Table 7.2 Results for reliability anlysis and cost calculations of a plant with a shorter life of plant

| Distribution Network Topology | Availability [%] | Capital Cost | Cost of Loss of Production | Cost of Ownership | Cost of Ownership [p.u.] |
|---|---|---|---|---|---|
| Alternative Topology 1 | 99.95431 | R54310608.00 | R241775326.52 | R296085934.52 | 1.29 |
| Alternative Topology 2 | 99.97189 | R71893008.00 | R148748181.84 | R220641189.84 | 0.96 |
| Alternative Topology 3 | 99.97083 | R140036688.00 | R154357327.09 | R294394015.09 | 1.28 |
| Alternative Topology 4 | 99.98220 | R172100016.00 | R94191306.90 | R266291322.90 | 1.16 |
| Existing feed to 2M3-SS-8 | 99.99252 | R189531936.00 | R39581515.48 | R229113451.48 | 1.00 |

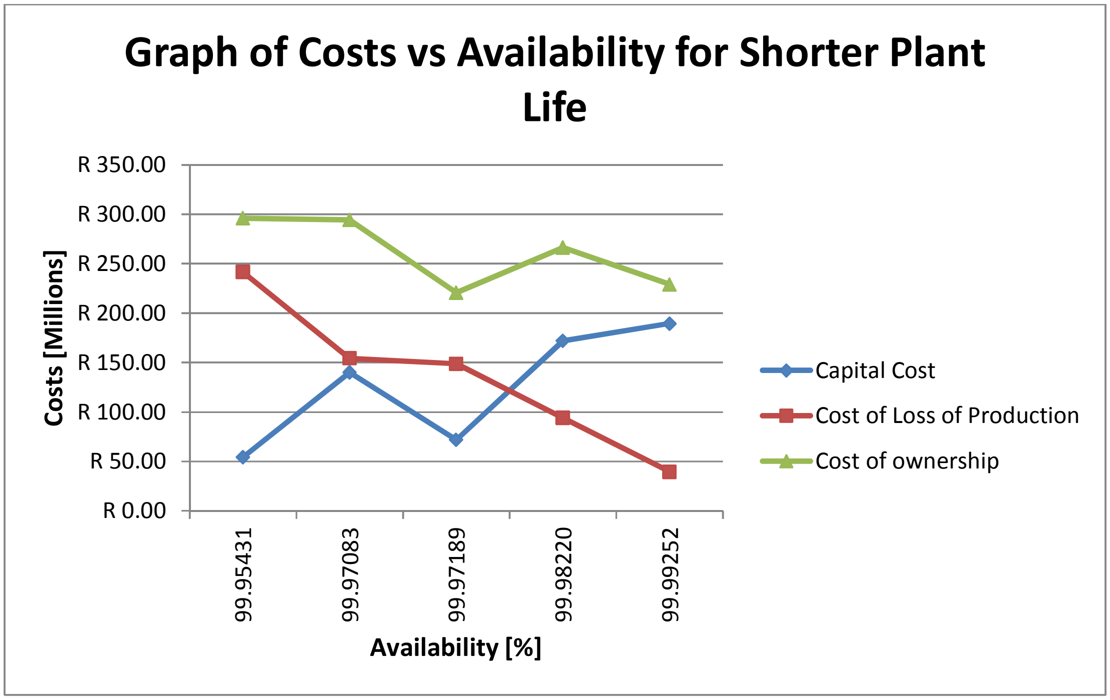

Figure 7.2 Graph of the costs associated with the reliability of a plant that has a shorter life of plant

These results shown in Table 7.2 and Figure 7.2 are very similar to those given in Table 7.1 and Figure 7.1. This is because in the same way that a lower average cost of loss of production results in a lower cost of loss of production over the life of the plant, so too does a shorter plant lifespan result in a in lower cost of loss of production over the life of the plant. Thus, the shape of the graph in Figure 7.2 is very similar to that in Figure 7.1, and, as in the case with the lower average cost of production, Alternative Topology 2 is the optimal solution for a plant with a shorter lifespan.

It is therefore important to note that the conclusions drawn in this study are based on an assumed value that cannot be objectively quantified, namely the life of the plant. This assumption is based on the fact that the Sasol Secunda Factory had been in operation for over 30 years at the time that this study was undertaken, and for all intents and purposes, the same factory is expected to be in operation for at least 20 years into the future.

At the very least, it should be kept in mind that while the plant is expected to be operational for 50 years, many (or most) of the components that make up the plant will not last 50 years. These will be replaced as they fail and the cost comparisons that are made in this study do not take the replacement costs of these components into consideration.

## 7.3 THE EFFECT OF IMPROVED RELIABILITY

Table 7.3 and Figure 7.3 show the results of the cost calculations for the network topologies shown in Table 6.18 and Figure 6.7 as well as 7 additional topologies of higher reliability.

Table 7.3 Results of cost calculations of initial network topologies plus 7 topologies of higher reliability

| Distribution Network Topology | Availability [%] | Capital Cost | Cost of Loss of Production | Cost of Ownership | Cost of Ownership [p.u.] |
|---|---|---|---|---|---|
| Alternative Topology 1 | 99.95431 | R54310608.00 | R1208876632.60 | R1263187240.60 | 3.26 |
| Alternative Topology 2 | 99.97189 | R71893008.00 | R743740909.22 | R815633917.22 | 2.11 |
| Alternative Topology 3 | 99.97083 | R140036688.00 | R771786635.43 | R911823323.43 | 2.35 |
| Alternative Topology 4 | 99.98220 | R172100016.00 | R470956534.48 | R643056550.48 | 1.66 |
| Existing feed to 2M3-SS-8 | 99.99252 | R189531936.00 | R197907577.41 | R387439513.41 | 1.00 |
| Additional Topology 1 | 99.99686 | R246391516.80 | R83165652.34 | R329557169.14 | 0.85 |
| Additional Topology 2 | 99.99868 | R320308971.84 | R34948261.31 | R355257233.15 | 0.92 |
| Additional Topology 3 | 99.99944 | R416401663.39 | R14686122.62 | R431087786.02 | 1.11 |
| Additional Topology 4 | 99.99977 | R541322162.41 | R6171471.47 | R547493633.88 | 1.41 |
| Additional Topology 5 | 99.99990 | R703718811.13 | R2593404.75 | R706312215.88 | 1.82 |
| Additional Topology 6 | 99.99996 | R914834454.47 | R1089812.73 | R915924267.20 | 2.36 |
| Additional Topology 7 | 99.99998 | R1189284790.81 | R457966.23 | R1189742757.04 | 3.07 |

