

**AN IN-DEPTH STUDY INTO THE
VARIOUS FACTORS CONTRIBUTING
TO THE UNEXPLAINED LINE FAULTS
ON A LARGE
HIGH VOLTAGE NETWORK**

by

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**This Thesis was submitted to the University of Natal in fulfilment of the
requirements for a Master's degree in Electrical Engineering**

DECLARATION

I, HJJ Bekker, declare that the work contained in this thesis is my own and has not been submitted, in part or otherwise, to another university



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10 August 2003

ABSTRACT

The Eskom Transmission Network experiences an exceptionally high number of line faults, the cause of which, may not be correctly identified. This thesis analyses a number of all the possible factors responsible for causing these faults. The objective is to assign probable causes of these faults and that the correct preventative or corrective measures may be planned.

The percentage of unexplained line faults is estimated to be 35 % of the total system faults. It is important for the Transmission Group of Eskom to minimise the number of faults. Major efforts to minimise identified faults such as bird streamers, veld fires, sugar cane fires, lightning and a hypothesised light pollution, light wetting mechanism has been undertaken by the transmission grid authority.

This thesis presents an analysis of the statistical data of the unknown faults (unknown faults is defined as lines that trip due to a reason which could not be identified) that has been undertaken. This analysis takes into account a number of categories of causes of line faults. The period, for which the performance of the lines was analysed for was the years inclusive of 1993 to 1997.

The investigation has focused on the identification of the under-performing lines of the main Transmission Network. The identified poorly performing lines have been compared with each other from the perspective of the following variables:

- Region
- Voltage (System Voltage)
- Climatic Data

- Line faults – Time of Day analysis
- Line Faults – Time of Year analysis.

The analysis indicates that the majority of unexplained flashovers occur between 22:00 and 07:00 the following morning (Britten et al, 1999). Almost all of the under performing lines in South Africa fall in the sub-tropical/humid climatic area. All the lines studied are insulated with standard glass disc insulators.

The analysis indicated that most of the unexplained line faults occur during the months when the seasons change, e.g. from autumn to winter. The analysis further indicates that most unexplained line faults occurred during the months of April to May and August to September.

Of note is that during the period of this investigation bird guarding was performed on some lines. Installing bird guards may reduce those line faults that are caused by bird streamers. However, the bird pollution (deposited on glass disc insulators) that is not washed off at the same time as the bird guard installation may cause the line to trip due to the combination of the pollution and wetting resulting in a pollution type flashover. This is a possible cause of some unexplained line faults that occur from April to May.

Bird streamers are also identified as the most probable cause of the unexplained faults which occur during the late evening periods (22:00 – 00:00). Pollution (with wetting) during the early morning periods may result in faults for the period 00:00 to 02:00. Line faults in the early morning periods (04:00 – 7:00) could be due to bird streamers or pollution and wetting, depending on the time of year in which the faults occurs.

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1. INTRODUCTION

1.1. Description of the Eskom Transmission 220 kV, 275 kV, 400 kV & 765 kV Network

The Eskom Transmission Network consists of a well-integrated system. Thermal generation plants are mostly situated in the North Eastern part of South Africa (see Figure1). There are also two pumped storage schemes, two hydroelectric schemes, two gas turbine stations and one nuclear power station. Due to the long distances between the generating plants and the large industrial and metropolitan supply points, Eskom has built very long overhead Transmission lines (e.g. 1500 km long).

Unfortunately the transmission networks in South Africa run across regions of greatly varying climatic zones. This is suspected as one of the major reasons why some of the lines perform exceptionally well and other lines do not. The lines are adequately designed for certain regions and fault mechanisms but under designed for other regions where different fault mechanisms may occur. Figure 1 shows a map of the Eskom Transmission Network. Seventy five per cent of the generating plants are situated in the North Eastern part of the country (Region A) which forced Eskom to build very long lines (+/- 1500 km) from this area to the Cape Province (Region B), situated in the South Western part of the country. Large

industrial and metropolitan installations along the Kwa-Zulu Natal coast (Region C) require large amounts of power (3 GW) for these respective activities, and Eskom Transmission had to expand (and strengthen) the Network in this area due to an historically slack system.

Overhead transmission line faults affect the quality of supply to customers very negatively. It is important that Eskom Transmission limits the number of line faults and especially reduces the occurrence of unexplained faults on the network in order to improve the Quality of Supply indices.

1.1.1 Geographical extent of the Eskom Transmission 220 kV, 275 kV and 400 kV lines

The weather patterns and environmental factors that may affect the performance of a transmission system includes pollution, rainfall patterns, lightning occurrences and crop and other burning. A brief analysis of each of these factors as they apply to South Africa and its transmission network is given below.

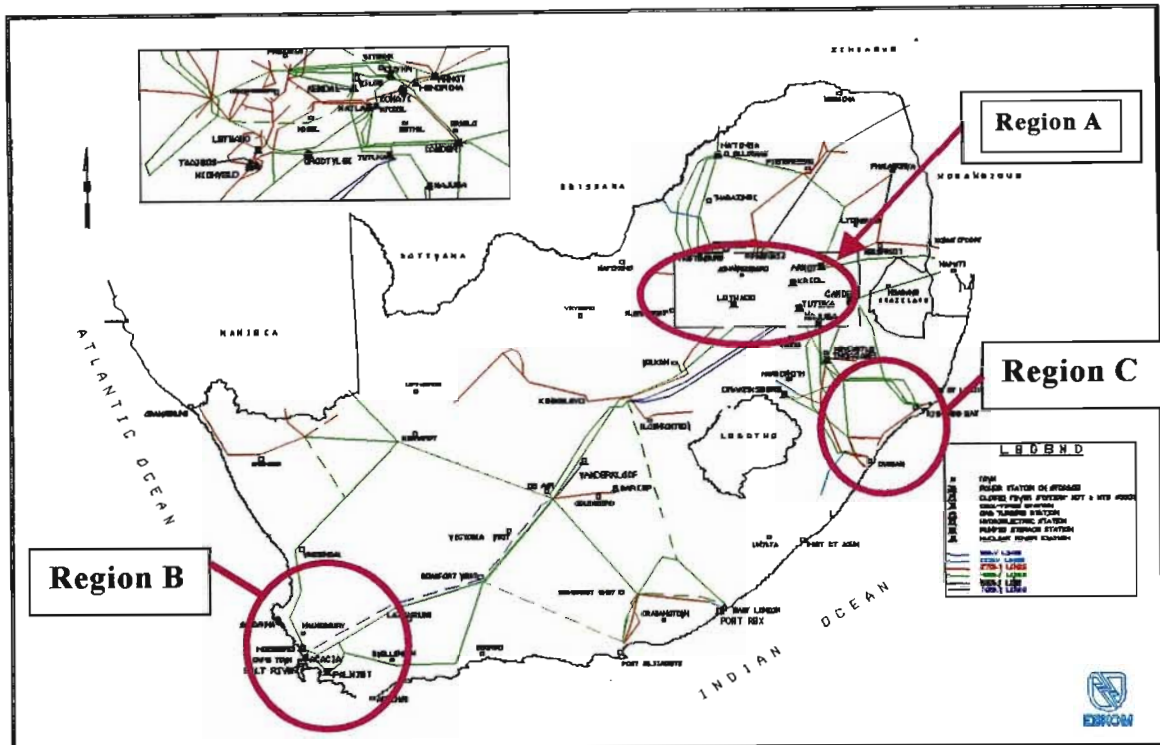


Figure 1. Map of the Eskom Transmission Network

The Eskom Transmission Network is spread across South Africa and the regions are very different in terms of biomes. The concept biome is the description of the types of vegetation present in an area such as grasslands and forests. The different biomes regions of South Africa are shown in Figure 2. The biomes may affect the performance of a constructed and operating transmission line in several ways. One of the more serious effects is the high number of line faults due to veld fires through the burning of savannah type grass.

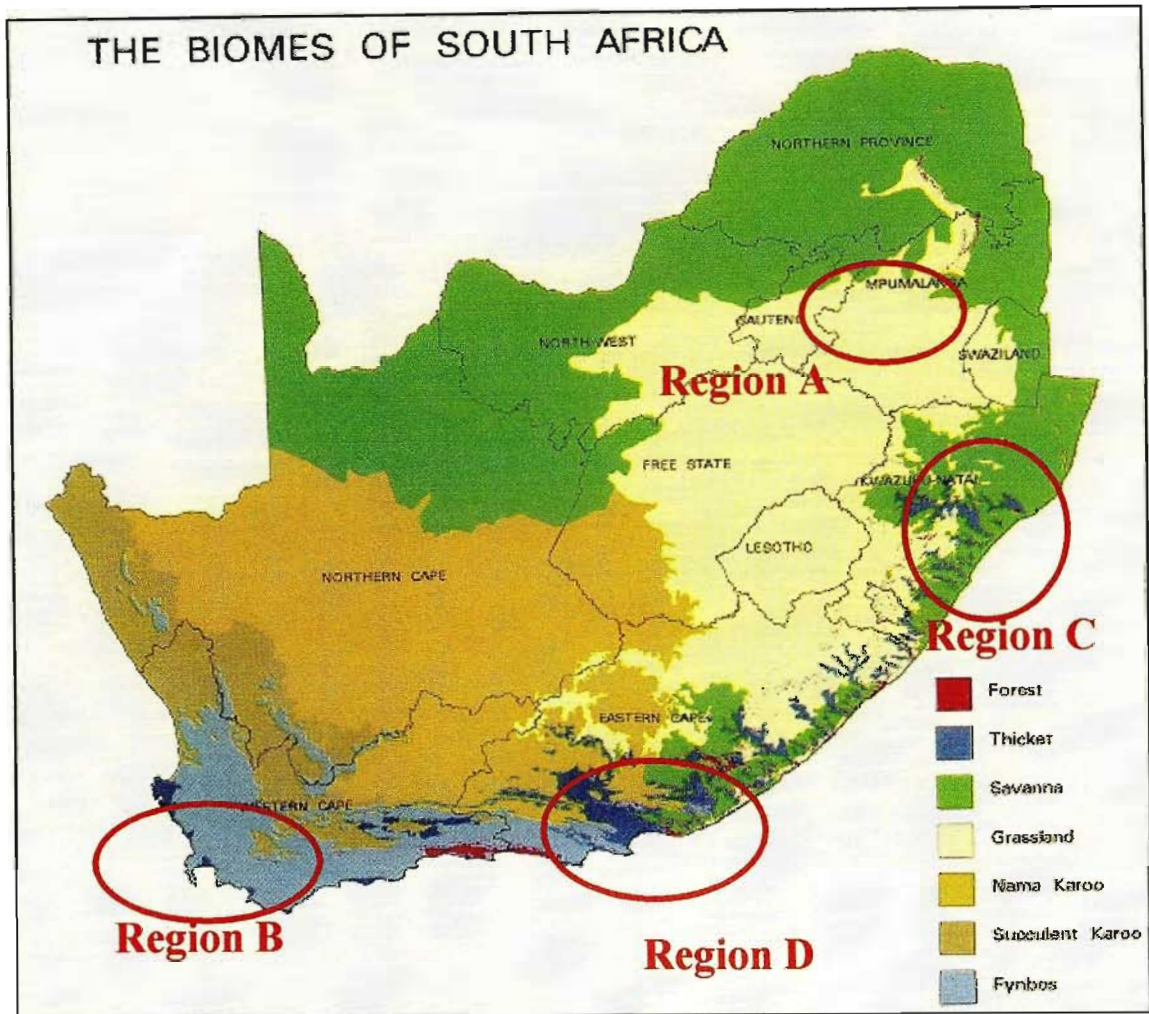


Figure 2. Biomes Map of South Africa

Of note is the fact that lines running from Region A (Generation Plant) to Region B are approximately 1500 km long and pass through widely varying regions of vegetation types (biomes) including grasslands, deserts, semi-desert and areas covered in species of plant unique to the Cape, i.e. fynbos. Region D also indicates an area with metropolitan and industrial loads but due to the vast distances between these loads (Region D) and the generation plant (Region A), long lines also run between these regions.

From the analysis it became evident that a high number of unexplained line faults normally occurred in the Savanna (grassland) areas.

1.1.2 Description of Rainfall Pattern

Figure 3 contains a map that shows the rainfall patterns over the whole country. The Western Cape area experiences a high winter rainfall pattern whereas the Northern and Eastern regions experience a summer rainfall pattern. The higher rainfall areas tend to have higher bird related activities, which may then influence the performance of the Transmission Overhead Lines. Depending on the cycles involved, it may be expected that the line faults caused by bird streamer or bird pollution follows the trend of wet and dry years.

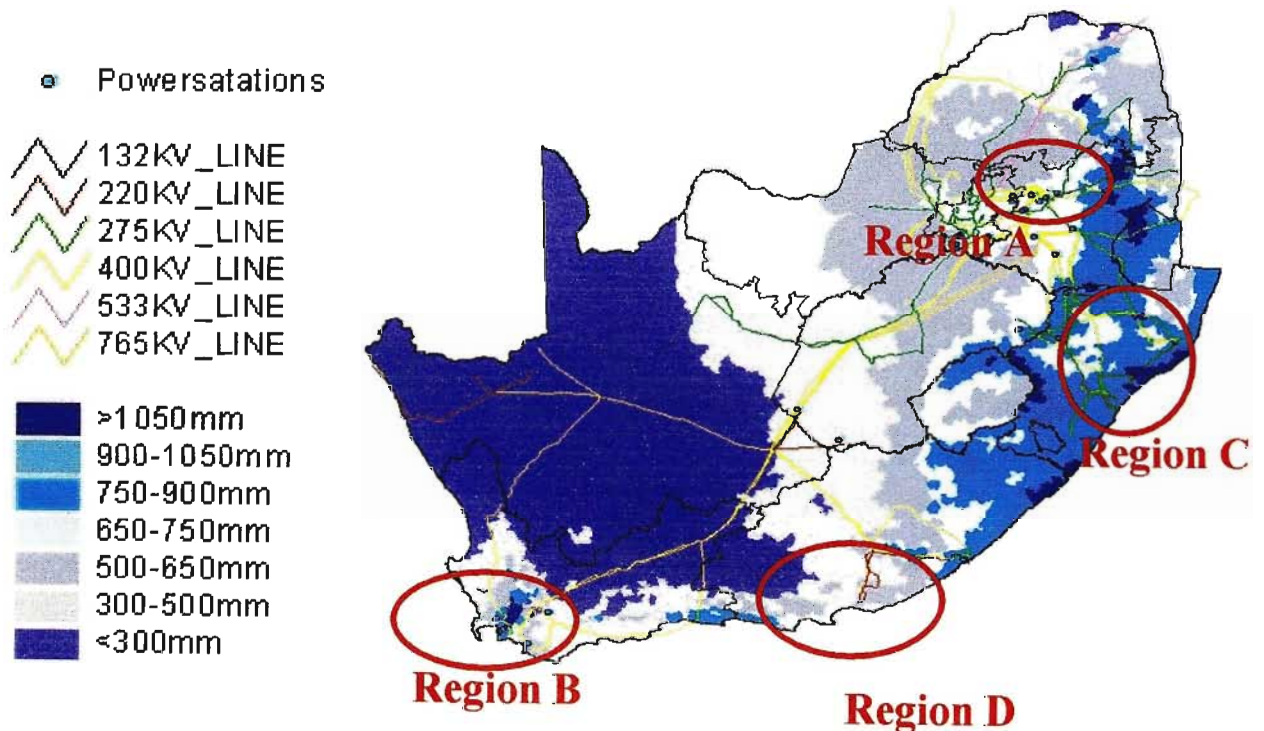


Figure 3. Rainfall Map of South Africa

1.1.3 Description of dew formation over South Africa

Parts of South Africa may be described as a desert environment as these areas are mostly dry areas with sand. As indicated by Rizk (Rizk et al, 1970), desert climates are characterised by hot days and cool nights. Dew formation on insulators due to the rapid and large temperature variations that result in the cooling down of the insulator surface during the night may lead to flashovers. Figure 4 below indicates that most of the regions have medium to high numbers of frost days. This will be shown later to be a possible cause of the high number of unexplained line faults during the early mornings.

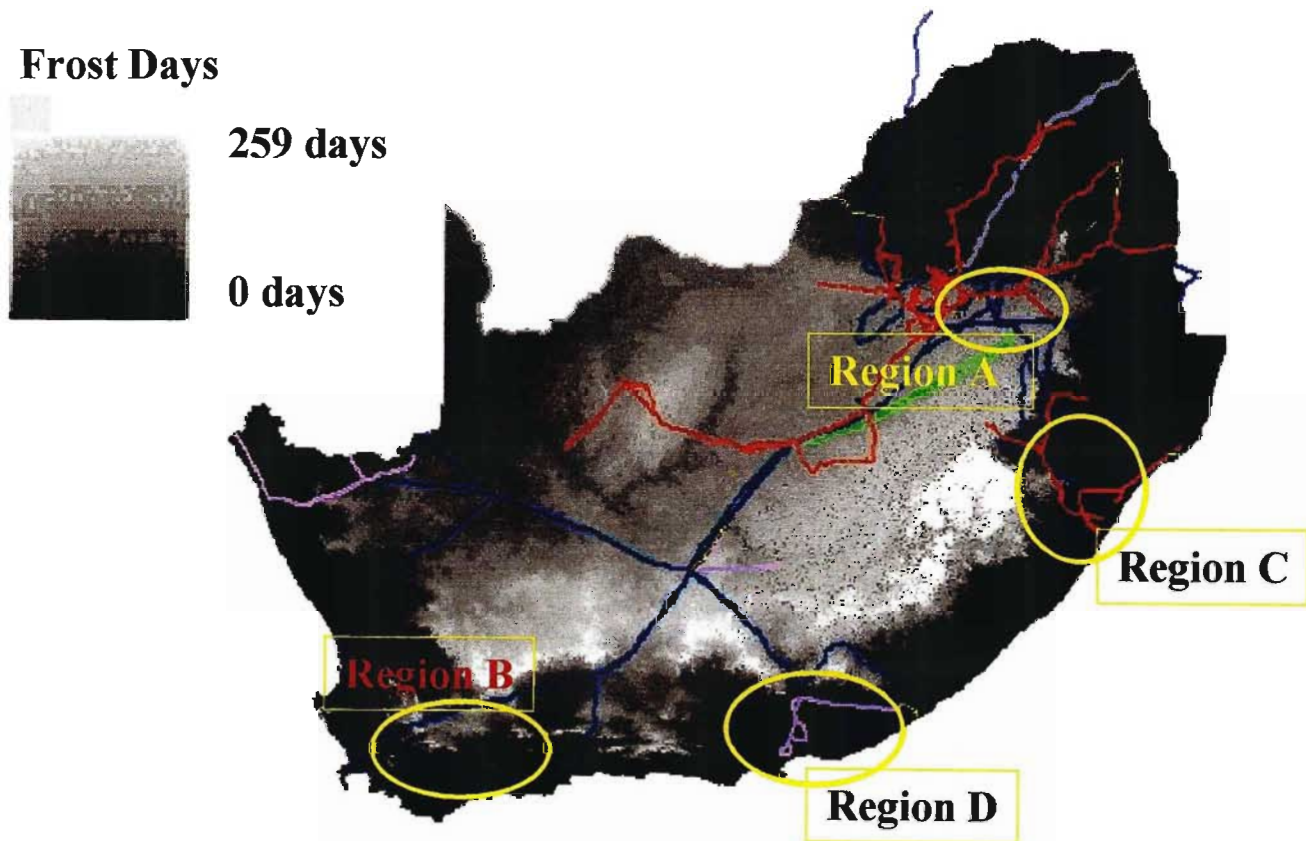


Figure 4. Frost Days Map of South Africa

1.1.4 Lightning map of South Africa

The coastal regions of South Africa do not experience high lightning activities compared to the Central and Northern area. Most of the identified problematic lines fall within the high lightning incidence areas. The Eskom Transmission Network is negatively affected by this high lightning activity.

Figure 5 below shows the lightning ground flash density map for South Africa.

