PERFORMANCE COMPARISON OF EXISTING AC AND DC TRANSMISSION LINES WITHIN SOUTHERN AFRICA WITH PREDICTIONS FOR LINES ABOVE 765 KV

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December 2008,

I declare that this dissertation is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

Transmission line faults caused by lightning, contamination, birds and fires largely determine the performance of AC and DC transmission line within Southern Africa. With the trend towards higher voltages, with specific reference to the Westcor HVDC link, been developed, a comparison of the performance between existing AC and DC lines will give insight not only into how the faults perform relative to each system but also what can be expected for lines exceeding 765 kV. This dissertation compares data for all the 400 kV transmission lines in South Africa and the ±533 kV Cahora-Bassa line, with reference made to the existing 765 kV AC lines in South Africa. Based on this comparison the findings include possible data acquisition inconsistencies, underperforming areas with respect to different fault types and performance predictions for lines exceeding 765 kV.

In memory of my dad,

Kenelm Grant Glossop

(Dec 2007)

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1 INTRODUCTION

Transmission line performance is a critical factor in ensuring a stable supply of electrical power to the consumer. Faults that occur on transmission lines not only have a detrimental effect on the actual electrical apparatus but can also incur high revenue losses. Studies show that a single fault on a three phase system can result in production losses ranging from ZAR5 000 to ZAR150 000 per voltage dip (Vajeth, Mtolo, & Dama, 2003). These indirect costs easily run into the millions considering the fact that over 8000 line faults on the entire South African AC Transmission system were recorded from 1993 to 2007 (Vosloo H. F., 2004).

It is important that the number of faults incurred on a line be kept to a minimum especially with the current developments made in lines exceeding 765 kV. One such line currently under development is that of the 3000 km HVDC link between the Congo River and South Africa where voltages up to 1 MV are being designed for (refer to Appendix A for details on the Westcor Project). Not a lot of historical data is available for these types of lines thus performance design considerations must make use of data from existing lower voltage lines in order to establish what can be expected for these lines. In addition, only data from lines installed under similar environments may be used as a base from which one can predict the outcomes for higher voltage lines.

The performance of AC lines is very well documented and understood and similarly, to a lesser extent, that of DC lines. The performance of these two systems has always been treated individually and as a result, the relative performance is unknown. A qualitative comparison of the two systems will reveal not only any inconsistencies in how the data is obtained for each system, but will also allow one to gain insight into how the performance of the lines compare to each other based on the different types of faults that occur on the line. This type of comparison can aid a designer in determining where additional focus on line design is required and also make a meaningful comparison between both AC and DC systems.

The aim of this dissertation is to compare line fault data for both AC and DC lines and predict what may be expected for those fault types on lines above 765 kV. A comparison between all of the 400 kV AC lines within South Africa and the ±533 kV Cahora-Bassa DC line was carried out with reference made to the existing 765 kV AC network in South Africa. The dissertation begins by first describing what type of faults can be expected and also the mechanism by which failures occur from these causes. This is followed by an overview of the existing methods currently employed to reduce the effects of these faults. With the fault types described and their corresponding mitigation methods, the report then proceeds to compare the AC and DC line fault data by first establishing the grounds for comparison and then identifying the possible inconsistencies that result from the methodologies employed in compiling the data. The comparison is then made from which the findings include data inconsistencies, identification of excessively high fault occurrences from the analysed data and recommendations for lines greater than 765 kV.

2 FAULT TYPES

Outdoor transmission line faults occur for a variety of reasons. The causes of line faults can originate from both environmental influences and internal design influences. Line faults caused by internal design influences (such as tower structural failure) are minimal since these are entirely under the control of the designer. Causes from environmental influences depend on where the line is situated and are often the limiting factor in terms of achieving the desired performance for a line. When looking at lines within Southern Africa, the dominant causes of faults which determine the performance of the lines include the following:

- Lightning
- Contamination
- Birds
- Fire

Other environmental influences such as snow, ice, falling trees and natural anomalies such as hurricanes occur too infrequently to be recognised and are thus not included in the discussion.