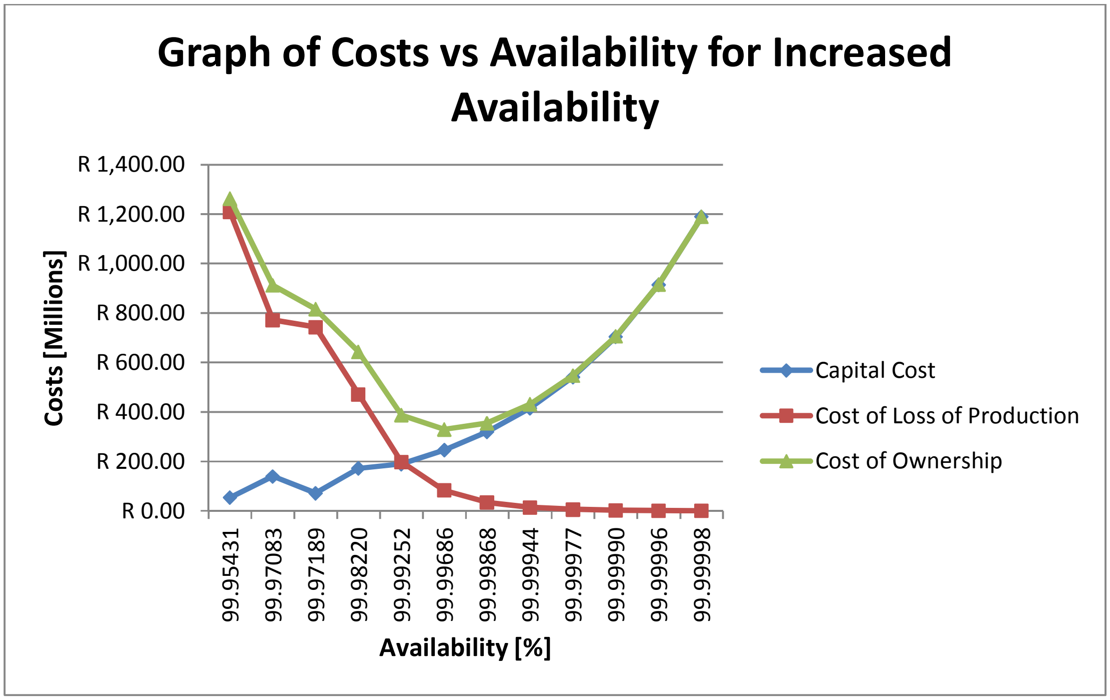

Figure 7.3 Graph of cost calculations of initial network topologies plus 7 topologies of higher reliability

The availability of each of the additional topologies is calculated by increasing the availability of each consecutive additional topology by 58% starting with the topology that is currently being used in Sasol Secunda. 58% is the greatest improvement in availability that was achieved by improving the topologies discussed in Table 6.18. Thus an increase of 58% represents the biggest improvement in availability associated with an investment that is likely to be achieved with any investment. The cost of loss of production for each additional topology is calculated using this availability and the average cost of loss of production for the particular plant as is done in Table 6.18.

The capital cost of each of the additional topologies is calculated by increasing the capital cost of each consecutive additional topology by 30% starting with the topology that is currently being used in Sasol Secunda. 30% is the average increase in capital cost that was associated with improving reliability of the topologies discussed in Table 6.18. Thus for each consecutive topology, the availability is increased by the biggest increment that was achieved in the topologies discussed in Table 6.18 by spending the average increment in capital cost spent in the topologies discussed in Table 6.18. This represents a more optimistic increase in availability associated with increased capital cost than what has been seen thin this study.

The data in Table 7.3 and Figure 7.3 show that by increasing the availability of the distribution network by one increment, either by the use of more reliable components or by the use of even more conservative design, an even lower cost of ownership can be achieved. However, the data also shows that by increasing the investment more than that (and thereby improving the availability of the network) the cost of ownership starts to increase. The optimal expenditure on reliability is achieved in Additional Topology 1.

This exercise of extrapolating the costs and benefits associated with topologies that achieve greater availability may be crude, but it does illustrate that the investment in improving reliability does reach a point where the investment bares no advantage, even in petrochemical plants. This point is reached in Additional Topology 2. Figure 7.3 has exactly the same shape the graph in Figure 1.1.

It should also be kept in mind that the increase in availability (and thus decrease in cost of loss of production) associated with the incremental capital cost associated with each investment in the additional topologies is very optimistic. In reality, it would be more difficult (and thus more expensive) to achieve the increments in availability that are shown by these additional topologies. Thus it can safely be said that the Dual Radial Network Topology is very close to, if not exactly the most optimal distribution network topology that should be used in petrochemical plants.

# 8 CONCLUSIONS

In Section 1.4 it was stated that the objective of this study was to establish a model for determining the reliability of petrochemical plants and comparing it to IEEE data. Furthermore, it was stated that this would be achieved by answering certain questions. In this chapter these questions, and how they were answered, are discussed.

## 8.1 MAJOR RELIABILITY COMPONENTS

What are the major reliability components that make up the electrical distribution network of a petrochemical plant?

This question was answered in Chapter 2 and Chapter 3. In paragraph 2.7.1 the types of equipment used in utility distribution networks was compared to the types of equipment used in the electrical distribution networks of petrochemical plants. The major reliability components of an electrical distribution network in a petrochemical plant were presented in Section 3.1. In addition, all the factors the affect the reliability of each of these components was discussed.

## 8.2 RELIABILITY INDICES

What are the reliability indices (failure rates [λ] and mean time to repair [MTTR]) for the electrical equipment used to make up the distribution networks in petrochemical and gas-to-liquid plants?

This question was answered in Chapter 4. Reliability indices have been established for all the electrical equipment that makes up the distribution network of a petrochemical plant. These indices are given in failure rate (number of failures per year) and in MTTR (hours). In Chapter 4 the method of calculating these indices was discussed and the final results were presented in Table 4.1.

## 8.3 VALIDATION OF RELIABILITY INDICES

How do the reliability indices that are calculated for petrochemical plants compare with the indices given by the IEEE Gold Book?