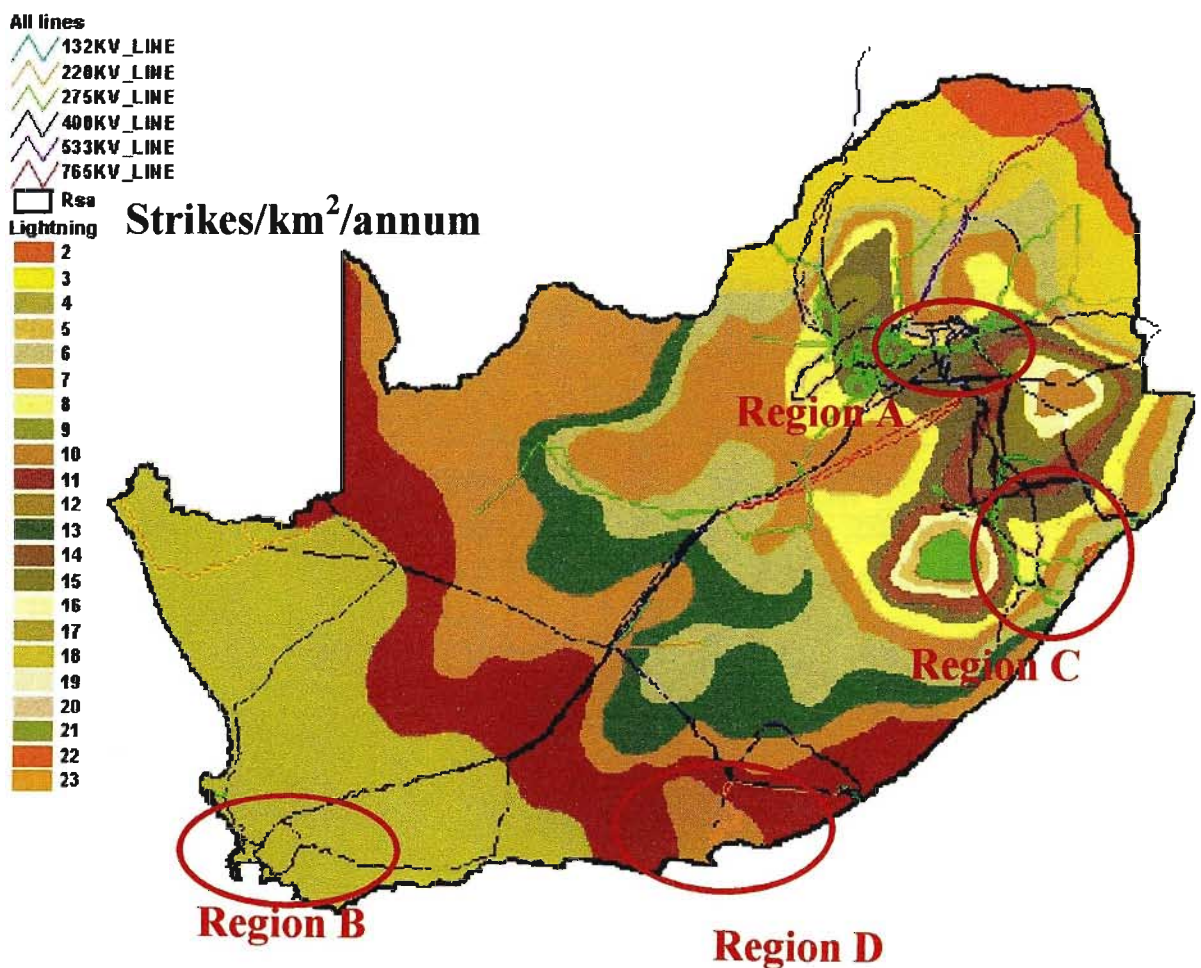


Figure 5. Lightning Map of South Africa

1.2 Line Construction Factors

The voltage levels, phase to phase and phase to earth clearances, tower types insulator and bundle types may all be reasonably expected to play a role in any flashover mechanism occurring on the system. A brief description of the Eskom network and its construction is therefore included below.

The Eskom Transmission network covers a large area of South Africa. To deliver the power to the Eskom Customers at the agreed quality, the network needs to be well integrated. The table below gives an indication of the total length of in-service lines per voltage category.

Voltage	Length
765 kV	870 km
533 kV (DC Monopolar)	1 035 km
400 kV	15 187 km
275 kV	7 409 km
220 kV	1 239 km
Total	25 740 km

Table 1. Eskom Transmission Line lengths per Voltage

Table 1 indicates that the longest lines are the 400 kV system followed by the 275 kV system. Relatively short length of lines at other voltages do occur but are not particularly problematic. The study therefore focuses on the 275 kV and 400 kV networks.

For each system voltage the types of towers most generally used are discussed below.

1.2.1. Tower Types in use

The four basic types of towers used by Eskom Transmission are: Guyed V, Self Support or stand alone, Compact Cross Rope or Cross Rope and Delta structures. The most commonly used structure is the Self Supporting tower. Figures 6,7,8 and 9 give examples of each major transmission tower type.

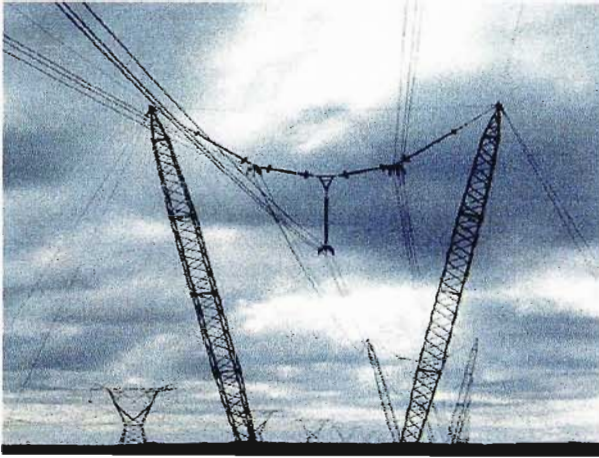


Figure 6. Compact Cross Rope Tower (400 kV)



Figure 7. Delta Tower (275 kV)

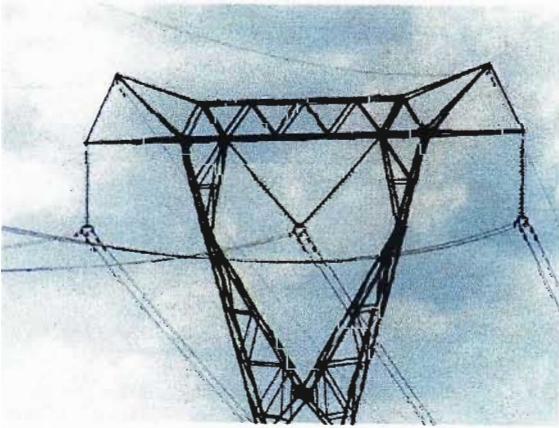


Figure 8. Self Support Suspension Tower (275 kV & 400 kV)



Figure 9. Guyed V Tower (765 kV)

The compact or standard cross rope tower is the only tower that does not allow birds to roost on the tower. Roosting birds may use all the other types of towers.

1.2.2 Types of glass insulators used

The most common type of insulators used on the transmission system in South Africa is glass discs insulator. The type of glass insulators used is the standard glass cap and pin. The standardised creepage length for the 275kV lines is 18 mm/kV whilst for the 400 kV lines it is 23 mm/kV. Anti-fog insulators are installed in limited areas.

In areas where pollution is present, such as industrial or marine pollution, it has become practice to install composite insulators. The pollution performance of these insulators (due to the hydrophobic surface properties) is much better than the normal glass insulators (which have hydrophilic surface properties).

From the early 1980's a large number of non-ceramic insulators have been installed on the Eskom system. At transmission level, these have all been silicone rubber based composite insulators. Failures of these insulators are rare but have occurred. As the performance of the non-ceramic insulators is not seen as problematic, this study focuses on lines insulated with glass disc insulators.

Table 2 includes an estimate of the number of glass disc insulators installed on the transmission network as a percentage of the total number of insulators installed.

Voltage	Number	% of Total Insulator Strings
765 kV	0	100%
533 kV DC (Monopolar):	600	95.27%
400 kV:	27 764	84.77%
275 kV:	22 956	74.18%
220 kV:	3 568	76%
Total:	53 288	82.81%

Table 2. Table of the estimated number of Glass Disc Insulators installed on the Eskom Transmission Network

This table indicates that approximately 75 % of the 275 kV network and approximately 85 % of the 400 kV network are still insulated with glass disc insulators.

1.2.3. Conductor bundles

Eskom Transmission uses different conductor bundles. The majority of these bundles are twin conductor bundles. On the 400 kV system quad types are also used. Other bundle types used are hexagonal (765 kV lines) and triple.

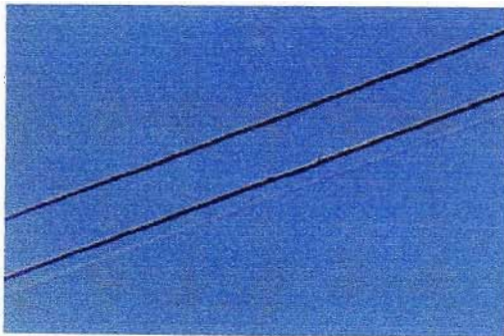


Figure 10. Twin Conductor Bundle

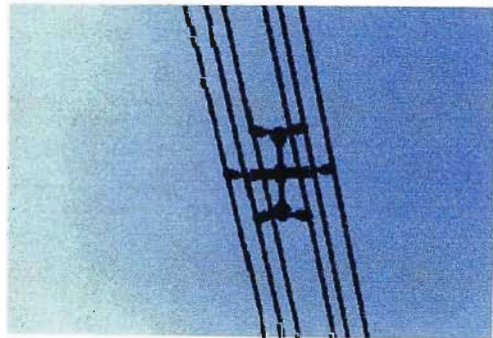


Figure 11. Hexagonal Conductor Bundle

It is not expected that the conductor bundle will be a factor in explaining unknown causes of flashovers.

1.3 Conclusion

This chapter has provided a description of the Eskom Transmission network. This description has identified those parameters that would most reasonably be expected to impact negatively on the overall system performance. These parameters include identification of biomes (considerations of crop and grass burning), rainfall patterns, dew and frost formations, lightning incidences and various construction factors including voltage levels used and the types of insulators used.

The theory of flashover of transmission level insulation is reviewed in the following chapter.

2. FLASHOVER MECHANISMS

2.1 Review of flashovers

Transmission line design has focussed on fault mechanisms related to overvoltages generated by lightning and switching surges as well as pollution flashovers across glass disc insulators. However the performance of a complete network may be adversely affected by other factors such as vegetation growth, fires and birds. Each of these mechanisms is reviewed below. A review of basic mechanisms of AC corona, streamer and leader breakdown is included although in general the review and later analysis focuses on long air gap breakdowns.

All of the unexplained line faults could be due to one of the above flashover mechanisms.

2.2 AC corona mechanisms and streamers

Corona is a phenomenon caused by the partial electrical breakdown or ionisation of the air surrounding a conductor fitting energised at a high voltage. It occurs when the electric field potential gradient on the surface of the conductor or fitting exceeds a critical value, usually given by Peek's law (peak) under standard atmospheric conditions (as given in Kuffel and Zaengl).

Corona manifests itself as a visible discharge, radio interference, audible noise and corona losses.

Townsend [Kuffel et al, 1984] investigated the growth of current as a function of the applied voltage across an air gap. Townsend proposed that for uniform fields the growth of charge carriers in the air gap be summarised as follows:

$$n = n_0 e^{\alpha x} \quad \text{Equation 1}$$

where n is the number of charge carriers

α is Townsend's first ionisation coefficient

x is the distance travelled by discharge

The above equation quantifies the growth of ions in an electrically stressed air gap, either by electron collisions or by photoionization, as an exponential function. The phenomenon is termed an electron avalanche. The equation was later modified to include the effect of electron attachment on the process of charge carrier multiplication. This relationship is summarised as follows:

$$n = n_0 e^{(\alpha - \eta)d} \quad \text{Equation 2}$$

where η is the attachment coefficient and $(\alpha - \eta)$ is known as the effective ionisation coefficient ($\bar{\alpha}$).

Raether [Kuffel et al, 1984] observed that when the number of charge carriers was greater than 10^6 but smaller than 10^8 the growth of the electron avalanche was weakened. When the number of charge carriers exceeded 10^8 the growth of the charge carriers was exponential and breakdown followed. At this point the electric field in the air gap was ≈ 31 kV/cm. In a uniform field the start of the electron avalanche ensures that the entire air gap will break down as $\alpha > \eta$ everywhere.

Raether attributed the observed weakening of the avalanche growth to the space charge effect of the ion concentrations on the head of the electron avalanche. In uniform fields, the space charge effects on the growth of the electron avalanche are negligible. However, in non-uniform fields the space charge effects play an important role in the mechanism of corona discharge and subsequent air gap breakdown. Townsend's electron avalanche model hypothesised that the breakdown time for the air gap should be at least the time taken for an electron to cross the air gap. Experimental evidence proved that the time to spark was quicker than this. This observation led to the establishment of the streamer breakdown model.

2.3 Long gap Breakdown and leader mechanism

Fundamental information on switching impulse leader characteristics was provided mainly through the work of Les Renardieres Group, 1972 and EPRI. Some of the aspects, which are important, are:

- Leader propagation is associated with charge injection at a rate $q_l = 40 - 50 \mu\text{C}/\text{m}$ of axial leader length for rod-plane gaps. The linear charge density is somewhat higher for spherical electrodes and somewhat lower for cylindrical conductors.
- Under critical conditions, the instantaneous applied impulse voltage increases so as to maintain a sensibly constant leader tip potential as the leader continues to penetrate the gap.
- The axial leader velocity is normally in the range 1-2 cm/ μs with a frequency quoted value of 1.5 cm/ μs .
- With the exception of probable lack of local thermodynamic equilibrium, the leader bears some resemblance to an electric arc, with a voltage gradient that depends on the life time, and which varies from an initial Value E_i of approximately 400 kV/m for a newly created leader segment to an ultimate value E_∞ of approximately 50 kV/m. An estimate of the time constant involved is 50 μs

From the work of Rizk (Rizk et al, 1989), it is suggested that, as the leader propagates into the gap, streamer discharges ahead of the leader (leader corona) will in general develop under the influence of the leader space charge that is continually injected into the gap at a rate of q_l C/m, the geometric field and streamers own space charge. As the leader approaches the final jump, the field

component due to leader space charge becomes most prominent and plays a decisive role in determining the height of the final jump.

Hutzler (Hutzler et al, 1978) suggested that the breakdown of a large air gap submitted to a positive switching surge is not an instantaneous phenomenon. The first corona is the first ionization phenomenon, which may be detected in the gap. Satisfactory explanations have been given and it has been shown by Carrara (Carrara et al, 1976) that its influence on the following aspects of the discharge is practically zero when the curvature radius of the anode is smaller than a critical value.

Under certain conditions, the first corona is followed by one or more dark periods, but the most important is that breakdown of gaps of several meters in length only occurs after the start of the leader propagation.

The last phase of the leader propagation is known as the final jump. It is only the conclusion of a process, which has already started and has no effect on the probability of breakdown as long as the voltage impulses applied to the gap do not decrease too rapidly as in the case of lightning surges.

The Corona Cloud Model

The corona cloud model described by Kline (Kline et al, 1977) is now discussed:

The following assumptions regarding corona cloud growth are made:

1. The corona cloud grows from the positive, high voltage electrode, along the shortest path to the grounded or negative electrode.
2. The corona cloud is a conductor.

The assumed corona cloud shape is based on the shape of the corona luminosity, which is experimentally observed in rod-plane gaps in the work of Stekolnikov (Stekolnikov et al, 1964) and Hutzler (Hutzler et al, 1975). The total corona cloud length is equal to $l + s$ where l is the leader length and s is the streamer length.

The assumption of a conducting corona cloud simplifies the calculations and results in a spatial distribution of charge which is qualitatively similar to the corona cloud charge distribution which were experimentally observed during long gap breakdown by the work of the Les Renardieres Group, (1974) and Waters (Waters et al, 1970).

The calculated electric field at the tip of the corona cloud is given by:

$$E_n = \frac{E}{E_{av}} \quad \text{Equation 3}$$

where $E_{av} = V/d$ is the average field in the gap of the length d with applied voltage V and E is the electric field at the tip of the corona cloud. The gap factor for any electrode geometry can be predicted with the corona cloud model by making the following additional assumptions:

3. Breakdown occurs at the crest of the critical switching surge.

4. The corona cloud length at breakdown is equal to $(l + s)$ critical, the corona cloud length corresponding to $E_{n,\min}$, the minimum value of E_n .
5. The actual corona cloud tip field at breakdown is the same for every electrode geometry.

These three assumptions imply that the gap factor, k , for any geometry is given by:

$$k = \frac{V_{s,ns}}{V_{s,rp}} = \frac{(E_{n,\min})_{rp}}{(E_{n,\min})_{ns}} \quad \text{Equation 4}$$

In the above equation rp denotes rod-plane geometry and ns any other geometry.

The corona cloud model as described by assumptions 1 to 5 is independent of gap length. The magnitude of the actual critical flashover voltage for any electrode geometry can be calculated from:

$$V_s = k(500d^{0.6}), d \leq 5m \quad \text{Equation 5}$$

$$V_s = k\left(\frac{3400}{1 + 8/d}\right), d > 5m \quad \text{Equation 6}$$

The increase in corona loss as well as the increase of radio interference levels attributed to atmospheric conditions has been investigated by Boulet (Boulet et al, 1996). Negative corona modes are suppressed under normal condition during alternating current operations. Trinth (Trinth et al, 1968) studied the modes from corona inception until the onset of breakdown streamers.

Rizk (Rizk et al, 1997) determined that there is no significant difference between the sparkover voltages in the presence of fog and dry air for air gaps less than 1 meter.

The flashover voltage of air gaps and insulators depends on the moisture content of the air. The breakdown voltage dependence on humidity of air gaps may be described by the expression (Kuffel and Zaengl):

$$V = \frac{V_0}{H}$$

Equation 7

where V_0 is the breakdown voltage at standard conditions and H is the humidity correction factor that depends on gap geometry.

With each half cycle of an AC voltage the role that ions play is reversed according to investigations done by Goldman (Goldman et al, 1978). The electric field distribution along the x-axis of the air gap can be determined by the following expression:

$$E_x = \frac{2V}{(r + 2x) \ln[(r + 2d)/r]}$$

Equation 8

Where r is the point radius, V is applied voltage, d is air gap length and E is the electric field in the air gap axis x .

2.4 Lightning flashover mechanism

The Lightning Ground-Flash Density Map indicates that the annual incidence of lightning in South Africa varies considerably, from less than flash/km²/yr to more than 12 flashes/km²/yr in the Drakensberg area.

A streamer starts from the cloud, becomes a leader and the current in the leader is in the order of 100 A. This is known as the pilot leader. Once the streamer has made contact with ground it is believed that a power stroke moves at a very high speed up towards the cloud along the already ionised path. It is here where the negative charge of the cloud is neutralised by the positive charge of the ground. This is clearly visible. There may be another cell of charge in the cloud near the neutralised charged cell. This cell will try to neutralise through the ionised path. This streamer is known as a dart leader.

The effect of the dart leader is much more severe than that of the return stroke. It is found that each thundercloud may obtain as much as 40 charged cells.

When a lightning strike hits an earthwire or tower it raises the voltage potential of the tower or adjacent towers of a span. The energy needs to be drained down to earth through the tower earth strap. In a case where the tower earth strap is broken or the resistivity of the ground is very high the voltage potential of the tower rises considerably and as a result it may cause back flash over to the live conductor causing the line to arc.

Lightning trips normally occur in the afternoons and with the Lightning Positioning And Tracking System (LPATS) it can easily be verified that it was indeed a line fault caused by lightning. In most of the lightning caused line faults it is suspected that the strikes do not hit the main live conductor directly as the earth wire normally shields the main conductor from such a strike. As such most of the lightning induced faults on the system are considered within Eskom to be due to backflashover.

2.5 Backflashover Mechanisms

The back-flashover caused by lightning occurs when a lightning strike hit a tower or the earth wire of an overhead line. When a lightning strike hits a tower the stroke current flows through the tower and due to the high resistance of the tower earth a voltage is produced.

The voltage of the tower rises higher than the earth potential due to the high resistance of the tower earthing. The potential of the phase conductors does not change as a result of the lightning strike on the tower. The current of the lightning strike running through the tower produces a magnetic field in the region of the tower window between the tower and the phase conductor. As a result a voltage is produced between the phase conductor and the tower. The voltage also changes according to the rate of change of the lightning current. A very basic expression for the voltage developed across the insulator string is;

$$V(t) = (1 - K)[I'R + LdI'/dt] + V_o \quad \text{Equation 9}$$

Where R is the tower footing resistance, L is the geometrical factor relating flux to current, K is the coefficient of coupling between the shield and phase conductors, and V_o is the phase to ground system voltage at the time the stroke occurs. The current I' is less than the stroke current because some of the stroke current flows away from the tower in the earth wire to the adjacent towers.

2.6 Standard Pollution Flashover Theory

The results presented by Schneider et al, (1978) indicated that the contaminated flashover voltage is a non-linear function of string length. This non-linear effect becomes pronounced for long columns of very large diameter.

A report compiled by Engelbrecht (Engelbrecht,1996) as well as work done by Rizk et al (Rizk, 1970) indicated that the driving force behind the pollution flashover process is the applied voltage. Classically dry band arcing is described in electrical terms as an arc in series with a resistance representing the conductive surface layer. It was concluded that the surface layer resistance is the underlying factor determining whether an insulator will flash over or not. In turn the surface layer resistance is determined by the conductivity of the layer and the profile/diameter of the insulator. The worst case conditions in terms of flashover are thus conditions of highest surface layer conductivity.

The following conclusions were made as a result of the work of Schneider (Schneider et al, 1978):

- Tests on long vertical strings of standard and anti-fog insulators in a fog chamber have shown that the contamination flashover voltage is a nonlinear function of string length.
- A substantial reduction in flashover voltage was obtained for uniformly contaminated posts of large diameter compared with smaller posts.
- Cold switch on performance of conventional and semi-conducting glazed Insulators for UHV string lengths is about the same.