3 FAILURE MECHANISMS

3.1 Lightning

Lightning is a common cause of line faults within South Africa based on the fact that South Africa has one of the highest ground flash densities in the world. As a result, line designers have had to take extra measures to ensure that the lines within South Africa perform within an acceptable levels or to specifications as required. An understanding of how lightning strokes interact with the line and how those interactions affect the performance of the line is important when developing mitigation methods to improve the performance of the line against lightning faults.

There are two possible ways for lightning to interact with the line that will in turn cause a failure of the line to occur. The first method is when a shielding failure occurs and the second is when a backflash occurs. Shielding failures are said to largely occur for strokes lower than 20 kA and backflashes occur for stroke currents exceeding 20 kA (EPRI, 2005). This relationship, depicted in Figure 1, has been adopted by the IEEE/PES Working Group on Estimating the Lightning Performance of Transmission Lines.

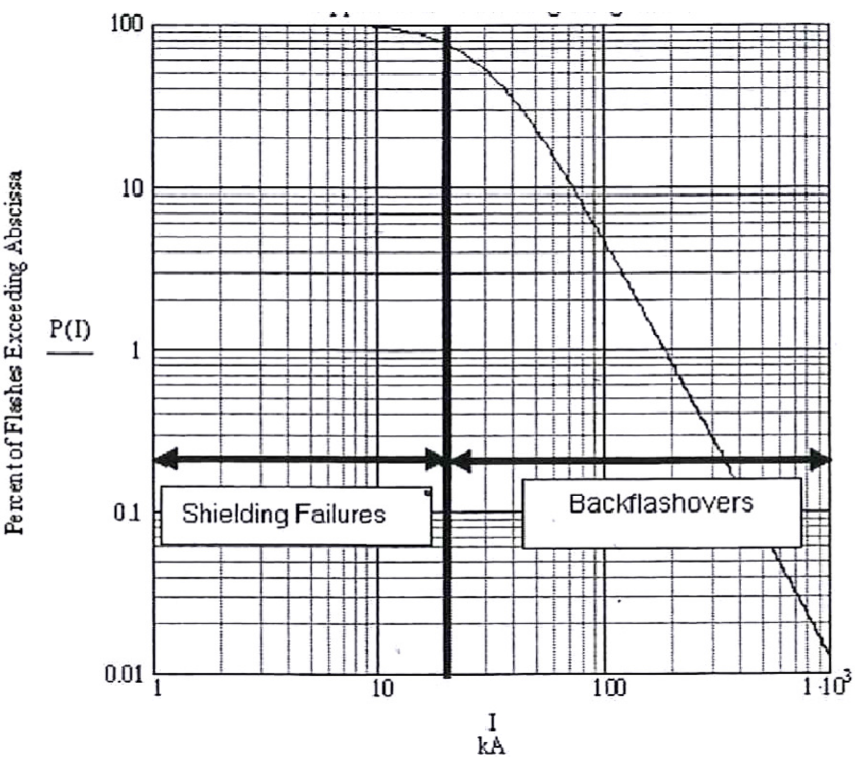

Figure 1 Cumulative distribution of first negative downward lightning flashes to objects < 60 (EPRI, 2005).

A shielding failure takes place when the stroke bypasses all shielding wires and terminates directly onto one of the phase conductors, the frequency of which is commonly referred to as the Shielding Failure Flashover Rate (SFFOR) (EPRI, 2005). The result of a shielding failure can be one of two things, either the stroke current will get absorbed through the surge protection or in the absence of any surge protection, will flashover to the nearest grounded object which in the case of transmission lines, will either be the shielding wires or the tower (effects on substations such as transformers have been left out). The majority of flashovers occur across the insulators. If a flashover does take place across the insulator strings, this may cause damage to the insulators such as stripping of insulator sheds or cracking of porcelain insulators (EPRI, 2005).