This question was answered in Chapter 5. The reliability indices that were calculated in Chapter 4 were compared to the reliability indices of the IEEE Gold book. Each component was discussed and it was found that 17 out of 20 reliability indices that have been calculated using the Sasol Secunda data were within the required factor of deviation. This is an 85% success rate, which indicates that the data collection and establishment of reliability indices for petrochemical plants has been successful.

It is generally found that the failure rate of equipment at Sasol in Secunda is similar to that of the industry average represented by the IEEE Gold Book data. In terms of MTTR, Sasol performed a lot better than the industry average given by the IEEE Gold Book data. Seven out of ten types of equipment had better MTTRs at Sasol in Secunda than the industry average.

A set of reliability indices that are suitable for use reliability analysis was compiled. They are listed in Table 5.4.

## 8.4 IMPACT OF NETWORK TOPOLOGY

What is the impact of network topology on the reliability of petrochemical plants?

This question has been answered in Chapter 6. The existing normal power distribution network that feeds the Ash Handling Plant has been analysed in terms of reliability, and the associated costs were calculated and compared to possible alternative distribution network topologies. It was found that even slight changes to the network topology result in large variations in the reliability of the network as well as in the total cost of ownership of the plant.

Generally, it has been found that adding more equipment or paths for power to flow increases the reliability of the distribution network, but this is not always true (the alternative topology in which a hospital bus was added). It is important to perform a reliability analysis before making any changes to an existing network topology, because it is possible that the investment could lead to decreased reliability and increased cost of ownership.

## 8.5 OPTIMAL DISTRIBUTION NETWORK TOPOLOGY

What are the optimal distribution network topologies that should be used in petrochemical and gas-to-liquid plants?

This question has been answered in Chapter 6. It has been found that the existing topology is the optimal topology because it is associated with the lowest total cost of ownership in terms of reliability. It has also been established that incremental additional expenditure that would increase the reliability of the distribution network would most likely result in a saving in total cost of ownership over the lifetime of the plant.

The existing distribution network topology that is used to feed the Ash Handling Plant is representative of the distribution network topology philosophy that is used throughout the distribution network of Sasol in Secunda. It can thus be concluded that the distribution network topology philosophy that is used at Sasol in Secunda, the dual radial philosophy, is probably the most suitable commonly used philosophy for this petrochemical plant.

## 8.6 OPTIMAL LEVELS OF RELIABILITY

What are the optimal levels of reliability for petrochemical and gas-to-liquid plants?

This question was answered in Chapter 1 and Chapter 6. In Section 1.1 it was stated that the optimal level of reliability for any plant is the point at which the total of the cost of improved reliability of that plant added to the potential cost of failure of that plant is at its minimum. Table 1.1 shows that the cost of loss of production in a petrochemical plant is far higher than in any plant in any other type of industry. In Chapter 6 it was shown that only the most conservative distribution network design is suitable for use in a petrochemical plant.

It is not possible to assign an exact figure to what the availability of components and systems should be in the electrical distribution network of a petrochemical plant. But it would be true to state that it is financially beneficial to purchase equipment and implement design philosophies that are associated with the highest levels of availability.

## 8.7 CHEAPER RELIABILITY

Are there cheaper ways of achieving high levels of reliability in petrochemical plants?

It was hoped, when this study was undertaken, that the study would show that the levels of reliability that are currently used by petrochemical plants are unnecessarily high or that the distribution network topologies that are used do not provide the highest level of availability. However, in Chapter 6 it has been shown that if it were possible to achieve even higher levels of reliability at an incrementally higher cost, the investment would reduce the total cost of ownership. In addition, it has been shown in Chapter 6 that the most reliable commonly used network topology is the dual radial network topology.

This study considered only the impact of design on the reliability of a distribution network. Thus, the additional investment that could improve the reliability (and thus the total cost of ownership) could be in the form of adopting a conservative maintenance philosophy as well as the establishment of a conservative spares inventory.

# 9 RECOMMENDATIONS AND PROPOSED FUTURE RESEARCH

It is recommended that for petrochemical plants that may be constructed in future, reliability analysis be carried out in order to determine the most effective distribution network topology. As a starting point for these analyses, it is recommended that the expected life of plant and average cost of loss of production be established, as they have a major impact on the reliability requirements of a plant.

There are opportunities to investigate the reliability of the 11kV non-process distribution network and to investigate the effect of the critical power network on the total cost of ownership of the factory. In addition, there is an opportunity to establish the reliability indices for motors, motor starters, different kinds of circuit breakers and switches and cable joints used in the Sasol Secunda Factory.

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## ADDENDUMS

| | |
|---|---|
| ADDENDUM A | LIST OF TABLES |
| ADDENDUM B | LIST OF FIGURES |
| ADDENDUM C | EXAMPLE OF SASOL TRIP REPORT |
| ADDENDUM D | EXTRACTS FROM TRIP SPREADSHEET |