For ease of understanding the pollution flashover mechanism it may be divided into the various phases given below:

1. Pollution is deposited on the insulator surface. Studies have shown that the most important mechanism of pollution deposit is through the movement of air (wind). Most common types of pollution are bird pollution, marine pollution (salt), agricultural pollution and industrial pollution. The solid layer deposit generally consists of a soluble component and non-soluble component.
2. Dry pollution normally has a very high resistance but with the addition of water the soluble pollution is allowed to dissolve and forms an electrolyte which will have a conductivity dependant on the type of soluble deposit and its concentration (usually expressed as mass per surface area i.e. mg/cm^2)
3. Once the insulator is covered with an electrolyte layer, current will start to flow across the insulator surface. Due to the corresponding Joule heating losses in the electrolyte layer the water will evaporate in some area creating dry bands. Under these conditions the electric field distribution of the insulator is highly disturbed (most of the voltage appearing across the dry bands) and normally the dry bands will spark over.
4. If the conductivity of the wet surface layer is high enough the dry Bands arcs may develop into a flashover of the insulator.

The whole process may be summarised as an interaction between the insulator and pollutants, wetting conditions and applied voltage. The degree to which dry bands form initially and the rate at which they reabsorb moisture depends on the relative humidity of the air surrounding the insulator string because the closer the air is to

saturation, the more the evaporation process is hindered and the more re-absorption is enhanced.

In a situation of light rain, the wetting action is also a function of the amount of rain actually striking the insulator surface. As a result, dry band formation may not be possible until after the rain ceases. Heavy rain washes the pollutants off the insulators.

2.7 Bird Streamers

Bird excreta are known to pollute insulator assemblies. When this deposit become wet, it forms an electrolyte and dry band arcing may result. This mechanism poses a quality of supply problem, which is prevented by re-insulation (silicone composite insulators) or spray washing. These faults occur frequently.

This was first postulated as a problem in 1920 in California. Since then Bonneville Power Administration and Florida Power and Light have referred to it (Burnham, 1995). In a recent survey of IEEE members, at least 75% of the respondents indicated line faults attributable to bird streamers. Faults caused by bird streamers occur when a continuous (or partial) stream of bird excrement, resulting in a line fault bridges the air gap. The solution offered is to move the streamer away from the live hardware by means of bird guards. Taylor et al, (1999) has investigated these mechanisms in South Africa. These faults pose a quality of supply problem. Successful reductions in the number of faults were achieved through the fitting of bird guards on the 275 kV and 400 kV networks.

Large birds can cause a flashover by releasing a long continuous emission of conductive fluid, which shorts out the air gap between the structure and the conductor. Birds capable of producing these streamers are large raptorial birds without webbed feet (West et al, 1971). However, in South Africa this category could also include perching ducks such as Egyptian and Spruwing geese (Van Rooyen, personal communication).

The ability of the bird excrement to cause a flashover has been demonstrated in laboratories on two occasions. West et al. simulated a flashover at 320kV ac and 400 kV dc in 1971 using a mixture, with viscosity and resistivity emulating that of the streamer. Burger et al, (1995), did a similar experiment in 1995 at 275 kV dc. In both cases strong evidence was provided that bird streamers could be a plausible factor responsible for line faults.

The quantity of excrement of large birds is estimated at 60 cm³ (West et al, 1971) and is confirmed by local ornithologists who put the figure at 50cm³ (Verdoorn, personal communication). The urinary and faeces tracts of a bird join and the excrement is made through a single orifice called the cloaca. The size of streamer is highly dependent on the diet and quantity to be eliminated.

A streamer produced by a vulture, estimated at 2,89 m (Van Rooyen et al, 1999) was observed on the Edwardsdam-Mareetsane 88 kV line.

A worker of Florida Power and Light recorded another streamer. “An eagle released a stream of excrement which extended from the crossarm above the insulator point to a point close to the conductor” (Burnham, 1995).

Streamers of similar length were produced in laboratory tests, using 50 cm³ to 60 cm³ of excrement substitute. These were capable of bridging both 320 kV and 400 kV dc line-to-ground air gaps (West, 1971). The excrement consists of a mixture of urine and faeces in the cloaca and the droppings can be grouped in three patterns: rod shaped, snail shaped and fluid droppings. Carnivorous birds which consume large amounts of tissue protein produce large volumes of liquid urates (Burnham, 1995). The consistency and volume of bird dropping varies greatly according to factors such as diet, quality of food, time of day and species (Burnham, 1995)(van Rooyen, personal communication). It is clear that predictions on the behavior of birds must be made with extreme caution.

The Bonneville Power Administration experiments, done with excrement substitute, indicated that samples of real excrement were alkaline with a resistivity between 30 ohm-cm and 120 ohm-cm (West et al, 1971). To simulate the viscosity, raw scrambled eggs were used. A small amount of salt was added to lower the resistivity from 130 ohm-cm to 120 ohm-cm (West et al, 1971).

2.8 Fire Caused Flashovers

Fire has been reported as responsible for power system outages in many countries. Types of fires which cause outages include burning sugar cane fields, forest fires, grass fires, refuse burnings and oil fires.

The flashover voltage of air insulation at high temperatures, as occur during under fire conditions, is drastically reduced when compared with values at ambient temperature. The dielectric strength is dependent on the type of voltage stress (AC, DC, and Impulse) and also on the proportion of the gap covered by flames.

At high temperatures the flashover voltage of an electrode configuration is reduced due to the decrease of the relative air density within the gap.

For constant pressure the relative air density decreases with increasing temperature according to the expression from the Epri Transmission Line Reference Book (Transmission Line Reference Book, 1982):

$$\delta = \frac{0.289p}{278.3+t} \quad \text{Equation 10}$$

where p is in mbar and t in °C

Field measurements have shown that in the flames, temperature values of 900 °C can be reached, thus δ can be reduced to 0.25. In the presence of fires a great number of floating particles are generated within the gap.



Figure 12. Photograph taken by the author of a sugar cane fire underneath Arnot – Maputo 400 kV line

The quantity of generated particles varies with the fire source being, for example, greater for grass or sugar cane fires than for alcohol or gasoline fires. These particles produced by burning are responsible for the greatest reduction on the breakdown voltage under fire.

Flashovers may be caused by fires, including forest fires, sugar cane fires, veld fires, refuse burning and structure fires (the most common ones). A tall fire column is necessary to produce hot ionized gases sufficiently close to the conductors to cause flashovers.

The majority of fire-induced flashovers occur at midspan. Past experience has shown that it is not necessarily just long grass that can cause a flashover when it burns underneath a power line but that the probability at flashover also depends on various other factors such as:

- The phytomass present on the ground where a fire is burning.
- The various types of grass and its moisture content.
- The type of day such as very dry, humid, temperature and wind.
- Period since last burn i.e. height of growth.

The above factors influence the probability of a line to ground flashover. The air density between the conductors and the ground changes as a result of veld fires.

A flame has a high ion and electron concentration making it reasonably conductive. When a flame becomes large enough to extend from the ground into the proximity of the conductor (within the sparking distance), the flame will

immediately cause flashover. If a smoke column is composed of burning particles it may be considered to be partially conductive.

2.9 Discussion

It is clear that each of the above fault mechanisms may contribute to causing faults on the Eskom Transmission system. Some of these are not likely to be classified as cause unknown (e.g. switching flashovers). The minimum clearances used on the system applicable to some of the above mechanisms is included in Table 3 below.

System Voltage Unom	220 kV	275 kV	400 kV
Umax	245 kV	300 kV	420 kV
Minimum Clearance at tower (air gap)	1.85 m	2.35 m	3.2 m
Minimum Clearance at centre	6.7 m	7.2 m	8.1 m
Glass Discs, mm/kV	15 mm/kV	18 mm/kV	23 mm/kV
PLIWL (Air gap at tower)	-	850 kV	850 kV
BIWL (Air gap at tower)	950 kV	950 kV	1175 kV
Conductor Bundle	Twin	Twin	Twin/Trip/ Quad

Table 3. Indication of the minimum clearances applicable to the various Voltages

2.10 Conclusion

This chapter discussed all the relevant flashover mechanisms and the applicable theory models. These models will form the basis of the discussion that will follow. From experience and the above models it is evident that mostly all line faults can be linked to one of the four flashover mechanisms.

The following chapters will discuss the performances and analysis of the Eskom Transmission network. It will also include the finding of evidences that can assist to identify the cause of the line fault.

3. PERFORMANCE OF THE ESKOM TRANSMISSION NETWORK

3.1 Introduction

The following chapter will discuss all the known causes of transmission lines faults. Actual field results and experience will be used to discuss the various causes for the line faults. The knowledge gained in investigating line faults is of vital importance as the unknown lines faults can be linked to any one of the four main fault causes in almost all cases.

3.2 Known Causes of Flashovers

Switching over-voltages are suspected to have a minor impact on the line flashovers. Causes of line faults that are relatively easy to identify are lightning and veld/sugar cane fires. These types of faults occur mainly during the day and are correlated via LPATS (Lightning) or observations of burning underneath the power lines at the time of occurrence of the fault.

The bird streamer fault mechanism is more difficult to determine (birds are transitory and not observed at the time of the fault) but in a number of cases one may find evidence of bird streamers on the towers which would be used as an indicator of the likely cause of the fault.

The methods to identify each known cause will now be discussed:

3.2.1 Lightning

Eskom Transmission uses the Lightning Positioning And Tracking System (LPATS) to determine whether a line fault was indeed caused by lightning. There are currently 6 antennas at various locations to detect lightning strikes. The data is then transferred to a central database at Megawatt Park.

A number of remote computers receive live data from this centralised database. Actual lightning strikes are superimposed on the routes of the Transmission lines. The actual location of the strikes can then be used to verify whether it did hit a Transmission line.

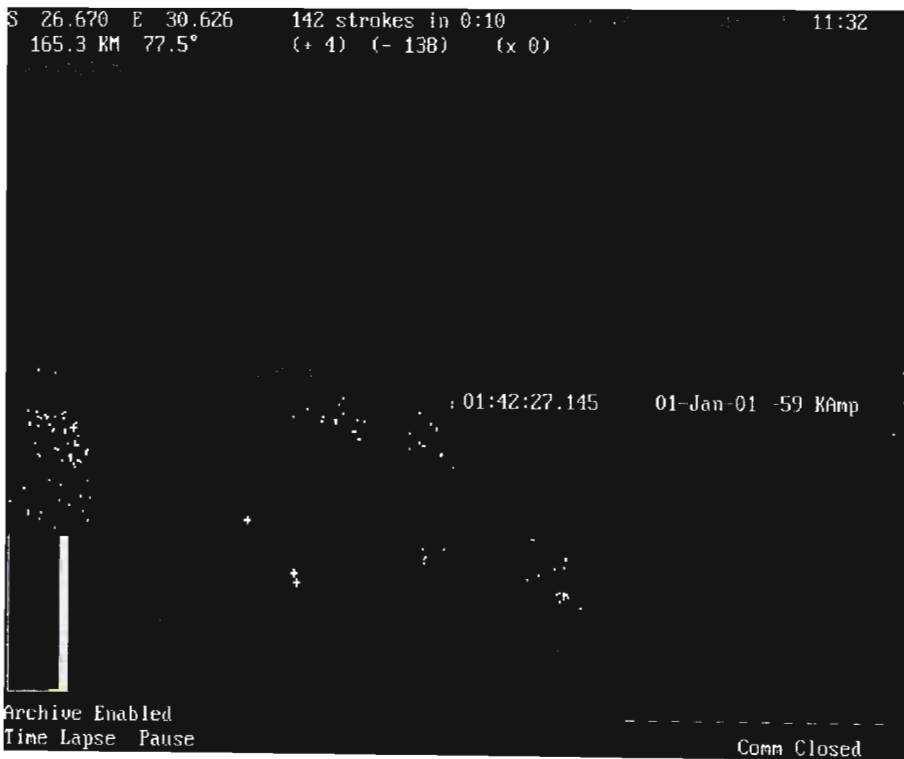


Figure 13. A file from the Lightning Positioning And Tracking System Used by Eskom Transmission to identify lightning caused line faults

Figure 13 above is an example of such a lightning strike that did hit one particular Transmission line and caused a fault. The time indicated on the figure next to the lightning strike is very important. This time can be correlated with the time stamp of the fault. The magnitude of the lightning strike is also indicated which is in this case -59 kA. In this specific incidence, the fault records were amended from “cause unknown” to “cause lightning”. Lightning related line faults normally occur in the northern parts of South Africa. The lightning activity normally occur during the late afternoon periods of a day and from September month to April month the following year. Figure 14 indicates a photograph of a flashover burn mark where the flashover was caused by lightning.

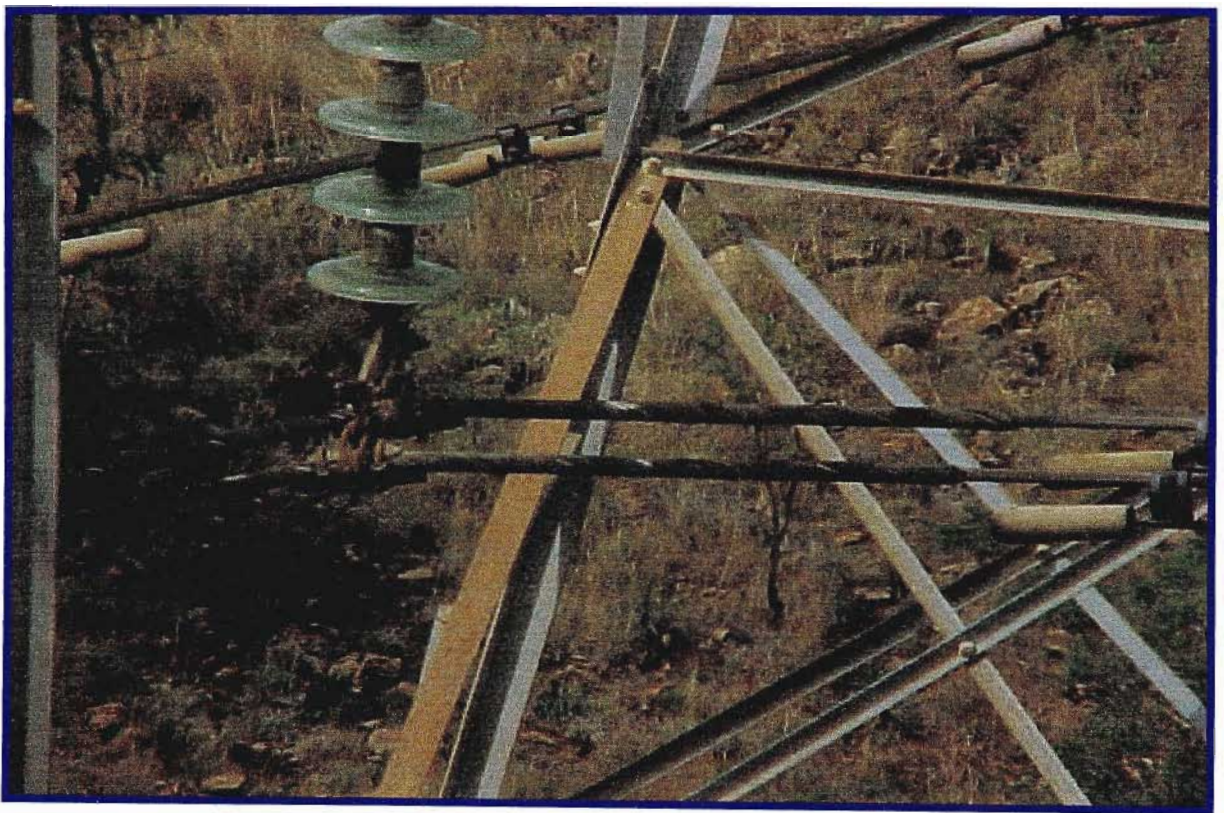


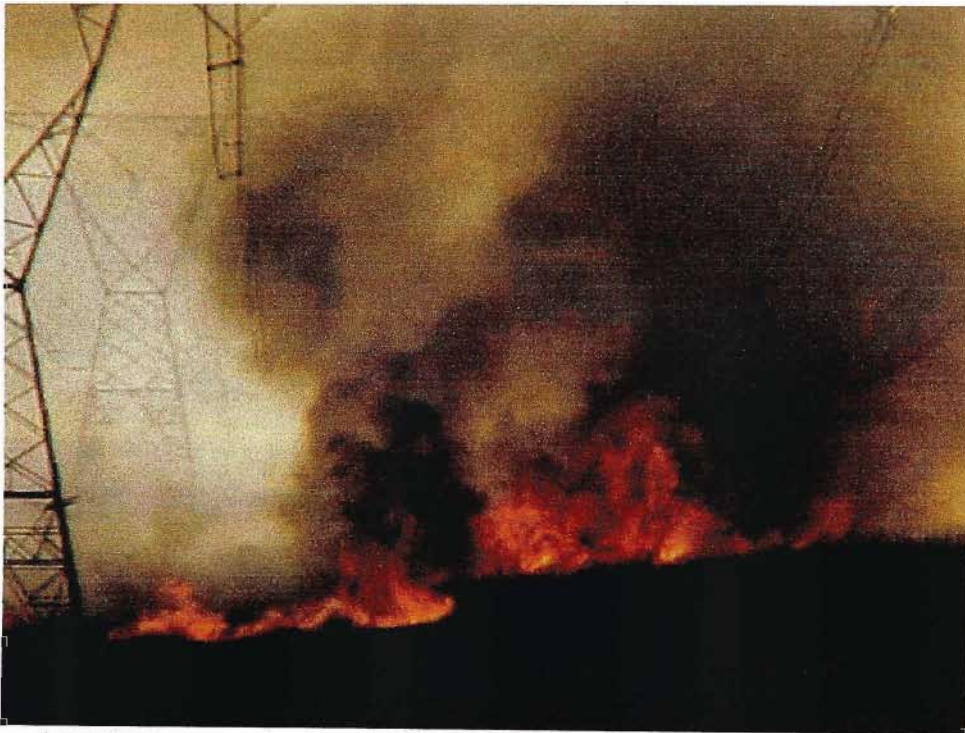
Figure 14. Photograph taken by the author of burn marks on the conductor caused by a lightning strike on the tower. Cause of fault identified by examination of LPATS data.

It must be noted however that the location of lightning strikes provided by LPATS are not 100% accurate.

The time recorded for each strike by LPATS is accurate as it is connected to the Geographical Position System (GPS). In certain cases the time recorder on fault locators that is also connected to the GPS may then be used to compare it to the time recorded in LPATS.

3.2.2 Veld/Sugar cane Fires

Veld or Sugar cane fires can normally be identified by visually inspecting the servitude underneath the line. Figure 15 shows the typical burning of veld grass underneath a power line.



**Figure 15. Photograph of veld fire the Apollo – Duvha 400 kV line
(Photograph taken by V Viljoen, Eskom Transmission)**

For a veld fire to be able to cause a flashover to ground, the fire must be a hot fire. As hot fires normally occur during the middle of the day (i.e. hottest period) it may be identified by examining the time of occurrence of the line fault.

Veld fires normally occur during the hot periods of a day, that is from 11:00 to 16:00 and during the dry months of May to September. The Fire Danger Index is an indicator that is increasingly used to determine the risk of flashover resulting from lines. The three factors that are taken into account are: humidity, temperature and wind speed. An investigation has revealed that overhead lines normally flash to ground more easily during days of high Fire Danger Index values.

The Fire Danger Index (FDI) gives a relative indication of how hot veld fires will be if it occurs on a specific day. Sugar cane fires may also cause a transmission line to flashover between phases or from the conductor to earth. Two possible remedies for these types of faults is to switch the line out as soon as there is a sugar cane fire underneath the line or to cut the sugar cane before it is burnt. Figure 16 shows the number of veld fire caused faults annually.

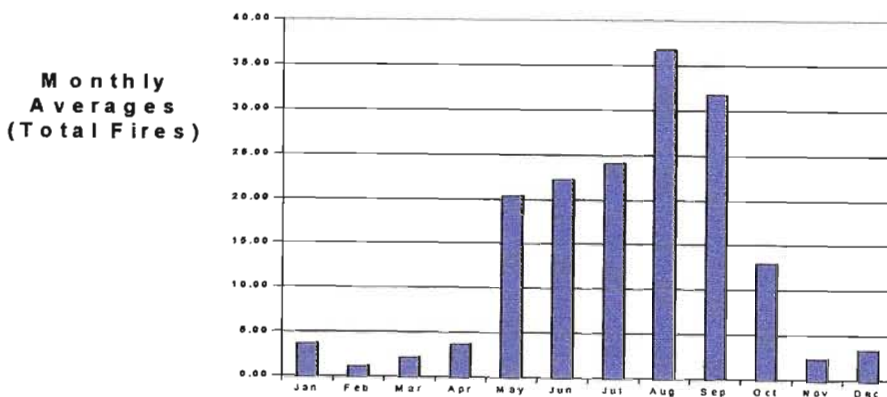
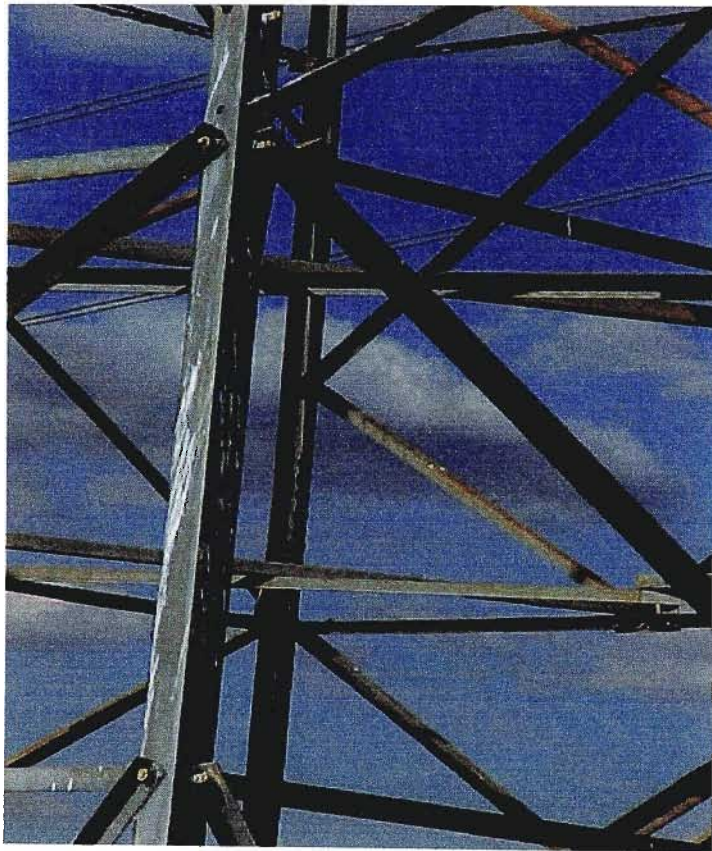


Figure 16. Annual Monthly Average Fires of the Transmission Network

3.2.3 Bird Streamer

Line faults caused by bird streamers normally occur before midnight (during roosting) and then again in the early mornings (prior to birds leaving their roosts). The evidence that a Line Patrolman is trained to look for is a burn mark on the cross member above the V or I string and on the conductor or yoke plate.