# ADDENDUM A

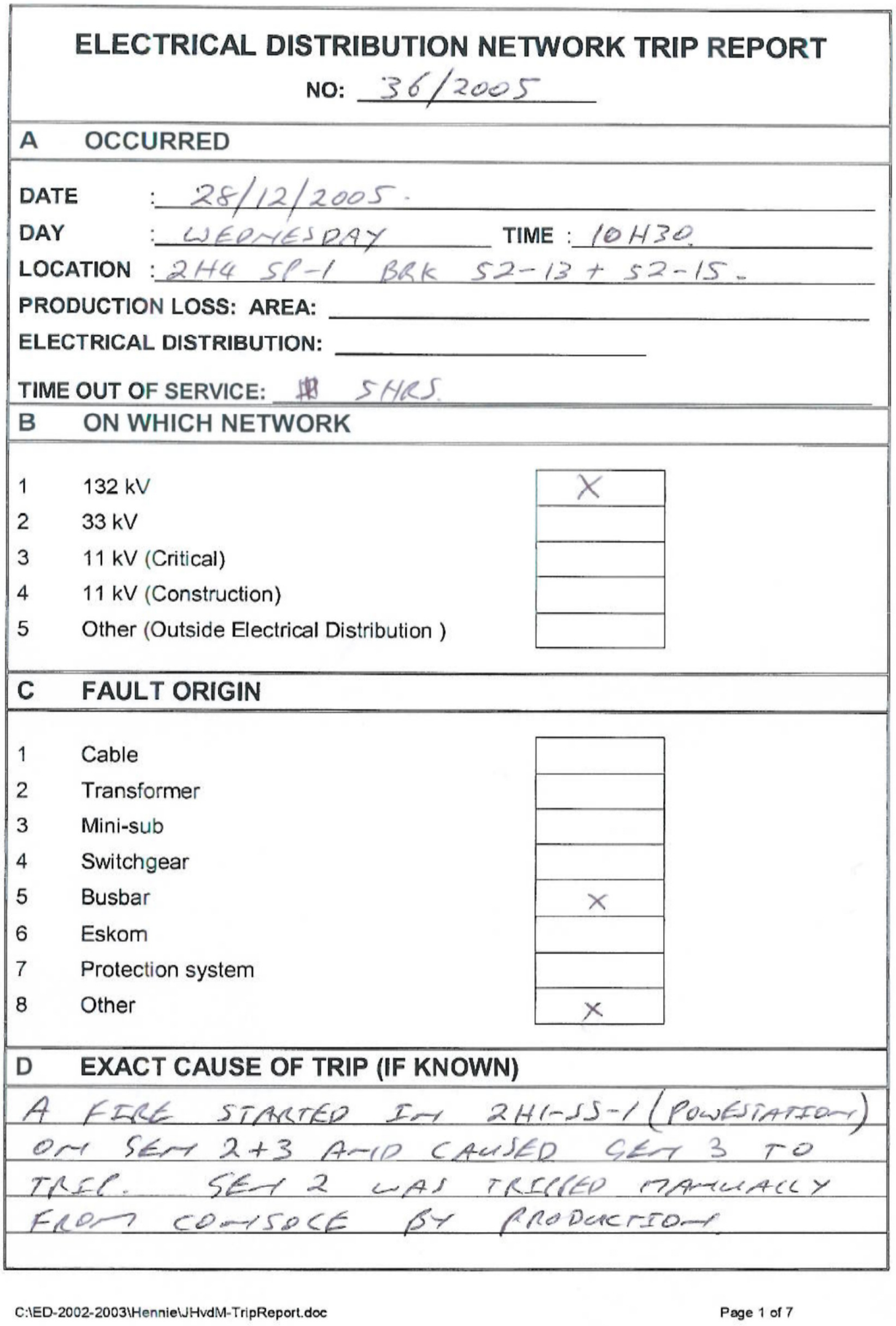
## LIST OF TABLES

# ADDENDUM B

## LIST OF FIGURES

# ADDENDUM C

# EXAMPLE OF SASOL TRIP REPORT



## ELECTRICAL DISTRIBUTION NETWORK TRIP REPORT

NO: 36/2005

### A OCCURRED

DATE : 28/12/2005.
DAY : WEDNESDAY TIME : 10H30
LOCATION : 2H4 SP-1 BRK 52-13 + 52-15.
PRODUCTION LOSS: AREA: 
ELECTRICAL DISTRIBUTION: 
TIME OUT OF SERVICE: 5HRS.

### B ON WHICH NETWORK

| | | |
|---|---|---|
| 1 | 132 kV | ☒ |
| 2 | 33 kV | ☐ |
| 3 | 11 kV (Critical) | ☐ |
| 4 | 11 kV (Construction) | ☐ |
| 5 | Other (Outside Electrical Distribution ) | ☐ |

### C FAULT ORIGIN

| | | |
|---|---|---|
| 1 | Cable | ☐ |
| 2 | Transformer | ☐ |
| 3 | Mini-sub | ☐ |
| 4 | Switchgear | ☐ |
| 5 | Busbar | ☒ |
| 6 | Eskom | ☐ |
| 7 | Protection system | ☐ |
| 8 | Other | ☒ |

### D EXACT CAUSE OF TRIP (IF KNOWN)

A FIRE STARTED IN 2H1-SS-1 (POWESTATION)
ON GEN 2+3 AND CAUSED GEN 3 TO
TRIP. GEN 2 WAS TRIPPED MANUALLY
FROM CONSOLE BY PRODUCTION

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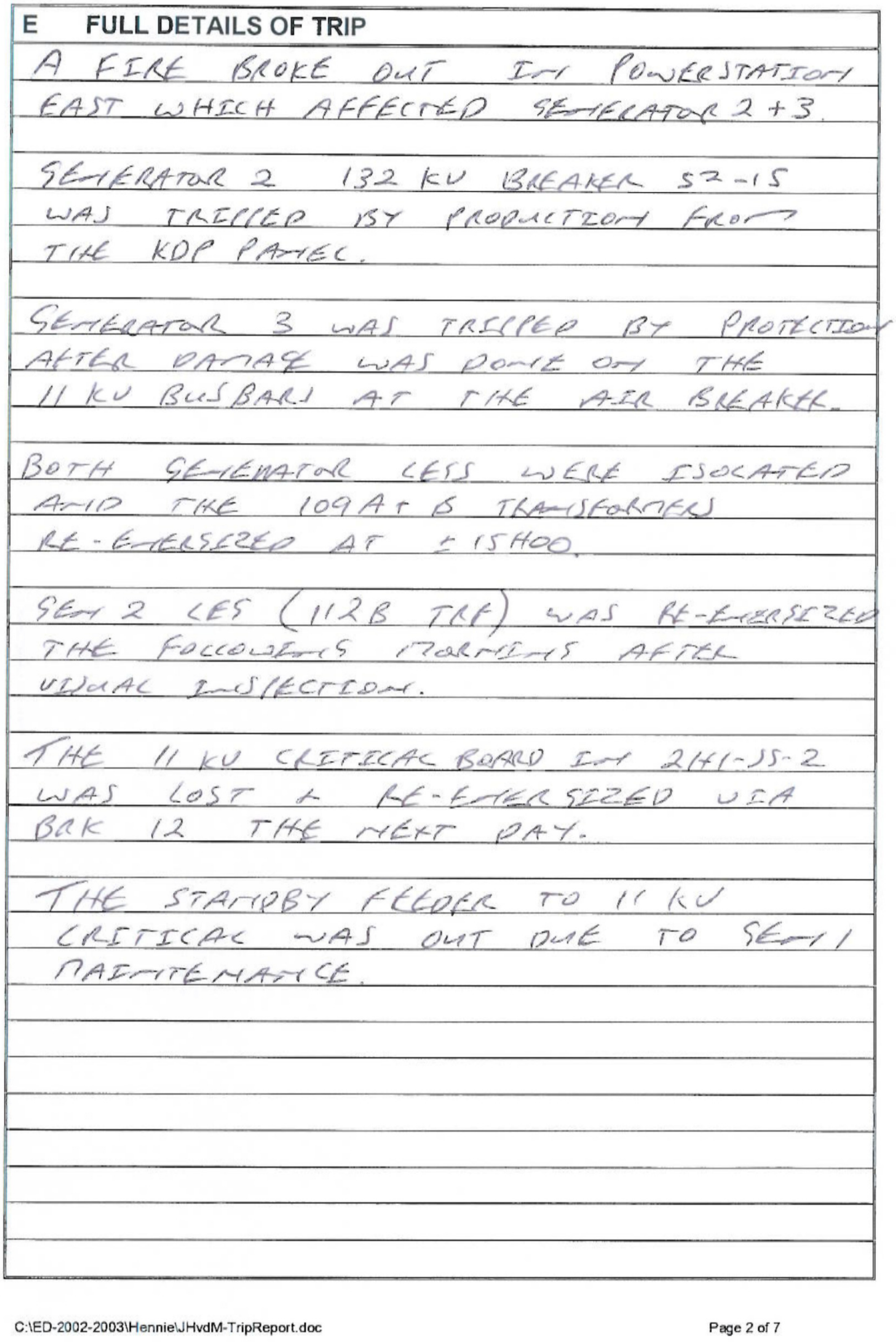