Residual bird streamer pollution may sometimes also be found on the tower via visual inspection. Photograph 17 gives an indication of evidence of the presence of bird streamers. Such evidence is sought by line patrolman who carry the post fault investigations.



**Figure 17. Photograph taken by the author of Bird Pollution
On a tower of the Arnot-Simplon 275 kV line**

The photographs below show evidence of burn marks on the yoke plate.

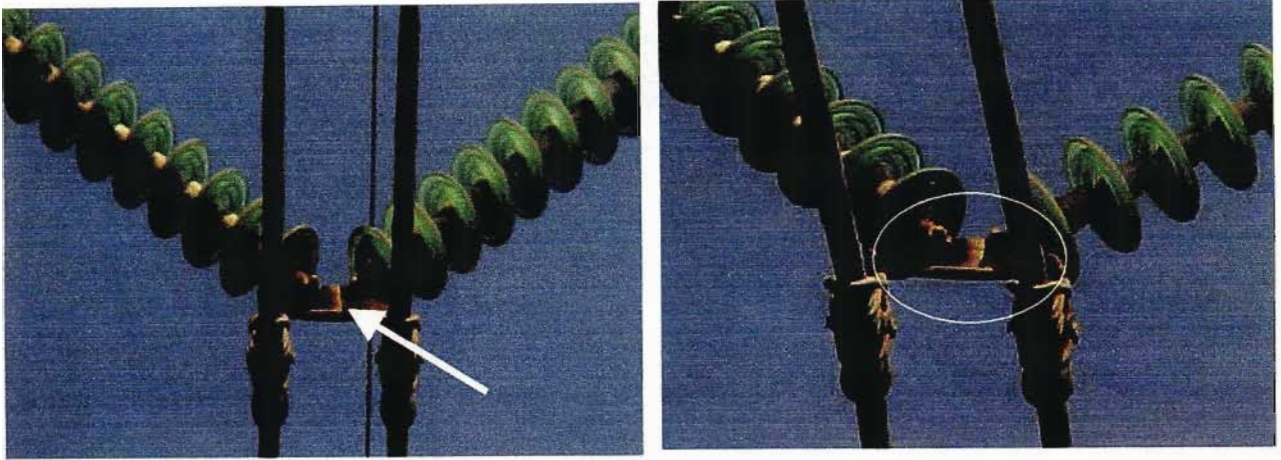


Figure 18. Photograph indicating the burn marks on a yoke plate caused by a flashover (Photograph taken by M Sibanyoni, Eskom Transmission)

3.2.4 Encroachment by Trees

In most cases line faults caused by trees occur during mid day (results of an investigation (Eskom Transmission Investigation, 2000)). The reason is that Transmission lines may sag considerably during hot periods of the day and causing the line to flash over from the conductor to the tree. These types of line faults are normally easily identified by a burned tree.



Figure 19. Photograph taken of the encroachment of trees under an overhead Transmission line (Photograph taken by C Chiloane, Eskom Transmission)

3.3 Unknown Causes

As indicated by Britten (Britten, 1999) the Eskom Transmission Network is experiencing an exceptionally high number of the so-called unexplained line faults. The intention of this report is to analyse a number of factors and compare each one to the other in order to reach a conclusion.

The high percentage of unexplained line faults (35 %) is very important for the Transmission group to minimise. Major efforts to minimise the number of “known” faults such as bird streamers, veld fires, sugar cane fires, lightning and light pollution, light wetting mechanism has been undertaken by Eskom Transmission.

When the statistical data of the unexplained line faults is analysed carefully and in detail it should be possible to categorise these unexplained line faults into the most probable known categories via statistical analysis. Correct identification of the cause of fault is usually done by a line patrol reporting back to operations and maintenance management. It is critical that the responsible patrolman is trained and is not pressured into falsely identifying the cause of fault.

The analysis excludes the following known fault mechanisms: the bird streamer mechanism, bird pollution, lightning, sugar cane fires and veld fires.

The report focuses on the following:

- ◆ Identification of the under performing lines (Rogue Lines) of the main Transmission Network,
- ◆ Comparison between the Rogue Lines with respect to: Area, Voltage, Weather information,
- ◆ Line fault during time of day and Line fault during month of the year.

The analysis of these lines indicated that unexplained flashovers normally occur between 22:00 and 07:00 the following morning. Almost all the Rogue Lines in South Africa fall in the sub-tropical/humid climatical area. All the Rogue Lines studied are insulated only with glass discs.

From the analysis it was concluded that most unexplained related line faults occur during the months when the seasons changes, e.g. from autumn to winter. The performance of the lines was analysed for the years 1993 to 1997. The

analysis indicates that most unexplained line faults occurred during April to May and August to September.

Unexplained line faults normally occur from 22:00 to 7:00 in the morning. One of the reasons could be due to dew formation on the insulator discs in the early morning period, or due to high voltages during night times as the loading is at its minimum. The presence of mist with other factors can also be a cause during these hours for the lines to trip

3.4 FACTORS INFLUENCING THE PERFORMANCE OF LINES

3.4.1 Network Loading

The voltages on the Transmission Network will generally be lower during periods of peak loading and higher during periods of off-peak loading. The loading for the Transmission Network over a 24 hour period is shown in Figure 20.

There is an obvious correlation between time of day of unexplained line faults and the system loading (i.e. lower system operating loading and hence higher system voltage) coinciding with larger number of unexplained flashovers.

Due to lower system demand the voltage tends to increase from 22:00 at night to 06:00. This higher system voltage would most reasonably be expected to increase the probability of flashover due to either bird streamer mechanisms or some type of pollution flashover. At night, on the high lying regions of South Africa, heavy dews may form causing heavy wetting of glass disc insulators

which, when combined with the higher operating voltage of the system, may cause flashover.

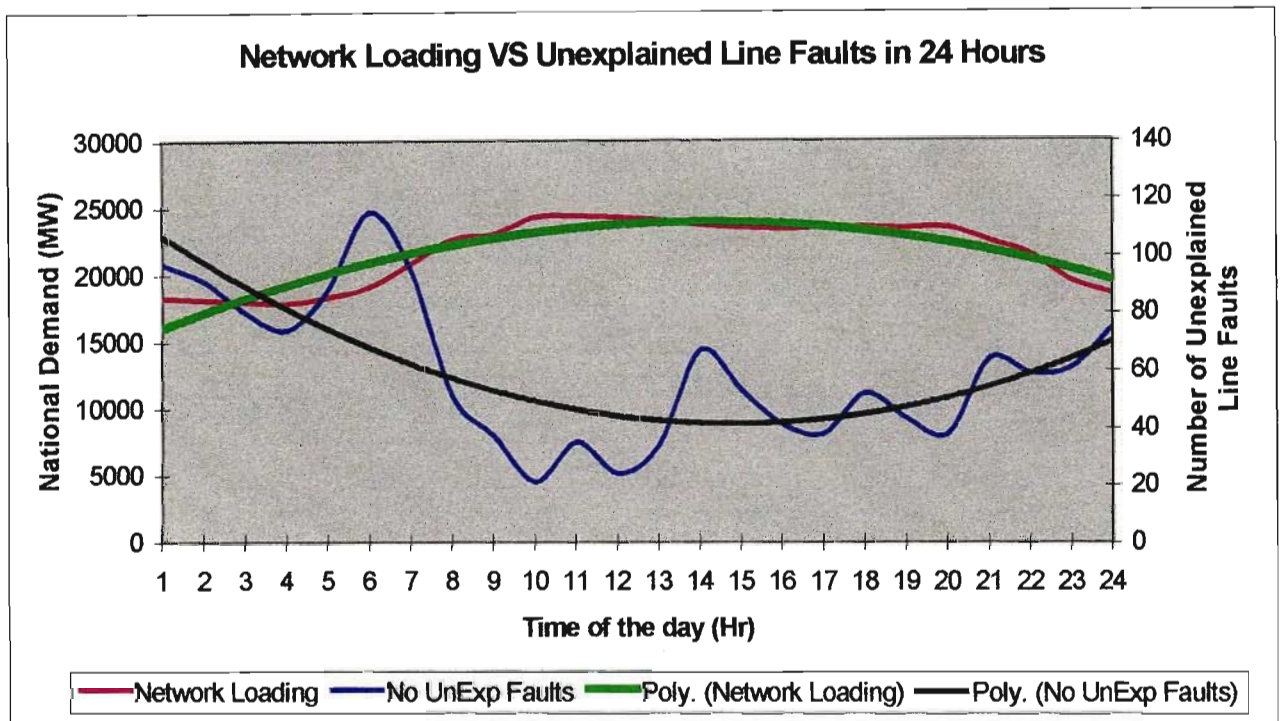


Figure 20: Maximum demand on the Eskom network versus the number of unexplained line faults over a 24-hour period

This may provide an explanation why there is an increase in unexplained faults that occur during the early mornings and evenings, as these are the periods with minimum *demand on the network and* humidity higher than 75 %, which could have caused the line trips due to some unexplained pollution phenomenon (pollution levels are generally quite light).

4. STATISTICAL ANALYSIS

4.1 Introduction

This chapter concerns itself with techniques for categorizing unknown fault mechanisms into one or more possible known causes. This section focuses on the 220 kV, 275 kV and the 400 kV voltage levels. The performance of the entire network was subjected to statistical analysis for the period of 1993 to 1997. The faults that were recorded for this period were analyzed in terms of Time of Day, Month of Year and climatic region. This analysis provides some indication of which of the mechanisms described in section 2 may be playing a dominant role in causing faults particularly for the category of faults listed as unknowns.

Figure 21 gives an indication of the percentage of line fault categories on the Transmission Network for the time period 1993 to 1997. This chart has been derived from the line fault records of Eskom Transmission.

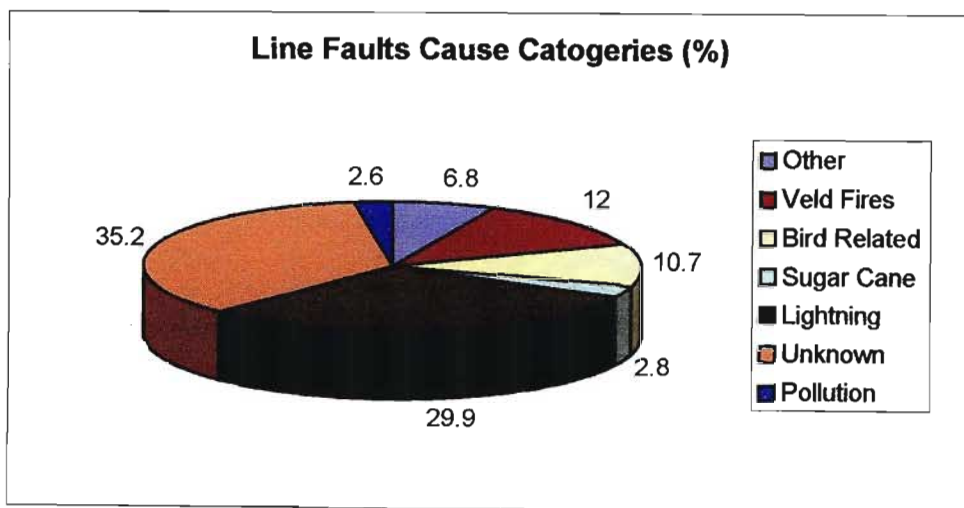


Figure 21.
Indication on contribution of the various line fault causes of the Transmission Network in percentage.

Important information contained in this figure is that 35 % of all faults are categorized as unknown or unexplained. A major effort has focussed on minimizing the "known" faults, such as bird caused faults. The focus of the statistical analysis is to determine the causes of the unexplained faults

The analysis was performed from a consideration of identified parameters that may impact on the system performance such as weather condition, climatic areas, network loading, bird activity in the vicinity of the line.

4.2 Time of Day analysis for the whole network.

An analysis of time of day of the unexplained faults for the whole Transmission Network is given in Figure 22. The total number of faults subjected to this analysis was 1433. The figure indicates that across the whole network the number of unexplained faults for the whole network is a strong function of time of day. The largest number of unknown faults occur at night.

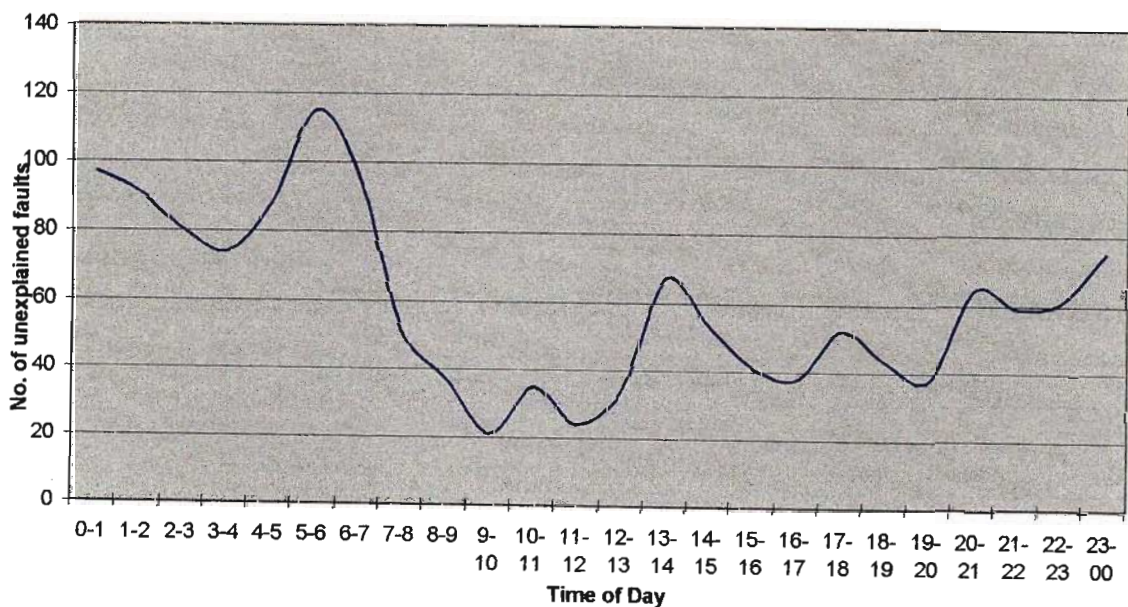


Figure 22. Unexplained Line faults over a 24-hour period

The time of day occurrence of unexplained line faults normally exhibits a peak from 22:00 to 07:00 in the morning. One of the reasons could be due to dew formation in the insulator discs in the early morning period, or due to high voltages during night times as the loading is at its minimum. The presence of mist with other factors may also be a cause during these hours for the lines to trip.

Further, a slight increase can be seen on Figure 22 around 13:00 to 14:00. A possible reason for this is that line sagging may occur at that time of day due to high system load and high day time temperature, the line could flash over to a line it crosses, such as a distribution line. Another reason may be the incorrect classification of a known flashover e.g. due to veld fires or sugar cane fires. During hot humid days the system experience in the past has been that veld fire caused line faults tend to occur more. The role that system loading condition plays regarding this issue will be discussed later.

A brief summary of the performance of the 220 kV, 275 kV and 400 kV networks is given as follows:

- ◆ The 275 kV lines tend to trip more during lightning storms as compared to 400 kV and 220 kV lines over a 24-hour period.
- ◆ The 400 kV lines tend to trip more often at 06:00 due to unexplained reasons, but the 275 kV lines trip more often at 09:00.
- ◆ During the time period from 13:00 to 19:00 the 275 kV lines also trip more than the 400 kV lines as a result of unexplained causes. This corresponds with the fact that the 275 kV lines trip more due to lightning

as lightning occurs normally from 13:00 to 19:00. One possible explanation then is that lightning caused faults are probably misclassified as “unknown” when, in fact, the cause is lightning.

Figure 23 compares the flashovers of 220 kV, 275 kV and 400 kV lines over a 24-hour period (average over 3 years). The vertical axis indicates the percentage fault contribution for each of the three voltage levels investigated as a function of time of day (horizontal axis).

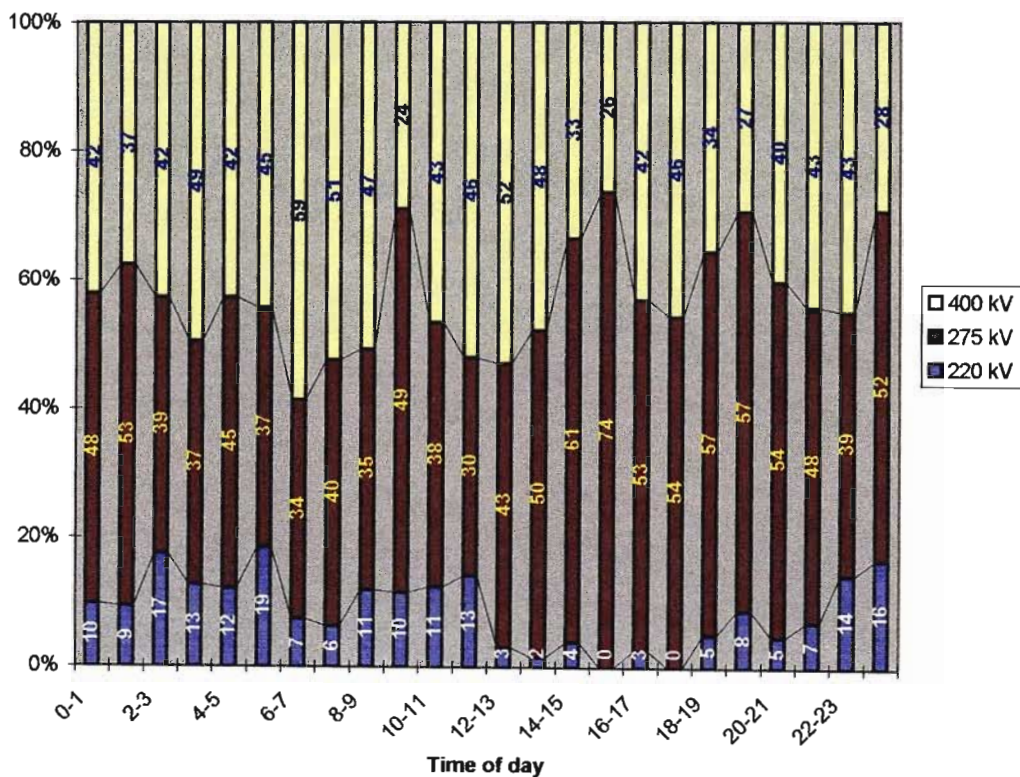


Figure 23. Number of unexplained line faults over 24 hour period including 275 kV versus 400 kV versus 220 kV

Figure 23, indicates that a major cause of 275 kV line faults may be lightning activity and that this is a more significant cause of faults on the 275 kV system than the 400 kV system.

From Figure 23 the following conclusions may be drawn:

1. The 400 kV lines tend to trip more often during the period of 6:00 am to 7:00 am due to unknown reasons. The 275 kV lines trip more at 09:00 am.
2. During the time period from 13:00 to 19:00 the 275 kV lines also tend to trip more than the 400kV lines as result of unexplained causes. This corresponds with the fact that 275 kV lines trip more due to lightning as lightning activity is highest during this period.

From the research report on the unknown category of line faults by Britten et al, it was determined that the predominant specific creepages on the 275 kV and 400 kV lines are respectively 14.9 and 15.3 mm/kV. However, since U120 glass disc insulators were installed from 1988, the creepages have increased to 17.0 and 17.5 mm/kV respectively.

The higher insulation level of 400 kV lines compared to 275 kV lines may provide an explanation for the observation that the 275 kV lines trip more than the 400 kV lines during lightning storms.

4.3 Time of Year analysis

During seasonal changes (April-May) it is clearly visible, in Figure 24, that more unexplained flashovers occur. The reason for this phenomenon is that mist and fog normally occurs during these months of a year as a result of fairly high humidity and large daily temperature variations.

Number of faults Monthly

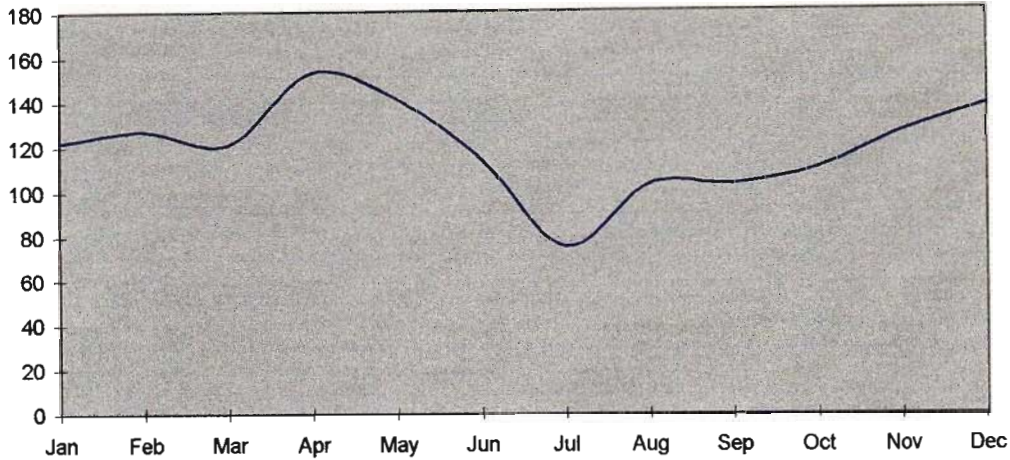


Figure 24. Number of unexplained faults over an annual base.

Humidity annual tends to follow the curve as shown in Figure 32.

The high number of unexplained faults during November to December could be due to early morning lightning which, normally may occur in the areas at higher altitudes.

The emigration of birds as a result of seasonal changes will influence the fault mechanism in the early mornings being either a bird streamer or light pollution, light wetting.

The above figures are then discussed in more depth below, firstly by looking at the Time of Day analysis and then by month of the year.

Feb

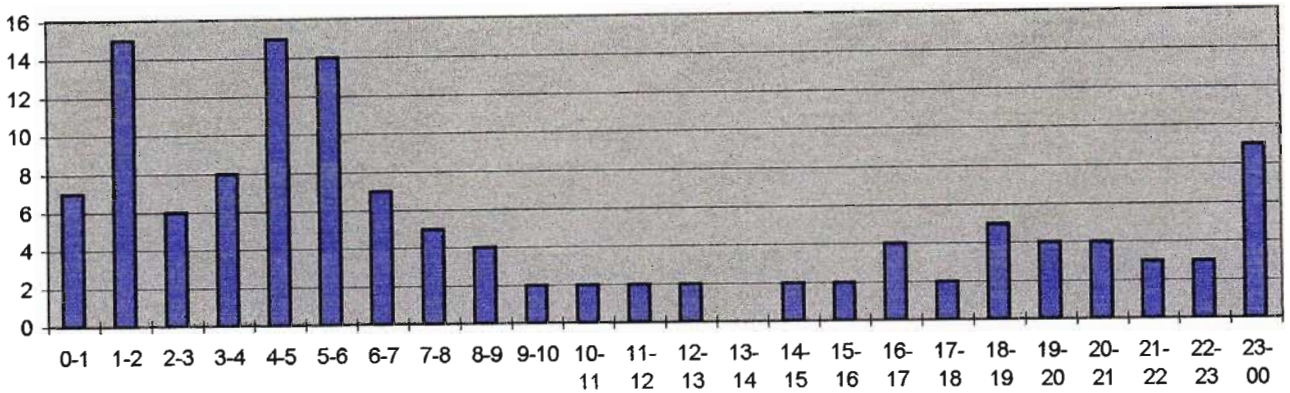


Figure 25. Number of unexplained faults in February over a 24-hour period

May

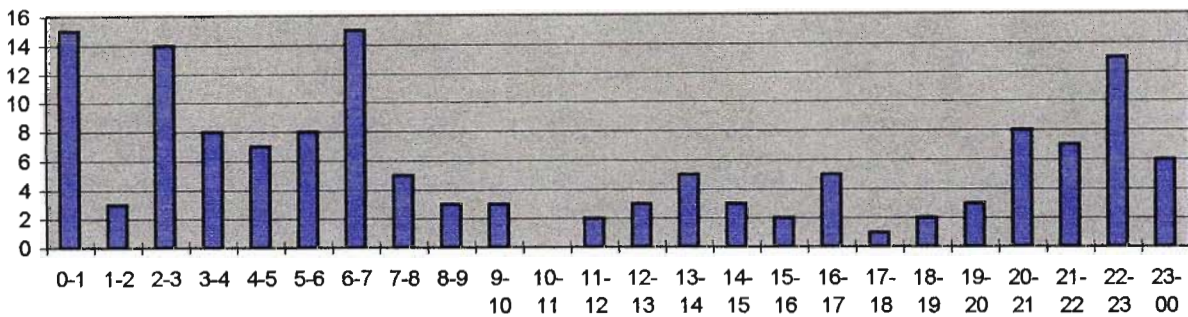


Figure 26. Number of unexplained faults in May over a 24-hour period

From Figures 25 and 26 above it can clearly be seen that in February the highest number of unknown occurs from 05:00 – 06:00 in the morning hours but for the month of May the highest number of unknown line faults occur from 06:00 – 07:00.

The possible reason for the change from the one month to the other is possibly due to:

- a) During February there is normally no mist/fog present.
- b) During the month of May there is normally mist or fog present in early morning periods.
- c) In February months the sun normally rises around 05:00 – 06:00 in the morning whereas the month of May the sun rises later (between 06:00 – 07:30).
- d) Early morning unknown faults may also be ascribed to the fact that roosting birds may become more active at sunrise; that is, failures associated with roosting birds (bird streamer flashover) will most likely follow the time of sunrise.

During the month of September (Figure 27) the number of unexplained faults is virtually identical to that pattern of the month of May. There is, however, an increase in the number of unexplained faults from 13:00 to 15:00. (This increase in line faults in September maybe due to the start of the lightning season).

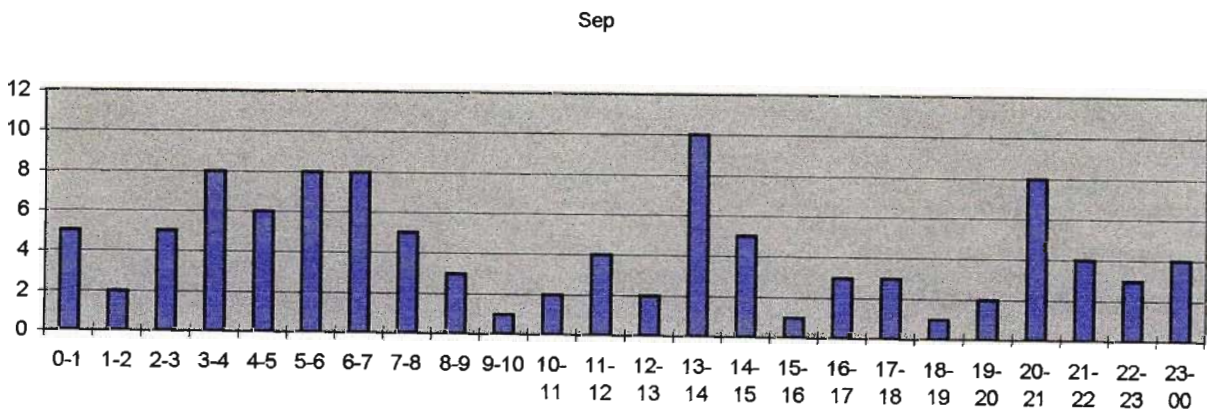


Figure 27. Number of unexplained faults in September over a 24 hour period.

Nov

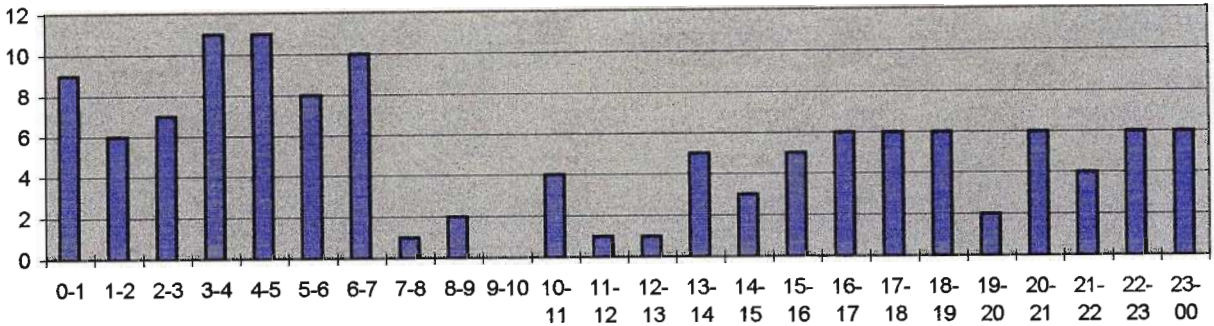


Figure 28. Number of unexplained faults in November over a 24 hour period.

In the month of November the highest number of unexplained faults occurs in the early morning hours (i.e. from 03:00 to 07:00). The summer rainfall pattern over much of South Africa results (in many years) in heavy rainfall (thunderstorms) in the months of September and October. Such heavy rainfalls may lead to the establishment of fresh water reservoirs in various catchments. Bird life tends to congregate in the vicinity of water locations and hence in these months it is likely that bird life and bird activity will stretch over a wider range than in dry months of the year. Hence unknown faults due to the bird streamer mechanism may become more widespread in September and October.

Figure 29 summarizes the above figures and clearly indicate the following:

December: The unexplained line faults could be due to lightning. From 10:00 in the mornings and especially around 17:00 – 19:00 is when lightning activities are very active.

November: Tends to have the same pattern as the December months

October Months: It can be seen that the line faults in the early hours of the morning 04:00 – 06:00 of is a bit higher than at the same times in November.

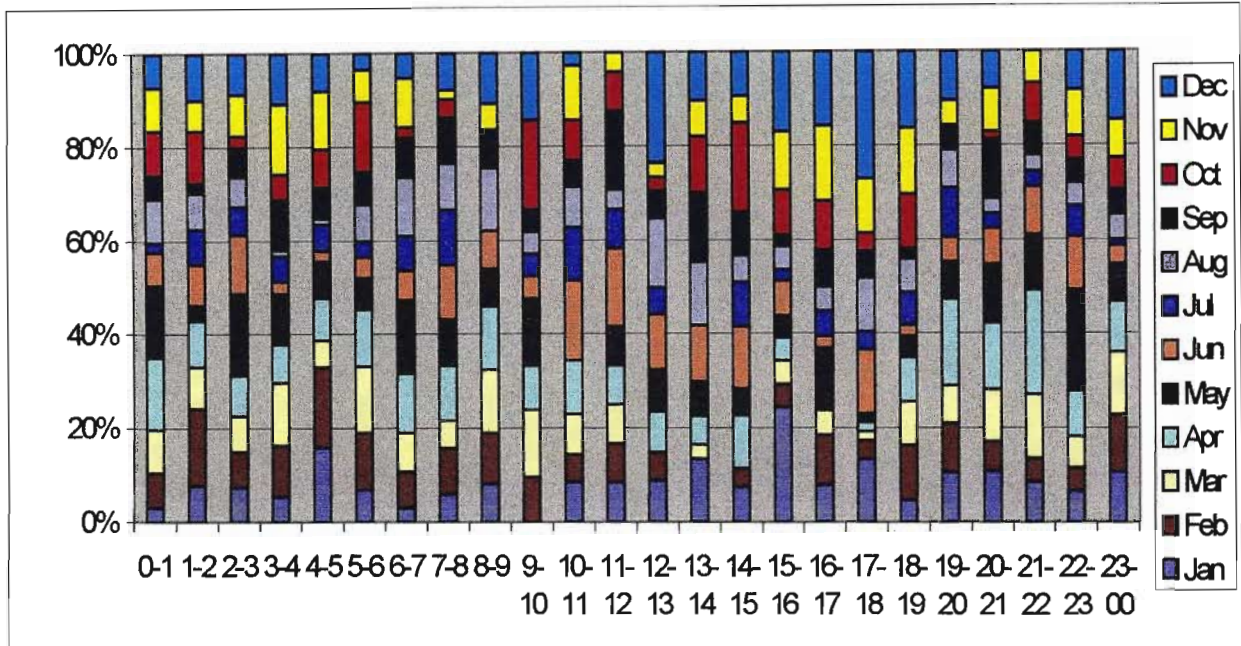


Figure 29. Number of unexplained faults monthly over 24 hour period.

June Months: The highest number of line faults occurs around noon in June. This tends to indicate that the faults are due to veld fires.

Comparing the time of occurrence of the highest number of unexplained line faults to specific hours of the day, the following conclusions may be drawn.

Sunrise in June normally occurs approximately 2 hours later than in January at the latitude of the poor performing lines. In summer, sunrise occurs at around 05:00 and in winter around 07:00. Figure 30 indicates that the number of unexplained line faults corresponds to this shift in time of sunrise. Most unexplained line faults

occur from 04:00 – 05:00 in January and from 06:00 – 07:00 in June. In March and April and then again in October the highest number of unexplained line faults occur from 05:00 – 06:00. Due to numerous reasons birds normally migrate to the north of South Africa. It tends to show then that the early morning line faults may be due to pollution and wetting of the glass of insulator discs.

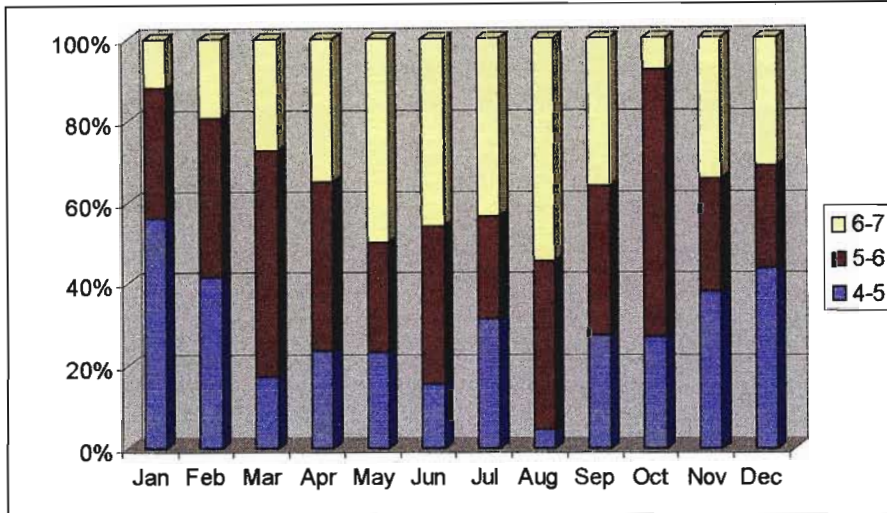


Figure 30. Percentage of Unexplained line faults from 04:00 to 07:00 over an annual base.

Due to the fact that mist and dense fog develops at night times in April and May Figure 31 indicates that the highest number of unexplained flashover from 00:00 – 01:00 occur during these two months and then again in August to October. This then supports the theory that the highest number of unknowns occurs in the seasonal change over months.

The same argument holds for the time period 23:00 – 00:00. From the discussions and analysis done to this point it may be noted that quite a number of the unexplained line faults may be connected to a known cause. Line faults labelled as unexplained are generally not unexplained but the evidence for the cause of fault could not be found by the patrolman. A further analysis was done to find the reason why there is no “evidence” after a large number of line faults.

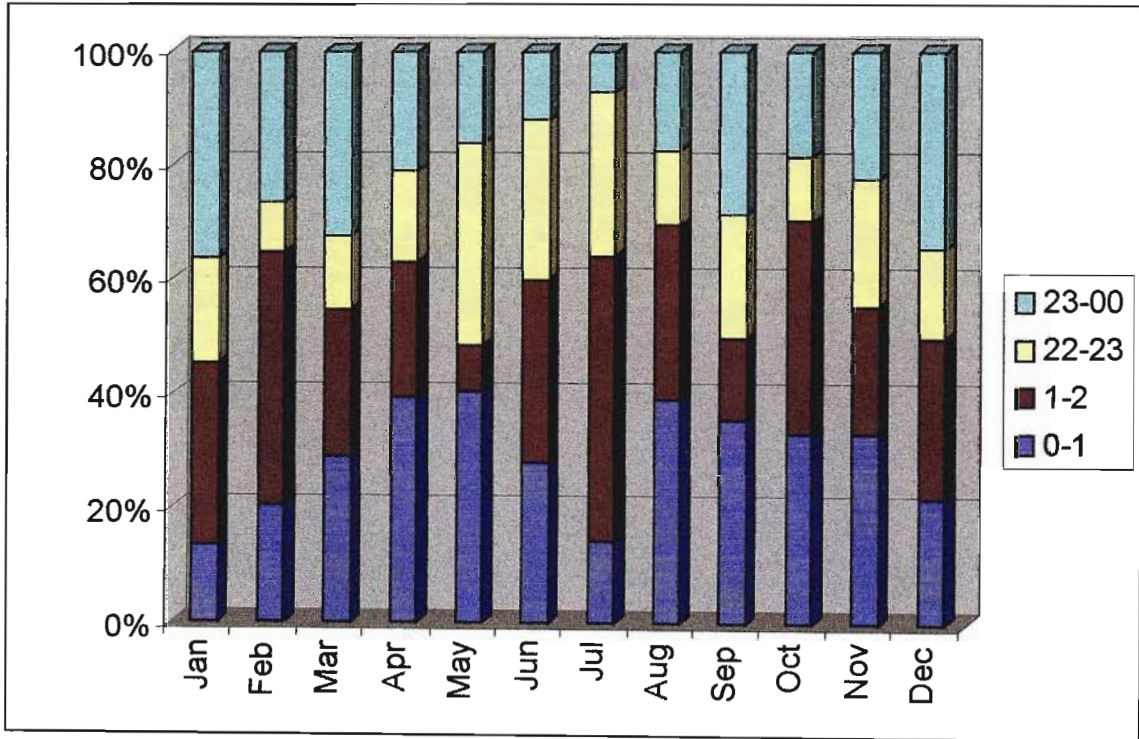


Figure 31. Percentage of unexplained line faults from 22:00 to 02:00 over an annual base.

It is of utmost importance then to start analysing the line faults more in depth, in order to answer the following questions :

1. Time of the line fault?
2. In which month did the line fault occur?
3. What is the fault current that did flow?
4. In what climatic area/vegetation is the line running through?

4.4 Relative Humidity

The relative humidity of the regions through which 10 rogue lines run per month is shown in Figure 32. The trend of this figures follows the trend of the number of unexplained line faults monthly of all the lines in Eskom Transmission in that the peak of unknown faults co-incides with the peak average monthly humidity (April and May).

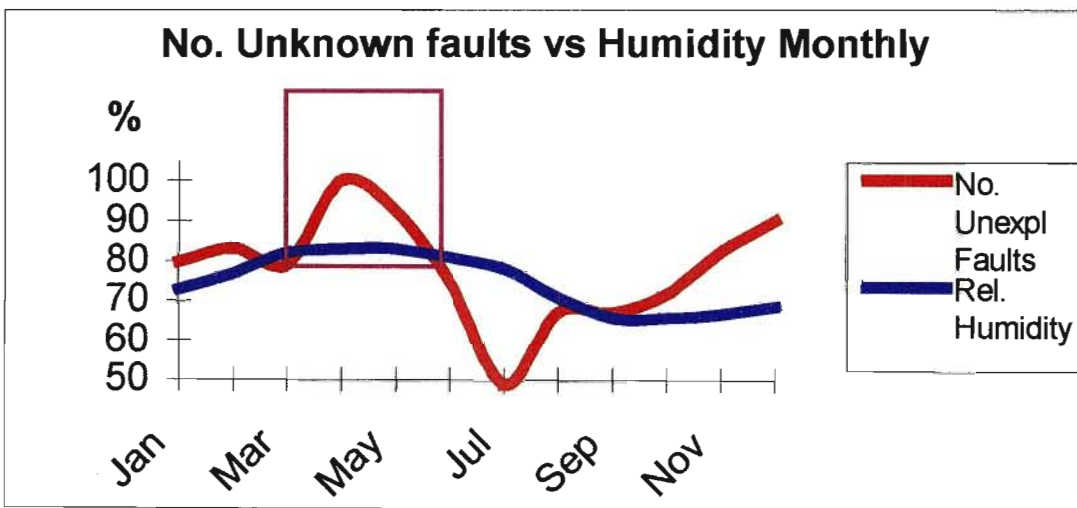


Figure 32. Percentage of unexplained line faults versus Relative Humidity over an annual base.

This indicates that the mechanisms by which a number of unknown faults are caused are related to high humidity. From the figure above it is interesting to note that during the seasonal change over months, May and September, the unexplained line faults increase.