**E FULL DETAILS OF TRIP**

A FIRE BROKE OUT IN POWERSTATION EAST WHICH AFFECTED GENERATOR 2 + 3.

GENERATOR 2 132 KV BREAKER S2-15 WAS TRIPPED BY PRODUCTION FROM THE KDP PANEL.

GENERATOR 3 WAS TRIPPED BY PROTECTION AFTER DAMAGE WAS DONE ON THE 11 KV BUSBARS AT THE AIR BREAKER.

BOTH GENERATOR LESS WERE ISOLATED AND THE 109A + B TRANSFORMERS RE-ENERGIZED AT ± 15H00.

GEN 2 LES (112B TRF) WAS RE-ENERGIZED THE FOLLOWING MORNING AFTER VISUAL INSPECTION.

THE 11 KV CRITICAL BOARD IN 2H1-SS-2 WAS LOST & RE-ENERGIZED VIA BRK 12 THE NEXT DAY.

THE STANDBY FEEDER TO 11 KV CRITICAL WAS OUT DUE TO GEN 1 MAINTENANCE.

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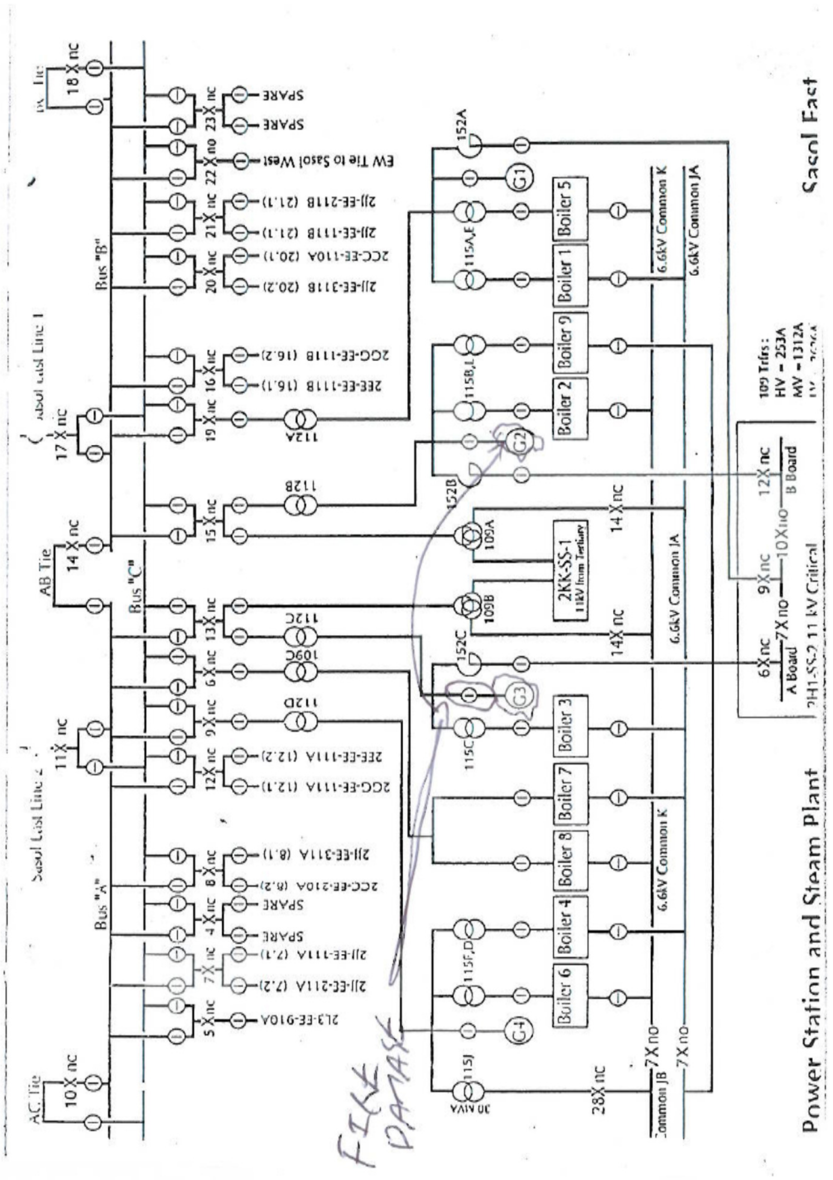
## F SKETCHES (IF NECESSARY)