4.5 Conclusion

The overall analysis of all the lines in the Transmission network indicates strong correlation between the occurrence of a large number of faults and a number of other variable parameters. In particular, there is a strong correlation between the periods of the highest numbers of unknown faults and the following parameters:

- system operating voltage
- expected times of bird activity (bird streamer mechanism)
- seasons of high lightning activity
- seasons of high humidity

This analysis indicates that it may be possible to categorise all unknown faults occurring on the system into categories of probable causes identified through a combination of time of day analysis, time of year analysis and the region through which an individual line runs. Case studies of the applicability of these ideas are included in the following chapter.

5. Identified Rogue Lines in Transmission

The purpose of this chapter is to present the results of an attempt to categorize unknown faults on 9 different transmission lines over the period 1993 to 1997 into categories of probable causes.

The time of day and time of year analysis developed in chapter 4 is applied systematically to each line (considered to be poor performing lines) and the probable causes of flashover and hence listed.

	Line Name	Total Trips over 60 Months
1	ARARAT-SPITSKOP 2 275KV LINE	32
2	KOMATIPOORT –MARATHON 275KV	25
3	HYDRA–RUIGTEVALLEI 400KV LINE	16
4	WARMBAD-WITKOP 1 275KV LINE	23
5	ARNOT-MERENSKY 1 400KV LINE	15
6	BETA – HYDRA 1 400KV LINE	16
7	MATIMBA – MIDAS 2 400KV	44
8	PLUTO – WATERSHED 1 275KV	19
9	TABOR – WITKOP 275KV LINE	19

Table 4: Indicates the number of unexplained faults these particular lines experienced over a period of three year, from 1993 – 1997.

5.1 Ararat – Spitskop 2 Line

From Figure 33 it can be seen that a large number of unexplained line faults occur in the early morning hours of the day, late afternoons and around midnight. When the monthly line fault (Figure 34) analysis is also brought into consideration it

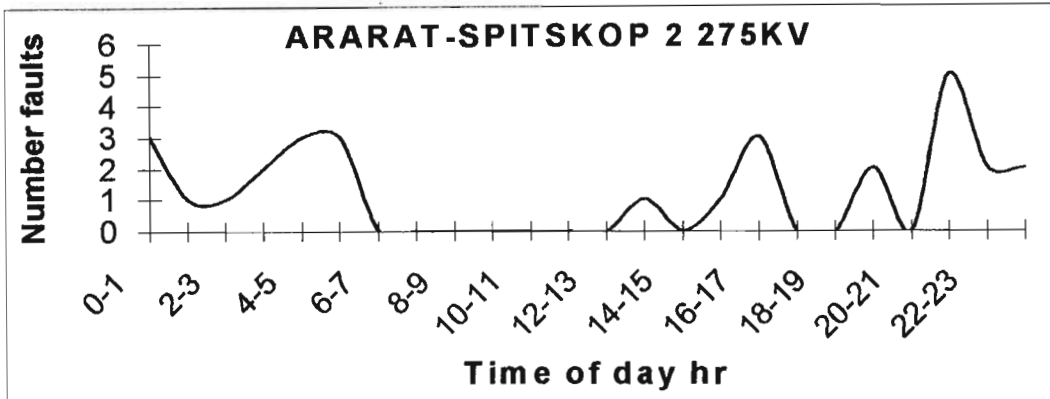


Figure 33. Number of Unexplained line faults of the Ararat-Spitskop line over a 24 hour period.

may be determined that this line tends to trip more during the seasonal changes (namely May and August) than during the rest of the year. As this line falls in the sub-tropical climatic area it indicates that dew could possibly form on the glass discs of the insulator string. The line faults occurring from 17:00 to 18:00 possibly indicates to lightning being the likely cause.

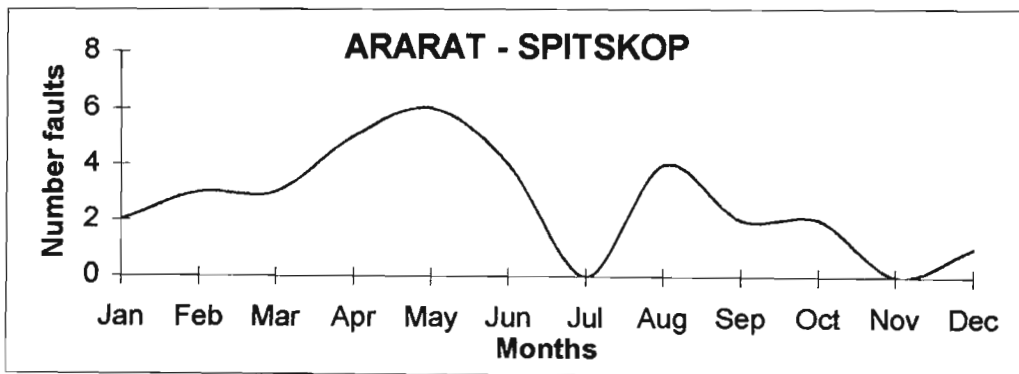


Figure 34. Number of Unexplained line faults of the Ararat-Spitskop line on an annual base.

This line is running in the North Western region of South Africa, which also falls within an area where frost occurs frequently. It is also running in the area with a fairly high density of lightning.

5.1.1 Identification of likely cause of unknowns for the Ararat – Spitskop line

a) Lightning as a possible mechanism

A significant number of the unexplained line faults occurred between the late afternoon hours of 16:00 to 18:00. This could indicate lightning is a probable cause.

b) Fires as a possible mechanism

No correlation between the records and unknowns can be found.

Fires are therefore not suspected as a cause of the line faults.

c) Bird Streamers as a possible mechanism

Good correlation with the time of day analysis and time of year analysis. Analysis indicates line faults just before mid night and some during early mornings.

Bird streamers therefore suspected as a cause of the line faults

d) Pollution and Wetting as a possible mechanism

Very good correlation with record especially, during April to May months, and again from August to September months.

Pollution with wetting (mist, dew) therefore suspected as a cause of the line faults.

5.2 Komatipoort –Marathon line

Figure 35 indicates that unexplained faults mostly occurred during the late afternoons. An analysis of Figure 36 shows that most of the faults occurred in June –July and November –December.

The time of day analysis indicate that line faults occur during mid day and late afternoons.

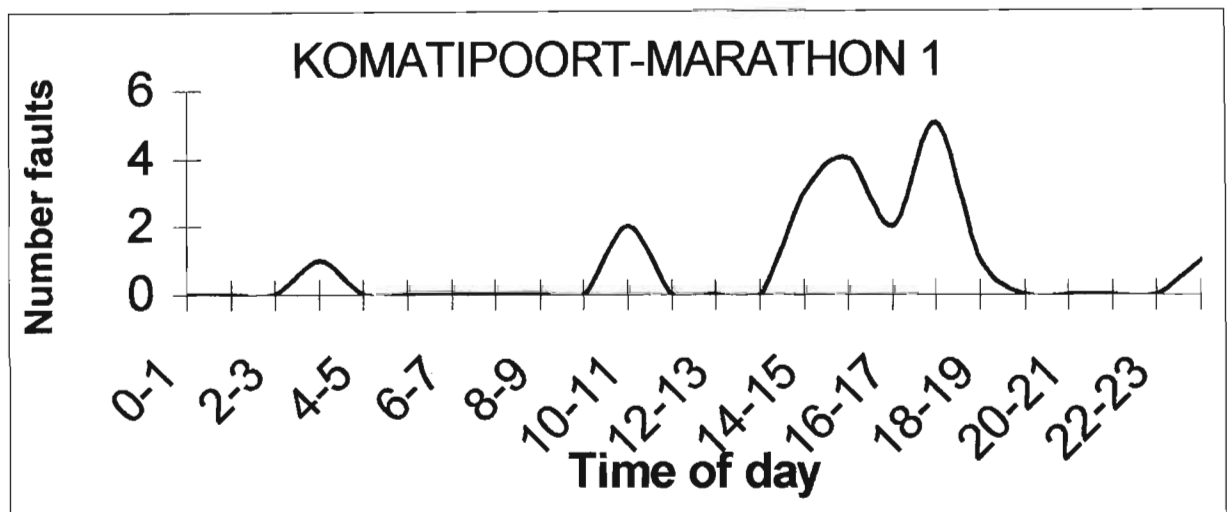


Figure 35. Number of Unexplained line faults of the Komatipoort-Marathon line over a 24 period

This clearly indicates that this line does not trip due to bird streamer, pollution or due to light pollution, light wetting but due to veld fires, sugar cane fires (June-July) and lightning (November –December).

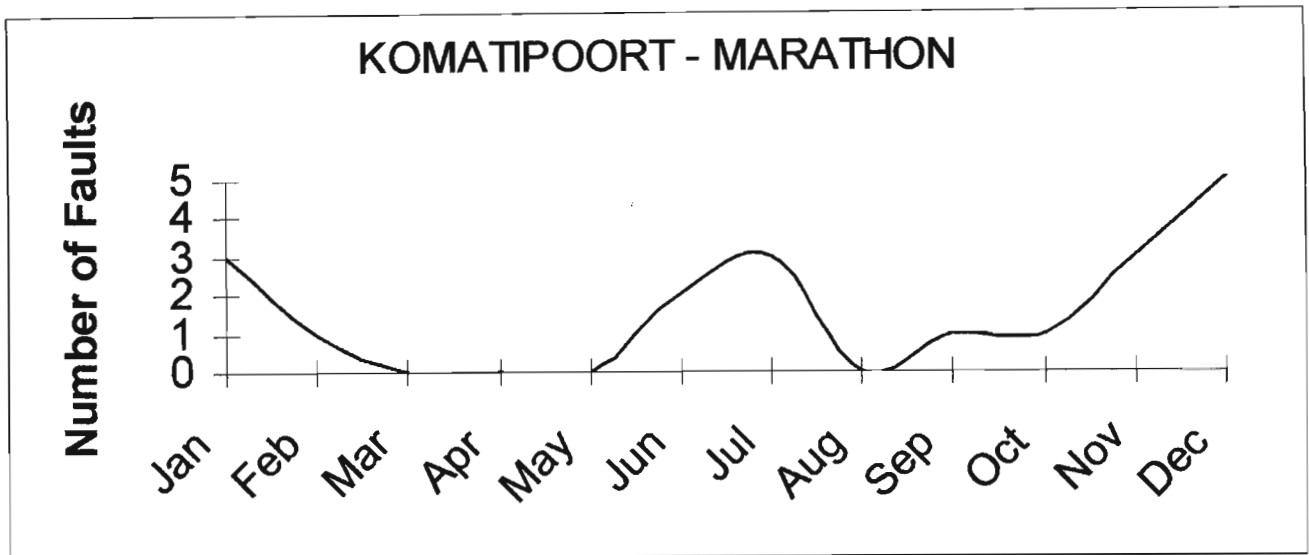


Figure 36. Number of Unexplained line faults of Komatipoort-Marathon line over an annual base

This line is running in the North Eastern parts of South Africa. From Figure 4 it can be seen that no days with frost occur in the region of this line. From Figure 5 it can however be seen that the lightning density in the area where the line is running through has a very high lightning density.

5.2.1 Identification of likely cause of unknowns for the Komatipoort-Marathon line

a) Lightning

Line faults during late afternoons indicate towards lightning activity.

Lightning is therefore suspected as a cause for the line faults.

b) Fires

The line is running over large areas of sugar cane. Correlation between records indicates that during mid days, when the farmers burn sugar cane, the line do trip due to sugar cane fires.

Sugar cane fires therefore suspected as a cause of the line faults.

c) Bird Streamers

Bird streamers normally occur from 22:00 to 01:00 am and in the early morning periods. This indicates that the line faults are probably not due to bird streamers.

d) Pollution and Wetting

No correlation between records and unknowns as no pollution are present on the insulator discs. Pollution and wetting therefore not suspected as a cause.

5.3. Hydra – Ruigtevallei line

As can be seen in Figure 38 most unexplained faults occur during the early morning periods (04:00 – 07:00) and then again a few line faults at 08:00 – 11:00.

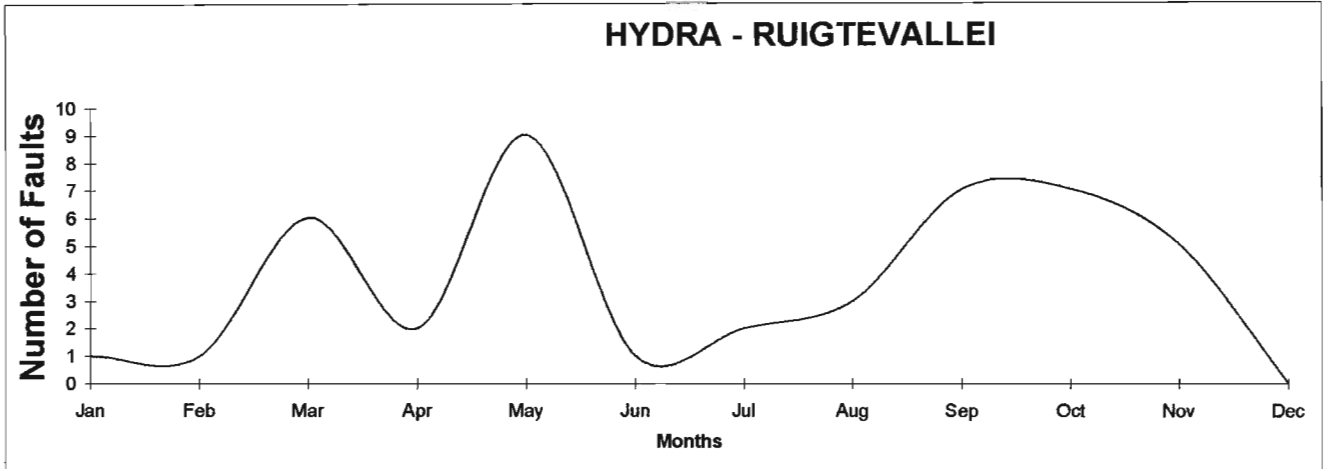


Figure 37. Number of Unexplained line faults of Hydra-Ruigtevallei line over an annual base

Just before midnight there is again an increase in unexplained faults.

Figure 37 gives an indication during which months of the year these line faults mostly occur.

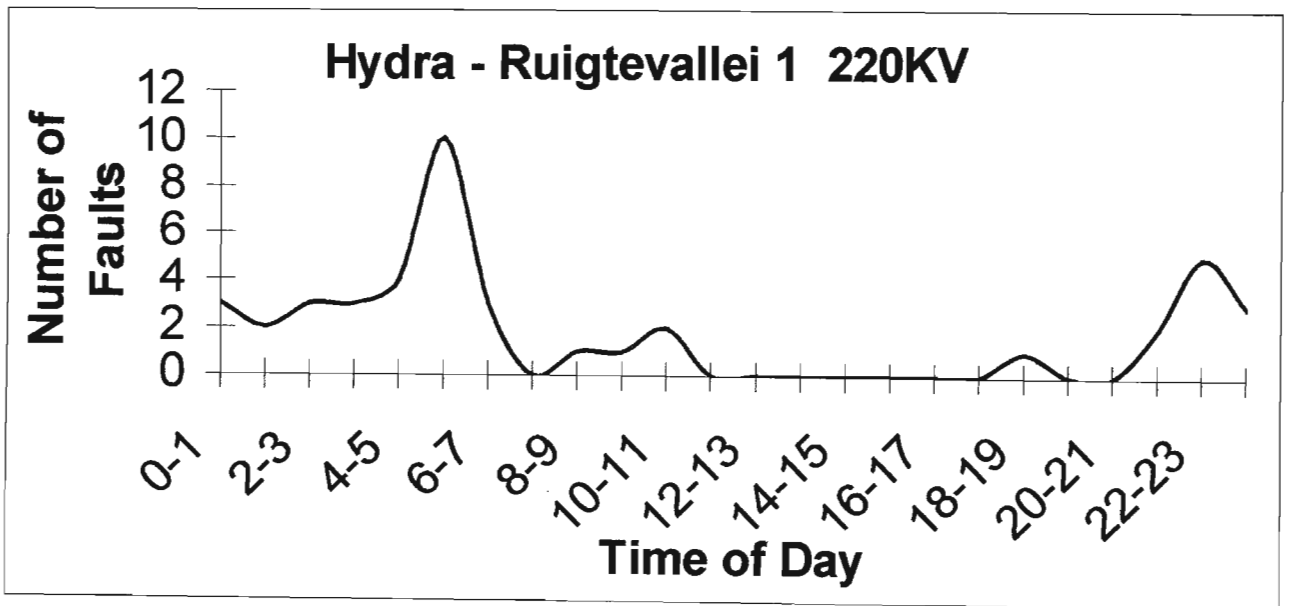


Figure 38. Number of Unexplained line faults of the Hydra-Ruigtevallei line over a 24 hour period.

From Figure 37 it is very clear that the unexplained faults occur mostly in April (Seasonal change from autumn to winter) and again from early September to November (spring to mid summer).

Evidence has shown that these unexplained faults are mostly due to bird streamers as well as bird pollution on the insulator discs. From April to May dew is forming on the insulator surface and thereby wetting the bird pollution. The light pollution, light wetting mechanism is then taking place. From early spring, September, the very familiar bird streamer mechanism applies.

5.3.1. Identification of likely cause of unknowns for the Hydra-Ruigtevallei 1 line

a) Lightning

No correlation between records and unknowns. During the day there is no line faults and lightning normally occur during the day. Therefore lightning is not suspected to be a cause for the line faults.

b) Fires

During midday, 12:00 to 16:00, veld fires are mostly the cause for line faults. There is no correlation between records and unknowns.

Fires are therefore not suspected to be a cause for line faults.

c) Bird Streamers

Correlation between records clearly indicates that bird streamers is most probably the main contributor to unknown line faults.

Bird Streamers are therefore suspected as a cause for line faults.

d) Pollution and Wetting

Pollution on the insulator discs is due to the bird streamers. This, however, may be also be a contributor to unknown faults.

Pollution with wetting is suspected as a cause for the line faults.

5.4 Warmbad –Witkop 275 kV line

The Warmbad – Witkop line is well known for all the unexplained trips it had over long period of time. Due to heat and wet conditions during the spring months and especially during the summer months one can make the assumption that high humidity will be present during these periods.

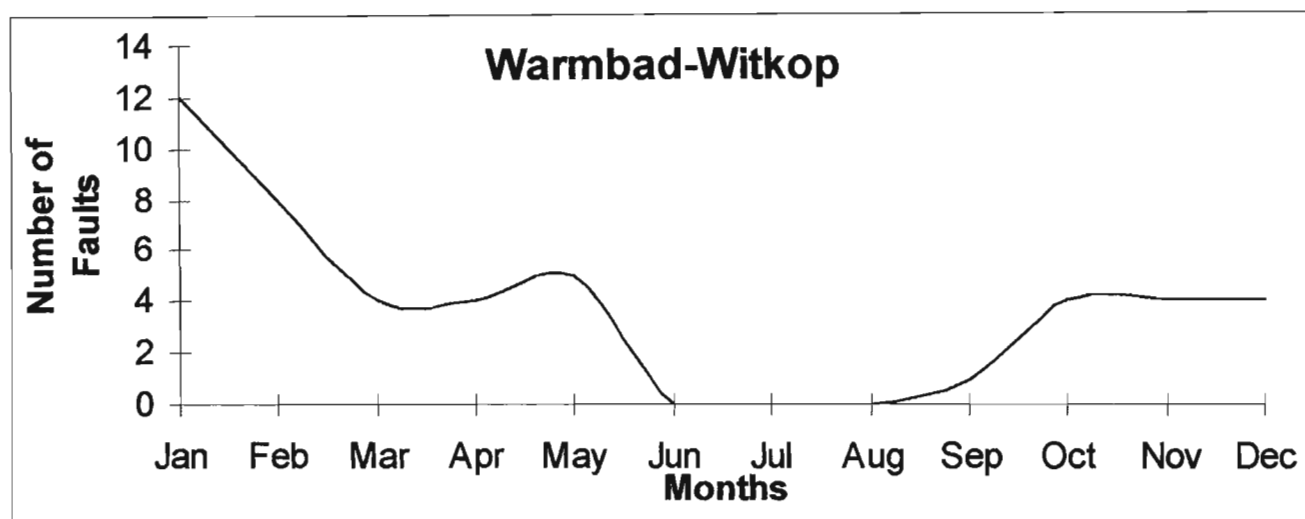


Figure 39. Number of Unexplained line faults for the Warmbad-Witkop line over an annual base.

The analysis of this line is complicated because bird streamers are also a known cause of faults but are often incorrectly diagnosed.

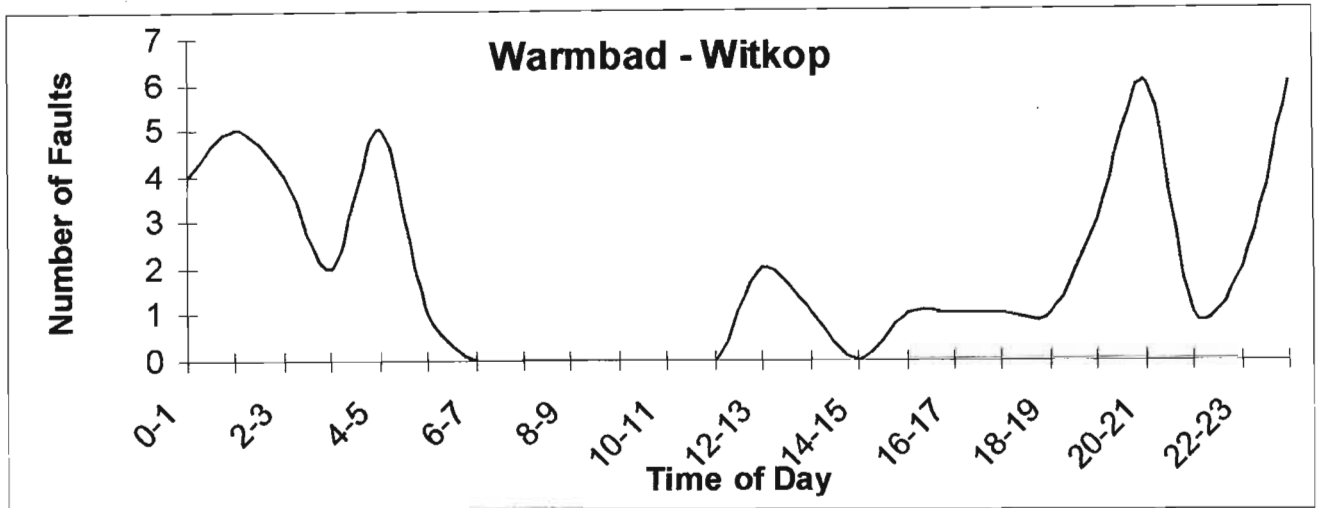


Figure 40. Number of Unexplained line faults of the Warmbad-Witkop line over a 24 hour period.

The time of day graph Figure 40 indicates that Time of Day and Time of Year do not indicate a definitive cause for these faults. During the evening hours of a day the line faults are most probably due to bird streamers and during the early morning (01:00 – 03:00) due to light pollution and light wetting. During the sunrise hours it is probably due to bird streamers again.

5.4.1. Identification of likely cause of unknowns for the Warmbad-Witkop line

a) Lightning

From the graphs it can be seen that lightning, which normally occur during the late afternoons, is not the major cause for the unexplained line faults.

b) Fires

The line faults mostly occur during the evenings. Veld fires, which cause the lines to fault, occur during day time. It is therefore suspected that veld fires are also not a major cause for line faults.

c) Bird Streamers

Excellent correlation between data especially just before mid night and early mornings can be noted. Bird Streamers are therefore suspected to be the major cause for line faults.

d) Pollution and Wetting

During the high humidity months of the year and time periods after midnight there is a very good correlation with data. Pollution and wetting is therefore expected to be a cause for the line faults on the line

5.5. Arnot-Merensky 400 kV line

As may be seen in Figure 41 unexplained faults normally occur from February months towards the end of April and then again during the mid winter months, middle May to the end of June.

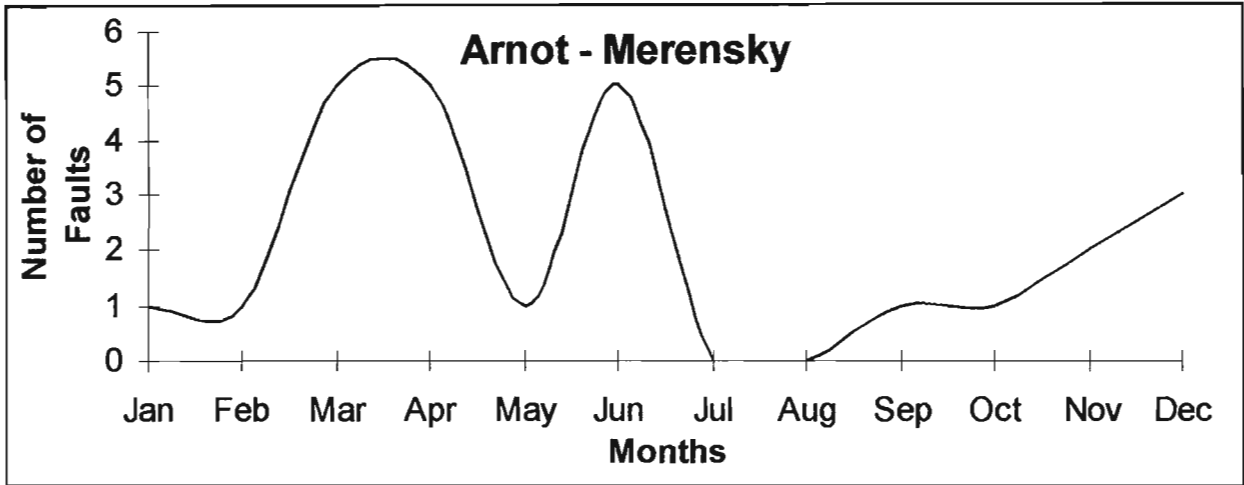


Figure 41. Number of Unexplained line faults of the Arnot-Merensky line over an annual base

The occurrence of mist/fog is very common during the changing over of seasons, from summer to autumn. Regular veld fires occur during the mid winter months towards the beginning of spring. The unexplained line faults start to pick up again from October to the end of December and the beginning of January.

The time of day figure indicates that the highest number of unexplained faults occur in the early morning, during mid day and some faults in the late afternoons and then again at 20:00 and 22:00.

This line is running through an area where mist/fog occurs regularly during March to May months. Birds are also very active in this area which means that a high number of unexplained faults may have been due to bird streamers and with the presence of the fog one can also expect light pollution, light wetting faults.

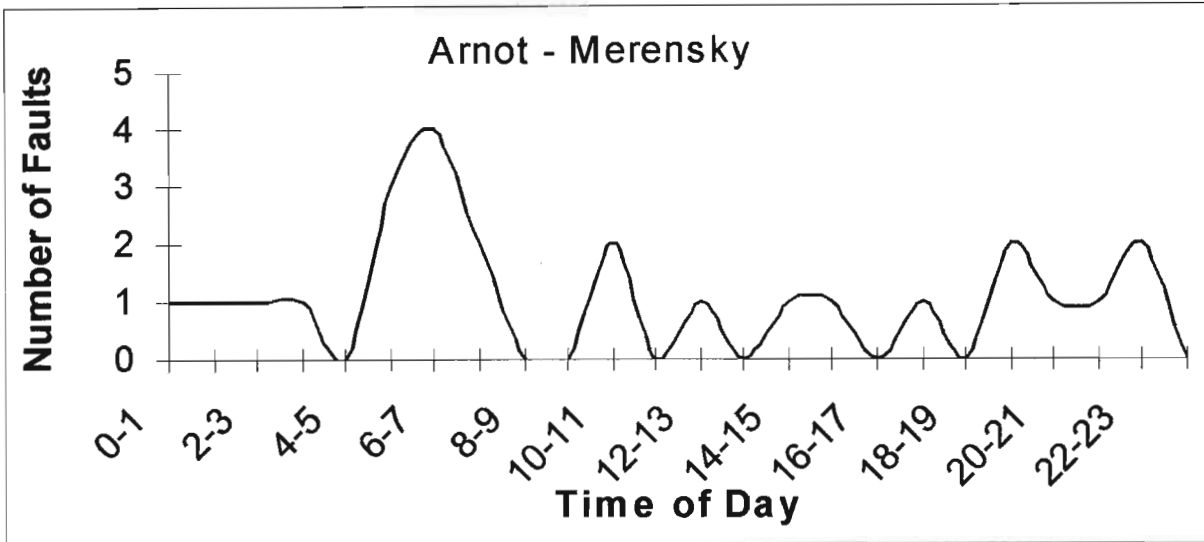


Figure 42. Number of Unexplained line faults of the Arnot-Merensky line over a 24 hour period.

The line runs through a rocky terrain and the number of lightning strikes per km² is very high. This type of fault normally occurs during the summer months. From the figure one can see that unexplained flashovers start to increase from September month again.

During the winter months the dry weather results in dry veld grass. Fire caused faults then become likely. This is noticeable in Figure 41. The time of day analysis correlate excellently with the time of year analysis.

5.5.1. Identification of likely cause of unknowns for the Arnot-Merensky line

a) Lightning

There is a good correlation between the number of unexplained faults and the time of day and time of year when lightning occur. Although it is suspected to be a cause for the line faults it is not the major cause for line faults.

b) Fires

There is a correlation between the records. It is also not suspected to a major cause for the line faults.

c) Bird Streamers

There is a good correlation between records. Bird streamers are therefore expected to be a cause for these line faults.

d) Pollution and Wetting

Pollution on the insulator discs is due to the bird streamers. This, however, may also be a contributor to unknown faults.

5.6. Beta – Hydra 1 400kV line

The Beta – Hydra 1 line is running through a very dry area with normally high daytime temperatures and low night time temperatures as is normal for typical desert characteristics.

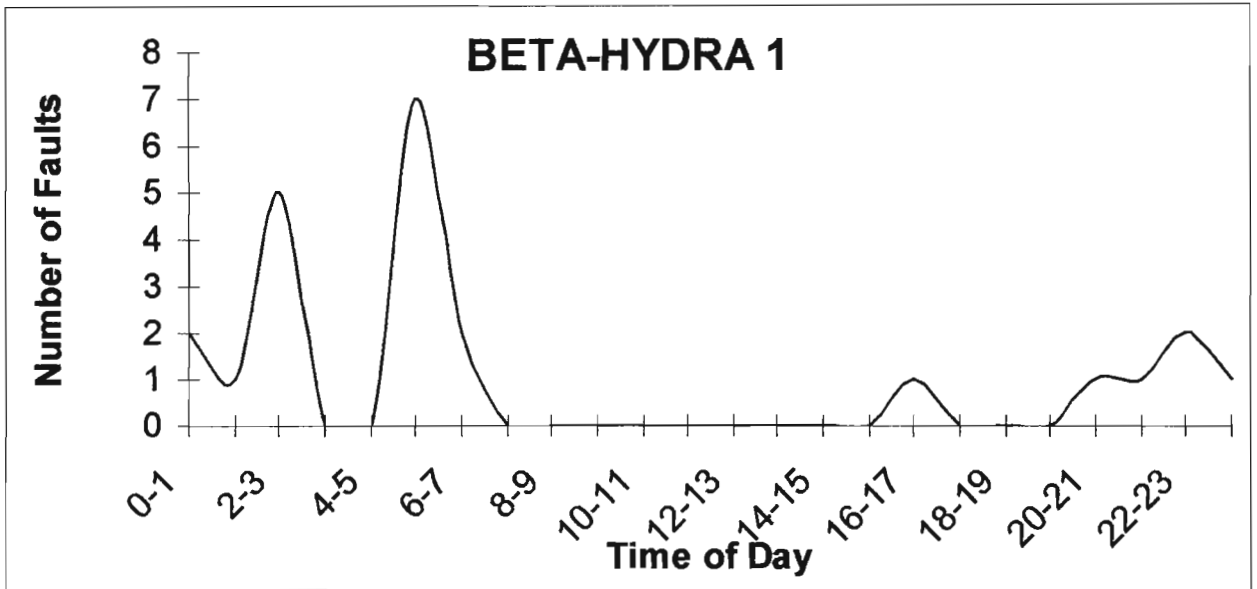


Figure 43. Number of Unexplained line faults of the Beta-Hydra 1 line over a 24 hour period.

In the early hours of the morning (02:00 – 03:00) the line most probably trips due to light pollution, light wetting and in the early mornings due to (06:00-07:00) bird streamers. This line has been known for tripping due to bird streamers for some considerable period.

The time of year graph shown in Figure 44 indicates clearly that the line tends to trip during the changing over of seasons (May) and spring as well as December and January months.

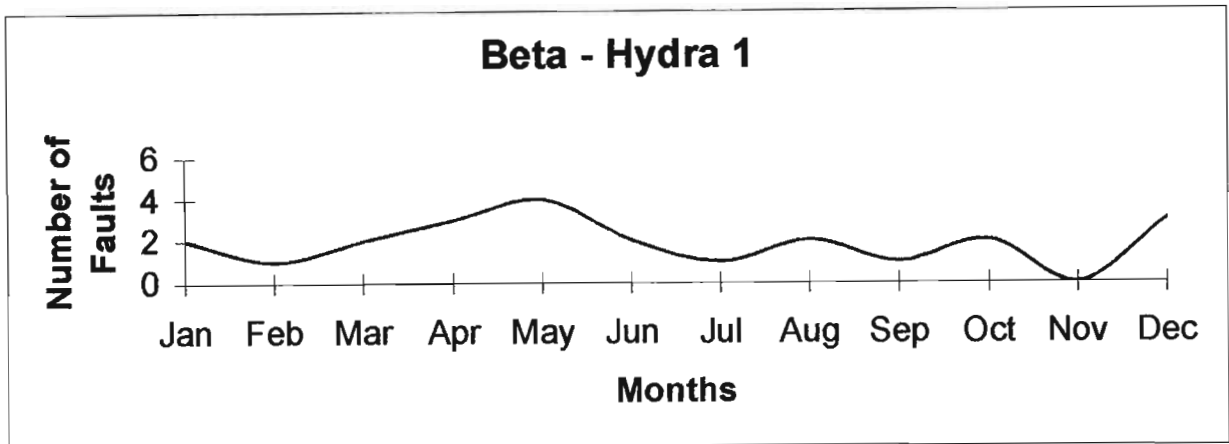


Figure 44. Number of Unexplained line faults of the Beta-Hydra 1 line over an annual base.

5.6.1. Identification of likely cause of unknowns for the Beta-Hydra 1 line

a) Lightning

Figure 43 indicates no correlation between fault records and unknowns. During the day there is no line faults and lightning normally occur during the day. Therefore lightning is not suspected to be a cause for the line faults.

b) Fires

During midday, 12:00 to 16:00, veld fires are mostly the cause for line faults. There is no correlation between records and unknowns.

Fires are therefore not suspected to be a cause for line faults.

c) Bird Streamers

Figure 44 indicates excellent correlation between records, especially just before mid night and early mornings. Bird Streamers are therefore suspected to be the major cause for line faults.

d) Pollution and Wetting

During the high humidity months of the year and time periods after midnight there is a very good correlation with records. Pollution and wetting is therefore expected to be a cause for the line faults on the line

5.7 Matimba – Midas 2

The Matimba – Midas 2 line is the most difficult line out of all rogue lines to investigate due to the fact that it trips almost during all times of a day (see Figure 45).

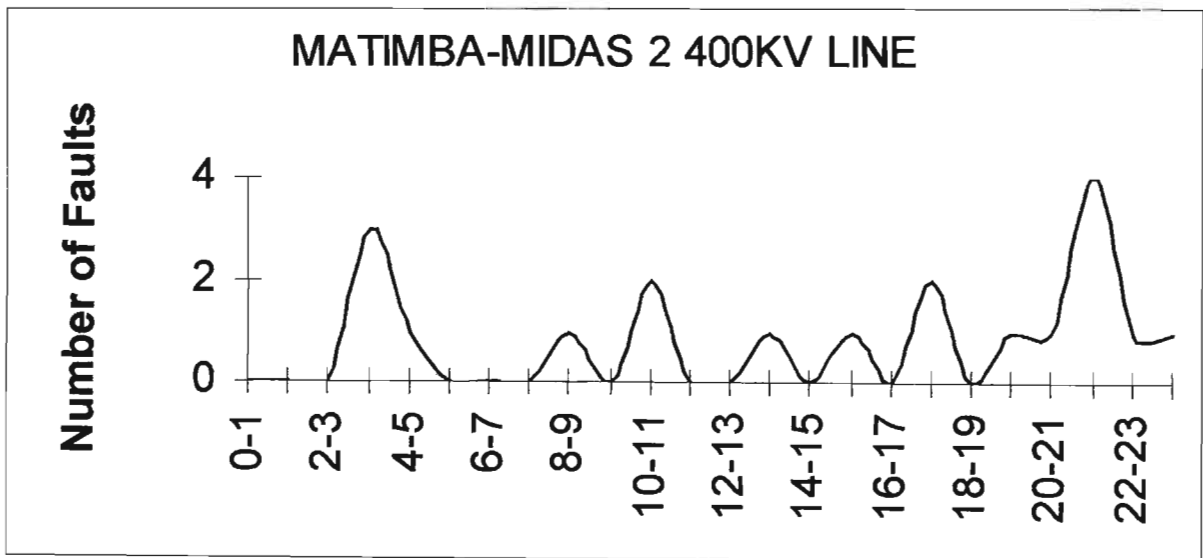


Figure 45. Number of Unexplained line faults of the Matimba-Midas 2 line over a 24 hour period.

The time of the year graph indicates that the line faults occur during all seasons. It is therefore possible that these line faults are due to various causes. The first cause may be light pollution light wetting. During April and May where the time of day analysis indicates trips during the early morning hours. During the winter months, June and August, veld fires are the likely cause. Time of day analysis indicates that the line trips from 10:00 in the morning to 18:00 in the afternoons during these months.

During the November to December months the line most probably trips due to birds during the night-time.

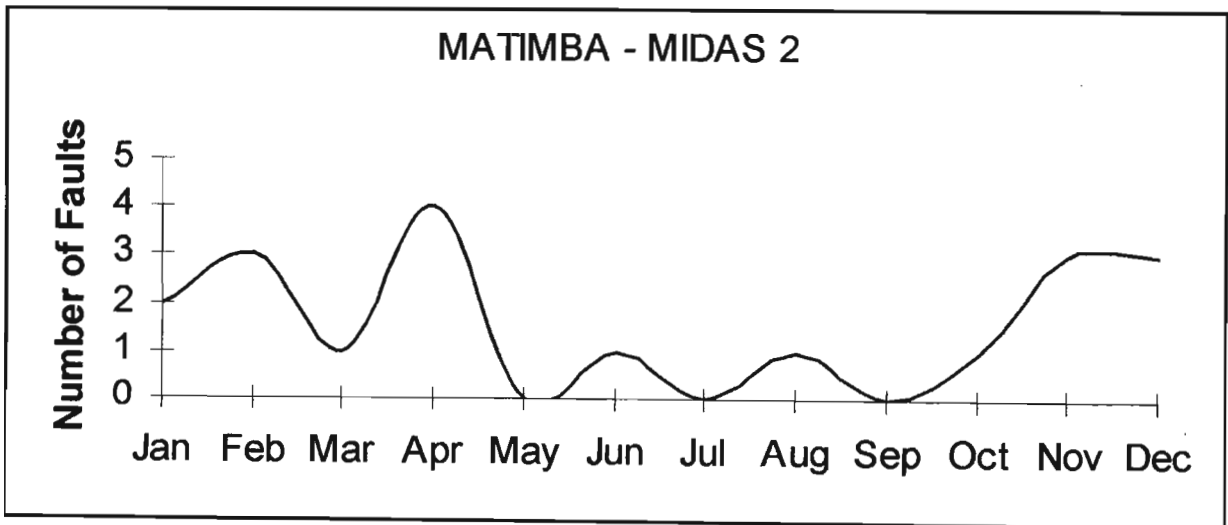


Figure 46. Number of Unexplained line faults of the Matimba-Midas 2 line over an annual base.

5.7.1 Identification of likely cause of unknowns for the Matimba – Midas 2 line

a) Lightning

From the graphs it can be seen that lightning, which normally occur during the late afternoons, are not the major cause for the unexplained line faults.

b) Fires

There is a small correlation between the records. It is also not suspected to a major cause for the line faults.

c) Bird Streamers

Excellent correlation between records, especially just before mid night and early mornings. Bird Streamers are therefore suspected to be the major cause for line faults.

d) Pollution and Wetting

During the high humidity months of the year and time periods after midnight there is a correlation with records. Pollution and wetting is therefore expected to be a cause for the line faults on the line

5.8 Pluto – Watershed

The Pluto – Watershed line is also very well known for its high number of unexplained line faults. From January to March the line tripped numerous times. More unexplained flashovers occurred in June and then again in September.

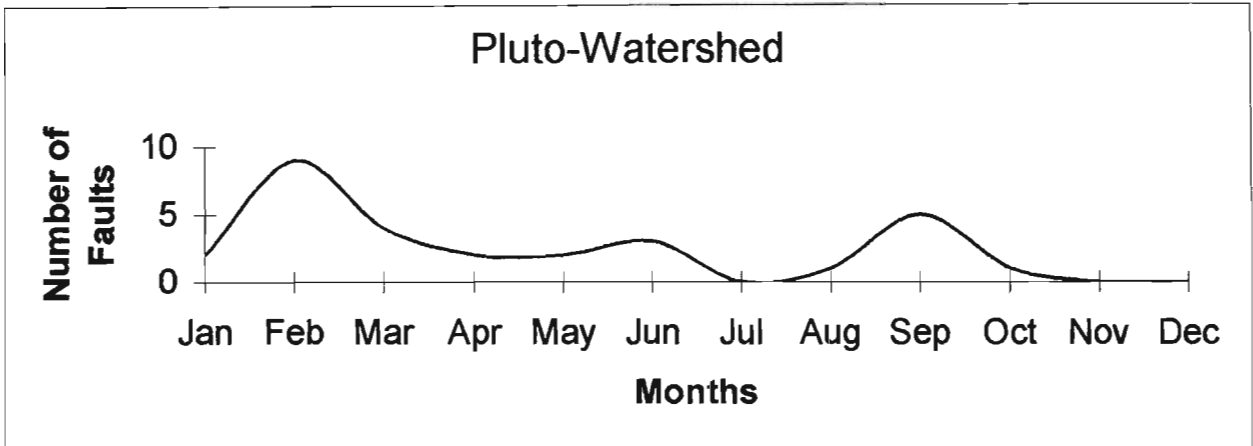


Figure 47. Number of Unexplained line faults of the Pluto-Watershed line over an annual base.