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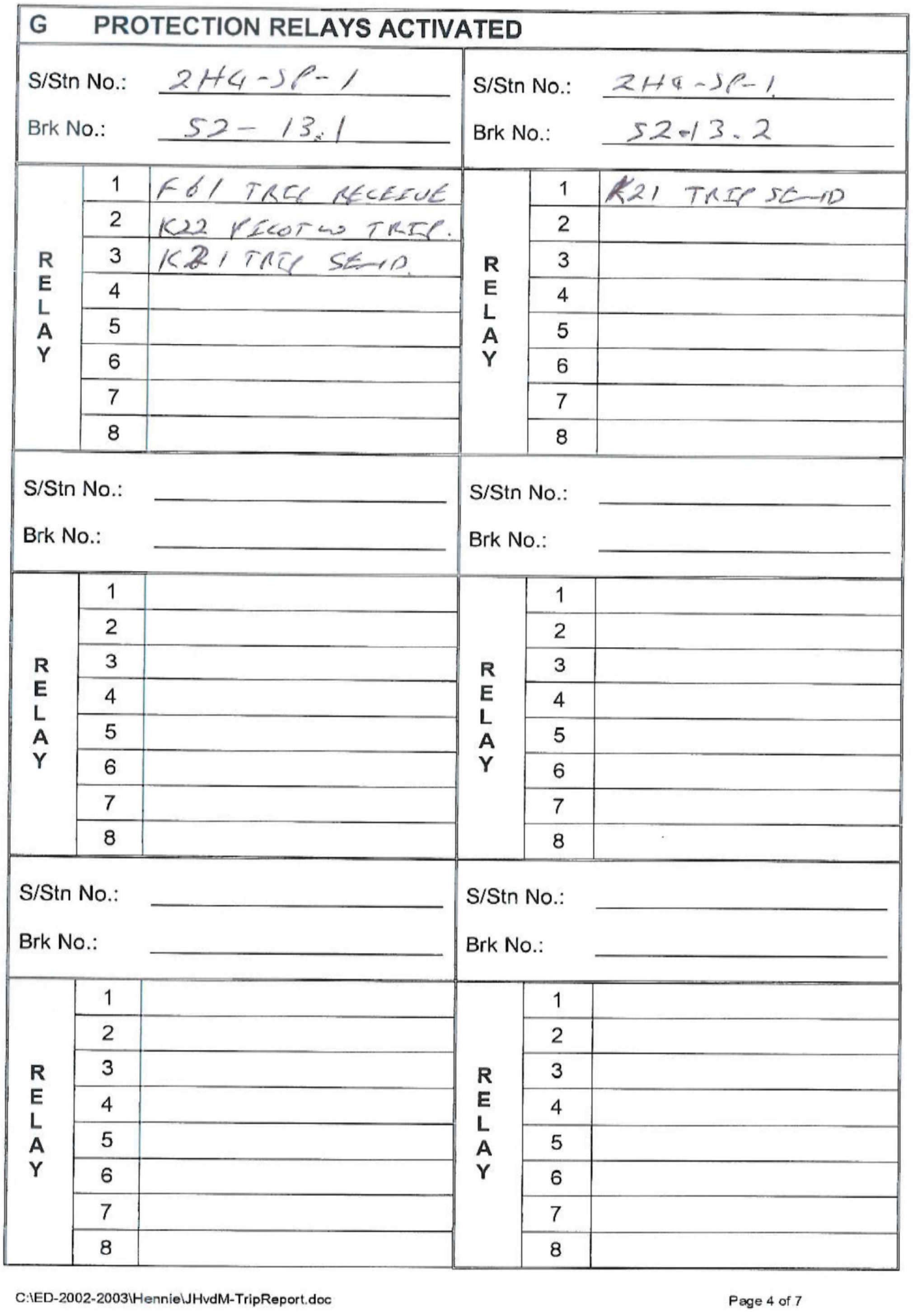

## G PROTECTION RELAYS ACTIVATED

| | | | | | |
|---|---|---|---|---|---|
| S/Stn No.: | | 2H4-SP-1 | S/Stn No.: | | 2H4-SP-1 |
| Brk No.: | | 52-13.1 | Brk No.: | | 52-13.2 |
| RELAY | 1 | F61 TRIP RECEIVE | RELAY | 1 | K21 TRIP SEND |
| | 2 | K22 PILOTWO TRIP. | | 2 | |
| | 3 | K21 TRIP SEND. | | 3 | |
| | 4 | | | 4 | |
| | 5 | | | 5 | |
| | 6 | | | 6 | |
| | 7 | | | 7 | |
| | 8 | | | 8 | |
| S/Stn No.: | | | S/Stn No.: | | |
| Brk No.: | | | Brk No.: | | |
| RELAY | 1 | | RELAY | 1 | |
| | 2 | | | 2 | |
| | 3 | | | 3 | |
| | 4 | | | 4 | |
| | 5 | | | 5 | |
| | 6 | | | 6 | |
| | 7 | | | 7 | |
| | 8 | | | 8 | |
| S/Stn No.: | | | S/Stn No.: | | |
| Brk No.: | | | Brk No.: | | |
| RELAY | 1 | | RELAY | 1 | |
| | 2 | | | 2 | |
| | 3 | | | 3 | |
| | 4 | | | 4 | |
| | 5 | | | 5 | |
| | 6 | | | 6 | |
| | 7 | | | 7 | |
| | 8 | | | 8 | |

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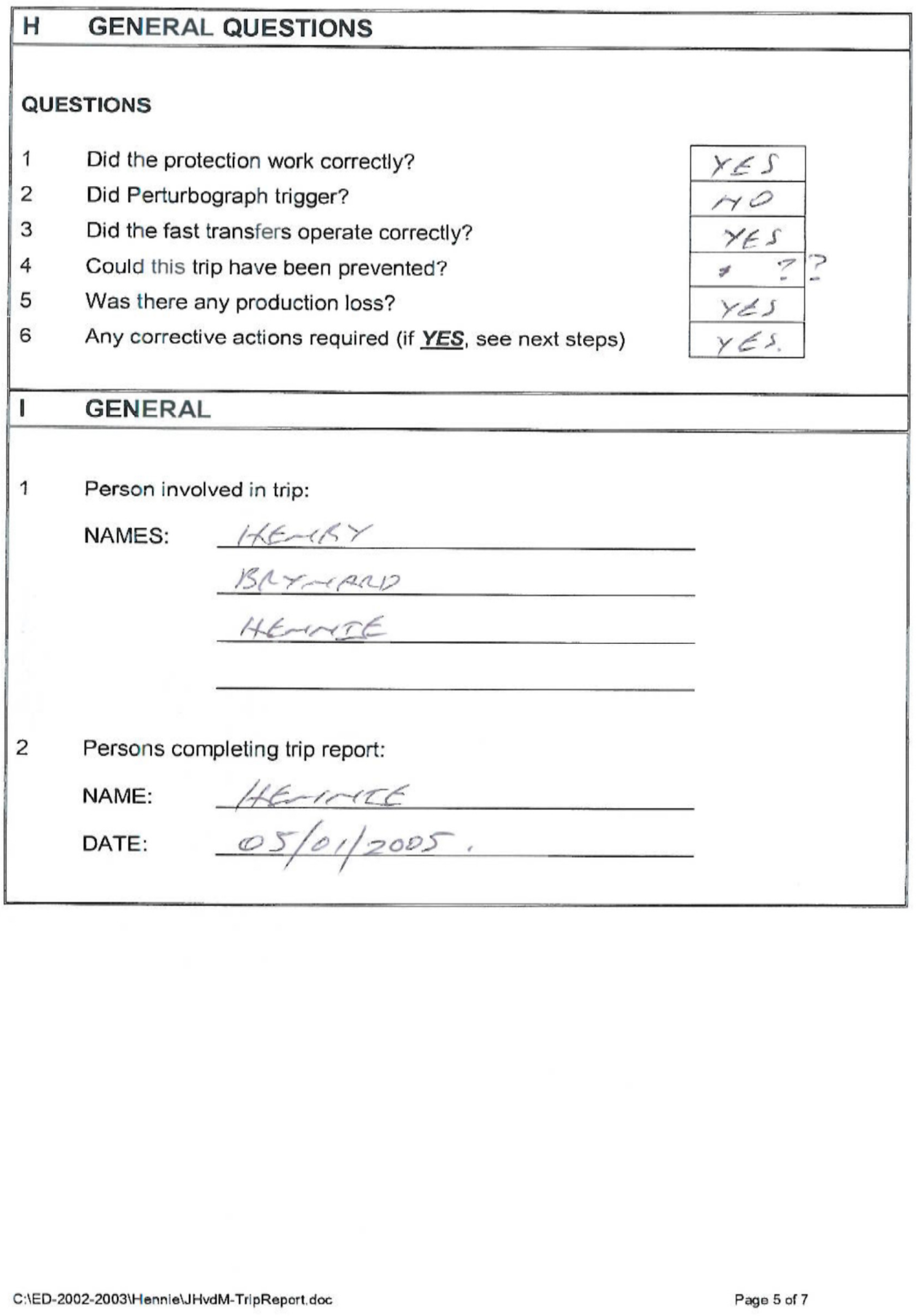

## H GENERAL QUESTIONS

**QUESTIONS**

| | | |
|---|---|---|
| 1 | Did the protection work correctly? | YES |
| 2 | Did Perturbograph trigger? | NO |
| 3 | Did the fast transfers operate correctly? | YES |
| 4 | Could this trip have been prevented? | ? ? |
| 5 | Was there any production loss? | YES |
| 6 | Any corrective actions required (if ***YES***, see next steps) | YES. |

## I GENERAL

1 Person involved in trip:

NAMES: HENRY
BRYNARD
HENNIE

2 Persons completing trip report:

NAME: HENNIE
DATE: 05/01/2005.

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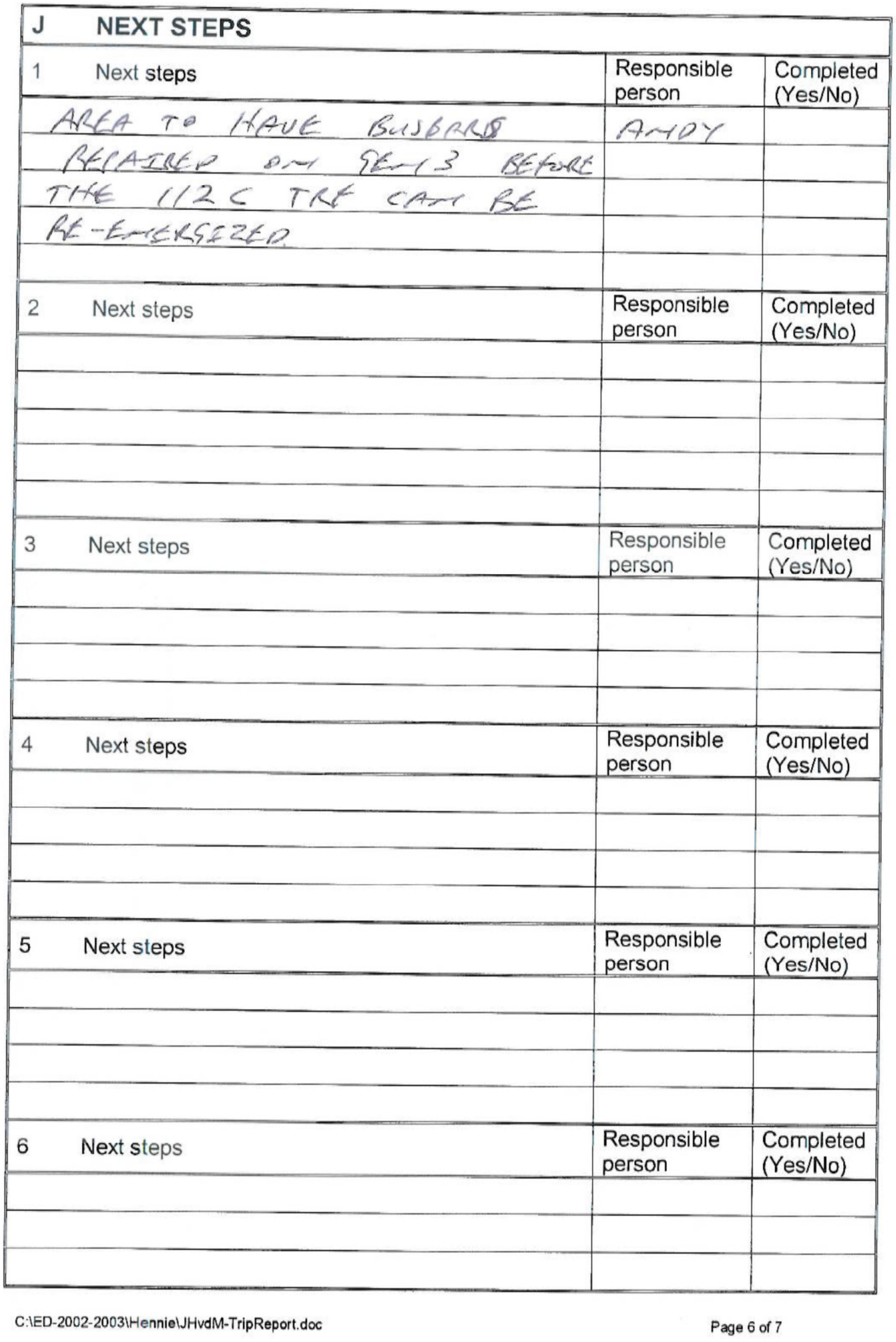