When the time of day graph is also analysed it may be seen that the line tend to trip throughout the night time, peaking at around 21:00 at night. Due to the fact that this line also runs in an area that experiences a high density of lightning strikes, it probably is faulting due to lightning strikes during the late afternoon

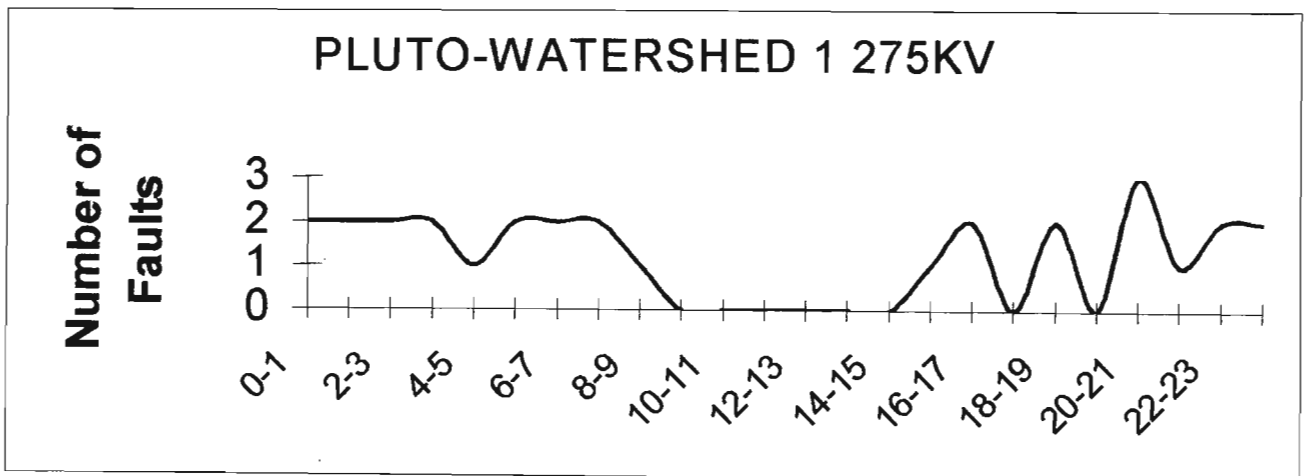


Figure 48. Number of Unexplained line faults of the Pluto-Watershed line over a 24 hour period.

periods of a day. This correlates back to the time of year when the line tended to trip more during the typical changing over of seasons, in April and September months.

5.8.1 Identification of likely cause of unknowns for the Pluto-Watershed line

a) Lightning

The graphs indicates that there may be a few line faults in the later afternoons and during January to May months of the years. Lightning is not suspected to be a major cause for the unexplained line faults.

b) Fires

During midday, 12:00 to 16:00, veld fires are mostly the cause for line faults. There is no correlation between records and unknowns. Fires are therefore not suspected to be a cause for line faults.

c) Bird Streamers

There is correlation between records, especially just before mid night and early mornings. Bird Streamers are therefore suspected to be the major cause for line faults.

d) Pollution and Wetting

During the high humidity months of the year and time periods after midnight there is a good correlation with records. Pollution and wetting is therefore expected to be a cause for the line faults on the line

5.9 Tabor – Witkop

The Tabor – Witkop line tends to trip from the early morning hours of 01:00 till 07:00. In the evenings there are one or two faults between 22:00 and 23:00. The line faults occur during seasonal changes. During seasonal changes mist or fog is present. Bird activity is also present in areas where this line is running through. The two possible causes for line faults can therefore be bird streamers and light pollution, light wetting.

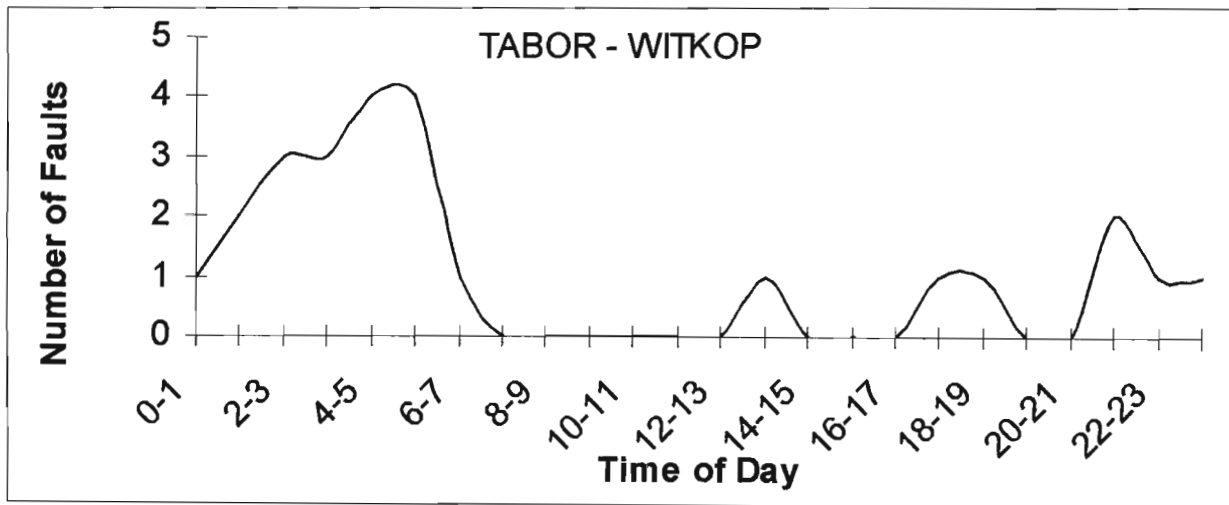


Figure 49. Number of Unexplained line faults of the Tabor-Witkop line over a 24 hour period.

In the beginning of the year there is an increase of unexplained faults. This correlates with the behaviour patterns of birds, as they are very active during that period of the year. As a result it can be concluded that the unexplained faults in January and February are due to bird streamers and the faults in April and May are due to bird pollution and light wetting.

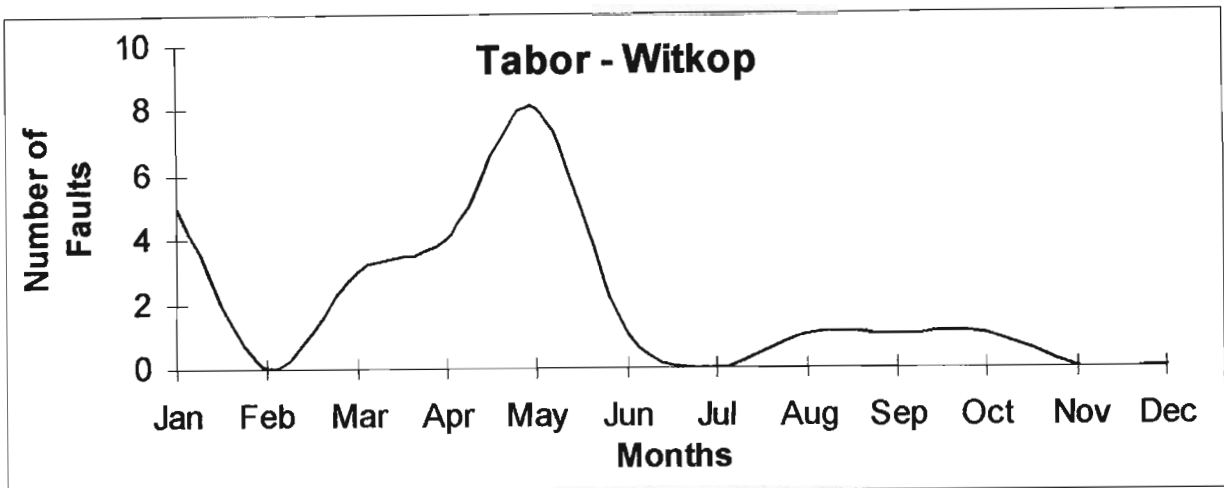


Figure 50. Number of Unexplained line faults of the Tabor-Witkop line over an annual base.

5.9.1 Identification of likely cause of unknowns for the Tabor-Witkop line

a) Lightning

No correlation between records and unknowns. During the day there is no line faults and lightning normally occur during the day. Therefore lightning is not suspected to be a cause for the line faults.

b) Fires

The time of day graph indicates that the unexplained line faults is probably not due to veld fires.

c) Bird Streamers

Correlation between records, especially just before mid night and early mornings. Bird Streamers are therefore suspected to be the major cause for line faults.

d) Pollution and Wetting

During the high humidity months of the year and time periods after midnight there is a very good correlation with records. Pollution and wetting is therefore expected to be a cause for the line faults on the line.

5.10 Conclusion

In this chapter the advantage by doing analysis of line faults during the time of day and month of the year, was realised. It also supports the view point that all line faults can be linked to the four basic line fault mechanisms.

When a line fault occur and no evidence can be found, like flash marks, one can then use the methods as discussed in this to determine to determine the most probable cause for the line fault.

	Line Name	Possible causes of unexplained line faults			
		Lightning	Fires	Bird Streamers	Pollution & Wetting
1	ARARAT-SPITSKOP 2	X		X	X
2	KOMATIPOORT –MARATHON	X	X		
3	HYDRA–RUIGTEVALLEI			X	X
4	WARMBAD-WITKOP 1			X	X
5	ARNOT-MERENSKY 1			X	X
6	BETA – HYDRA 1			X	X
7	MATIMBA – MIDAS 2			X	X
8	PLUTO – WATERSHED 1			X	X
9	TABOR - WITKOP			X	X

Table 5. Summary table of Rogue Lines and probable line Fault causes

6. DISCUSSION AND IMPLEMENTATION OF FINDINGS

The current process followed to identify the causes for transmission line faults are:

- The distance to fault is used to identify the nearest tower at which the line faulted.
- The patrolman investigates the fault by inspecting the line and look for visible flash marks on the tower or insulator strings.

Table 6 below intended to assist field personnel to identify or determine what was the cause for a line fault. The table is intended as a guide and is not intended to replace the fault findings and investigations to be carried out by Patrolmen. From the discussion in the previous sections, the following general conclusions can be made to identify line fault causes:

- a) The identification of flash marks on those lines, that have a low fault current is very difficult.
- b) The identification of flash marks on lines which tripped outside of the morning and evening peak is difficult as the fault currents will be lower and the evidence of the flashover does not show a visible mark.
- c) Line fault investigators should always find out whether mist or fog was present during the time of trip. This will not always assist in finding the fault as a flash over may occur due to dew that formed on the insulator discs.

- d) The winter months of May to August have proven to be the months in which lines trip in the period of mid day to late afternoon due to veld or sugar can fires and in the mornings due to pollution and wetting.
- e) During the seasonal change over months of April and September the lines normally only trip in the early morning as the veld and sugar cane fire burning seasons have not initiated or have been completed.

During the spring and summer months lightning is normally the cause of line faults from 14:00 to early evenings.

The above analysis involving Time Of Day (TOD) and Time Of Year (TOY) analysis enables the network operator to identify the causes of unacceptable performance to a higher degree of confidence and hence implement remedial measures on problematic lines, which after involves major capital expenditure.

At this stage indications that have been derived from investigations into the causes of unknown flashovers on the lines investigations point to birds and fires as well as some events occur during periods of heavy condensation, which may indicate a pollution type of mechanism.

Various actions may be taken. Examples include retrofitting bird guards, increasing specific creepages and fire monitoring. Of further importance is the ability to train line inspectors to correctly identify causes of faults to ensure accurate records for later statistical analysis.

The identification of line faults depends purely on the know how of the person inspecting the line fault, usually the patrolman, and the accuracy of the distance from the substation to the fault in order to assist the inspector to find the fault.

The techniques developed in this thesis are intended to assist the engineering staff in determine beforehand what could have caused the line to trip by examining the time of day and time of year during which the line tripped. Hence the cause which is most probably responsible may be identified particularly if an inspection team does not find visible evidence.

The two mechanisms of transmission line faults that are the most probable cause of unexplained line faults are the light pollution, light wetting mechanism and bird streamers. The fact that historically a high percentage of faults were categorised as unexplained or unknown due to the low fault currents at night and due to the faster protection installed on the Transmission Network.

Lack of experience of the line inspectors also plays a major role. If inspectors are trained to determine a possible cause before an inspection team investigates a fault will greatly assist in locating the evidence as the inspection team will be able to focus there inspection on specific regions of flashmarks.

In order to minimise bird streamer and light pollution light wetting caused line faults, bird guards should be installed. By doing so the birds can no longer roost on the towers but the insulators should also be cleaned or replaced. Where a transmission line is running close to other types of pollution sources, such as Hendrina Power station or industrial pollution sites, the insulators should be replaced with composite insulators.

A main factor playing a role for a line to flash over during a veld fire is the temperature of the fire. The smoke particles may play a much smaller role. Experience has showed that when the grass is cut underneath a line it then does not necessarily mean that it will not cause the line to flash over. The probability of a fire causing a flashover will depend upon the fire danger index (FDI) and the location of small or large trees that may catch fire underneath a transmission line.

Sugar cane fires will, in probably all cases, cause a line to flash over between phases or to ground. The only remedy is to have an outage management plan for sugar cane fires and to visually check that no fires are started underneath the lines.

7. CONCLUSIONS

This thesis has developed a systematic approach to the identification of the most probable cause of transmission line fault where the cause is not accurately identified but listed as “cause unknown”. In particular the following conclusions are drawn:

- The South African network is constructed over widely varying geographic and climatic regions.
- Time-of-day analysis is a useful tool for identification of probable causes of faults but does suffer from limitations.
- Time-of-year analysis, when coupled to considerations of climatic zones and identified possible flashover mechanisms, has been shown to be a powerful new technique for assessment of the probable causes of flashovers.
- The developed techniques may be used to substantiate corrective action such as the fitting of bird guards or may provide evidence as to whether a particular corrective action is likely to reduce the number of line faults on the system or not.

Table 6. Cause of line fault identification table

Time of Day																										
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-00		
January	1																									
	2	Yellow	Yellow			Yellow	Yellow	Yellow															Yellow	Yellow	Yellow	Yellow
	3					Green	Green	Green																		
	4												Red	Red	Red	Red	Red									
February	1					Yellow	Yellow	Yellow																		
	2																									
March	1					Yellow	Yellow	Yellow																		
	2													Red	Red	Red										
April	1					Green	Green	Green	Green	Green																
	2						Yellow	Yellow	Yellow						Red	Red	Red						Yellow	Yellow	Yellow	Yellow
May	1					Green	Green	Green	Green	Green																
	2									Yellow	Yellow	Yellow														
	3																									
June	1					Green	Green	Green	Green	Green	Green															
	2																									
	3																									
July	1																									
	2																									
	3																									

Time of Day	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-00
August	1																							
	2																							
	3																							
September	1																							
	2																							
	3																							
October	1																							
	2																							
	3																							
	4																							
November	1																							
	2																							
	3																							
	4																							
December	1																							
	2																							
	3																							
	4																							

 Conductor to Tree Flashover

 Veld/Sugar Cane Fires

 Pollution & Mist/Fog

 Bird Streamers

 Lightning

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ANNEXURE A

Field Test site

The On-line Leakage Current Analyser was installed on the first tower outside of Highveld Power station on the Everest – Highveld line. Highveld Power station is about 10 km South East of Sasolburg where the Sasol Industry generates heavy industrial pollution.

Different types of insulators were installed with the scope to determine the differences in the leakage currents between these insulators. All insulators were composites.

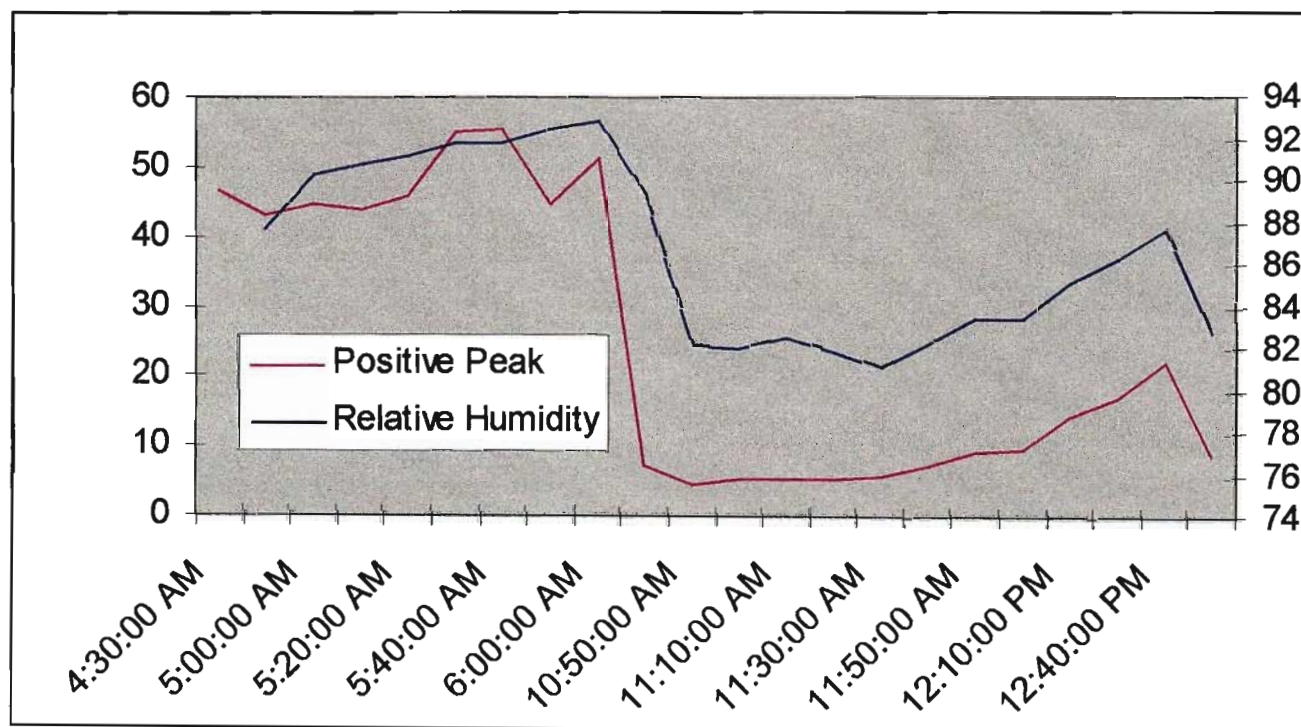


Figure 51. Positive Leakage Currents and Relative Humidity during a morning period.

Only a few days of accurate data was captured. It did, however give an indication on the leakage currents over the insulators one can expect with the humidity at the same time.

As can be seen on the Figure above the leakage currents is very high like the humidity, just before sunrise. These measurements were taken on the 9 September 1998. With high humidity like this it can be expected to have dew formation on the insulator discs. With the presence of light pollution on the insulator disc and the dew, the leakage currents increase leading to a flashover over the string from the live conductor to the tower. The process described above supports the hypothesis of the light pollution light wetting mechanism.

A fog chamber was build a laboratory to simulate the above. Unfortunately no measurements could be retrieved from the OLCA but visually it confirmed what is happening on the actual Transmission Network.

ANNEXURE B

LABORATORY WORK

The following tests were carried out in February 2000 in the laboratory. Due to the fact that the OLCA (On-line Leakage current analyser) sampling rate is defaulted at 10 minutes no actual leakage current measurement were obtained.

A Kaolin mixture with water was used. 2kg Kaolin and 0 litres water.
A string of 16 Glass Insulators were used. (U190?) .

Test 1.

Add 2.5 g salt / liter = 125 g for 50 liters

Pollute the complete insulator string with mixture.

■ Maximum of 12 mA leakage current measured

Test 2.

Pollute the complete insulator string with mixture with a mixture of
2.5 g salt / litre = 125 g for 50 litres)

Pollute only the bottom 3 Insulator discs with 5 g salt / litre = 500g for 50 litres

No abnormal leakage currents

Test 3.

Pollute the complete insulator string with mixture of 5g salt / litre = 250g for 50 litres

Pollute only the bottom 3 Insulator discs with 10 g salt / litre = 500g for 50 litres

No abnormal leakage currents

Test 4.

Pollute the complete insulator string with mixture of 10g salt / litre = 500g for 50 litres

Pollute only the bottom 3 Insulator discs with 20 g salt / litre = 1000g for 50 litres

Leakage currents can be seen on the discs on top of the three more heavily polluted discs.

Test 5.

Pollute the complete insulator string with mixture of 20g salt / litre = 1000g for 50 litres

Pollute only the bottom 3 Insulator discs with 40 g salt / litre = 2000g for 50 litres

Leakage activity more or less the same as in Test 4.

Test 6.

Pollute the complete insulator string with mixture of 40g salt / litre = 2000g for 50 litres

Put in a broken discs 4th from the bottom live end.

The first insulator on the live end showed a lot a leakage current activity. The three insulators from the live end showed leakage current activity as well.

Test 7.

Pollute the complete insulator string with mixture of 40g salt / litre = 2000g for 50 litres

Put in a broken discs 9th from the bottom live end.

The same activity as in Test 6. The first insulator on the live end showed a lot a leakage current activity. The three insulators from the live end showed leakage current activity as well.