| | | |
|---|---|---|
| **J** **NEXT STEPS** | | |
| 1 Next steps | Responsible person | Completed (Yes/No) |
| AREA TO HAVE BUSBARS | ANDY | |
| REPAIRED ON SEN 3 BEFORE | | |
| THE 112C TRF CAN BE | | |
| RE-ENERGIZED | | |
| | | |
| 2 Next steps | Responsible person | Completed (Yes/No) |
| | | |
| | | |
| | | |
| | | |
| | | |
| 3 Next steps | Responsible person | Completed (Yes/No) |
| | | |
| | | |
| | | |
| | | |
| 4 Next steps | Responsible person | Completed (Yes/No) |
| | | |
| | | |
| | | |
| | | |
| 5 Next steps | Responsible person | Completed (Yes/No) |
| | | |
| | | |
| | | |
| | | |
| 6 Next steps | Responsible person | Completed (Yes/No) |
| | | |
| | | |
| | | |

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## K FINALISATION

Is this trip completely finalised i.t.o. all Next Steps and Corrective actions? ☐

NAME: ______________________________

DATE: ______________________________

SIGNATURE: ______________________________

# ADDENDUM D

# EXTRACTS FROM TRIP SPREADSHEET

| Trip No | Date | Voltage [kV] | Substation | Breaker | Feed to | Down Time [hrs] | Production loss | Detail of loss | Fault Origin | Exact cause of trip |
|---|---|---|---|---|---|---|---|---|---|---|
| 08/2008 | 4/30/2008 | 132 | H4-SP-1 | 52-10 |  | 7 | No | 1 Separator off line | Protection | Unstable cable differential on H1-EE-112 is operated and tripped the unit due to a voltage dip on Sol-Zeus 400kV line (19% for 7 cycles). |
| 04/2008 | 2/19/2008 | 11 critical | 2H1-SS-2 | 52-4 |  |  | Yes |  | Cable | 11kV cable crutch failure at transformer 2EE-EE-315AZ |
| 02/2008 | 1/23/2008 | 132 | 2H4-SP-1 | 52-9 |  | 2 | Yes |  | Transformer | 112D transformer temperature protection operated. Not sure why, but the area had experienced 6 days of rain. There were no faults. |
| 01/2008 | 1/4/2008 | 132 | 2H4-SP-1 | 52-19 |  | 3 | Yes | Generation | Cable | A faulty low voltage cable between march line boiler and the maintenance bucholtz caused the bucholtz on transformer 2H1-EE-112a to operate |
| 38/2007 | 12/3/2007 | 525 | R4-SS-1 | 52-8 | R4-**SS**-3 |  | No |  | Switchgear | A fault occurred on the outside feeder to a busbar on the 525 Board in R4-SS-3 |
| 35/2007 | 11/16/2007 | 132 and 11 critical | 2H4-SP-1 & 2H1-SS-2 | 52-19 of 2H4 and 52-9 of 2H1 |  | 0.1 | Yes | R3395530.70 | Transformer | Vibrations due to heavy thunder caused an incorrect trip. Transformer 2H1-EE-112A |
| 34/2007 | 11/16/2007 | 132 and 11 critical | 2H4-SP-1 & 2H1-SS-2 | 52-15 of 2H4 And 52-12 of 2H1 |  | 0.1 | Yes | R3395530.70 | Transformer | Vibrations due to heavy thunder caused an incorrect trip. Transformer 2H1-EE-112B |
| 33/2007 | 11/13/2007 | 132 | H4-SP-1 | 52-14 | EE-EE-111B |  | Yes | Oil workup and O2 plant | Cable | Cable fault on white phase 600m from substation |
| 32/2007 | 11/2/2007 | 132 | H4-SP-1 | 52-14 | EE-EE-111B | 240 | Yes | 4 boilers + O2 plant R10850768.77 | Cable | The blue phase cable on the feeder to EE-EE-111B failed 3m below the termination |
| 30/2007 | 10/8/2007 | 132 | 2H4-SP-1 | Island |  | 0.67 | No |  | Eskom | K12 under voltage relay was picked up. On 2 gens the blue phase over current was flagged (heavy rain and thunder). |
| 23/2007 | 9/18/2007 | 132 | 2H4-SP-1 | 52-9, 52-13, 52-15 |  | 0.67 | Yes | Whole factory R46334996.63 + | Switchgear | A limit switch with connected wires fell onto an 11kV busbar. This caused an HV spike on the |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | R10149083.30 | | control wiring. |
| 4/2007 | 2/25/2007 | 132 | 2H4-SP-1 | 52-5 | 2L2-EE-910A | 3 | Yes | various throughout factory R275566.53 | Cable | A phase-to-phase fault on the 132kV Zandfontein lines caused instability on the system (40% dip for 95m) leading to the trip |
| 33/2006 | 12/7/2006 | 132 | H4-SP-1 | 52-24 | Gen 6 | 12.5 | Yes | R34375020.26 + R26797765.45 + R5234309.61 | Protection | A polarity problem on the restricted earth fault on the standby incomer from Gen 6 was activated due to the faulty PC102motor which generated the extra current. |
| 32/2006 | 11/20/2006 | 33 | 2JJ-DS-3 | 52-12 | Fertilizer plant | 1.5 | Yes | | Unknown | No definite cause found for trip |
| 28/2006 | 10/19/2006 | 33 | 2JJ-DS-1 | 52-7 & 8 | 2M3-SS-8 | 12 | Yes | R52Million | Cable | During excavation work two 33kV cables were damaged, one on each of the feeders to 2M3-SS-8 |
| 21/2006 | 8/1/2006 | 132 | H4-SP-1 | 52-5 | JJ-DS-3 and CC-EE-110A | 2 | Yes | R920,489.83 + R 2,995,208.64 | Low Oil Level | A low oil level on the NEC at transformer JJ-EE-311A operated the bucholtz trip and sent a trip to Brk 5 in H4-SP-1 |