A backflash is a flashover that occurs between the point of where the stroke terminates (or within the same vicinity) and a nearby object such as the line conductor. Backflash's occur with high stroke currents as indicated in Figure 1 since it is only at these higher stroke currents that the voltage induced is large enough to create another flashover to a nearby object. In the case of transmission lines, the lightning will terminate on the shielding wires and backflash onto the conductors thus resulting in damage similar to that seen in the shielding failures. The Backflash Rate (BFR) is defined as the number of flashovers per 100km per year and is a function of the insulation strength (length of insulator and strike distance[1]), surge arrestors, number of shield wires, tower footing resistance, ground flash density, span length, tower height and type of conductors used (EPRI, 2005).

3.2 Contamination

Contamination may occur on the transmission line insulators in a variety of forms. Major contributors to insulator contamination include the salt content of the air near coastal environments, general pollution content for heavy industrial areas and high dust content for agricultural or rural areas (particularly relevant for Southern African conditions). Separate modelling for all the before mentioned environments would be impractical thus a common method for modelling all types of environments, known as the Equivalent Salt Deposit Density (ESDD), has been generally and agreed accepted for use in performing any contamination laboratory tests (Refer to Appendix B for the various ESDD Level definitions) (Kuffel, Zaengl, & Kuffel, 2004). As the name suggests, a variation in the salt deposit on the insulator would imply varying the major contributing factor for any flashover occurrence which is the effective conductivity of the surface of the insulator. With a defined way of modelling the pollution on the insulators, one may then proceed to perform a myriad of laboratory tests such as the salt fog-chamber testing, inclined plane test and insulator HV testing. The objective being to determine what the withstand capabilities of the insulators would be and to understand under what conditions an insulator deterioration / failure would occur.

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[1] The strike distance is the clearance from the current-carrying conductors to the tower body and its components (EPRI, 2005).

The actual failure mechanism of insulator strings due to contamination occurs in stages. Complex models do exist that describe the insulator string as a set of resistances and capacitances that vary as the stages preceding flashover take place however, provided here is only a basic understanding of the processes that occur before a flashover occurs (EPRI, 1982). During the initial stages, under constant wetted conditions, leakage currents are present across the insulator string (usually around 100 to 600 μA (rms)) with more heat forming at the base of the insulator string on the HV side. As a result, the heat evaporates the contaminate around the HV terminal and a dry-band of a few millimetres starts to form around the base of the insulator at the connection point. Once a dry-band has formed, scintillation starts to take place and evaporation increases gradually from the base of the insulator string. As these dry-bands increase in size, flashovers across the bottom few insulators occur and as a result, more heating occurs further up from the base of the insulator string. From the flashovers, non-uniform voltage distributions start to form and points where the flashover had occurred, tend to absorb more moisture upon rewetting hence repeated flashovers will occur on that same point. As the number of arcs increases, and along with the heated areas (or dry areas) and moisture absorbing areas along the insulator string, the flashovers start to grow until a complete flashover occurs spanning the length of the insulator (EPRI, 1982). It is important to remember that under severe wetting conditions, this phenomenon will not occur due to the fact that the constant cooling effect of the contaminant will not allow for heated areas to form.

Another form of contamination flashover takes place within very heavily polluted areas where actual conductive deposits lead to the formation of carbon tracks along which the leakage current is allowed to flow. This is commonly referred to as ‘tracking’ and occurs over a much longer period of time. The carbon track effectively shortens the length of the insulator string by creating a conductive path from the live terminal of the insulator which in turn causes a change in the voltage distribution across the insulator.

All of what has been discussed above within this section is equally applicable to both AC and DC transmission systems. Even though the mechanism of failure may remain the same, the response to the contamination for each system is different. Under similar conditions, the DC line would contain a higher level of contamination than that of the AC line and in particular, the negative pole of the DC line would contain more than the positive pole. The reason for this is that the static electric field created by the DC line attracts a larger amount of charged aerosols thus creating a higher contamination severity on the insulators (EPRI, 1982). The extent to which the DC line attracts more contamination than the AC line may be understood by observing Figure 2 below. The graph in Figure 2 shows that at the lower ESDD levels, DC lines will have up to six times more contamination than that of similar AC lines. As the ESDD level increases, the DC lines will attract proportionally less than the AC lines up until a ‘saturation’ point is reached of approximately 0.12 mg/cm². From this point, both systems will contain equal amounts of contamination.

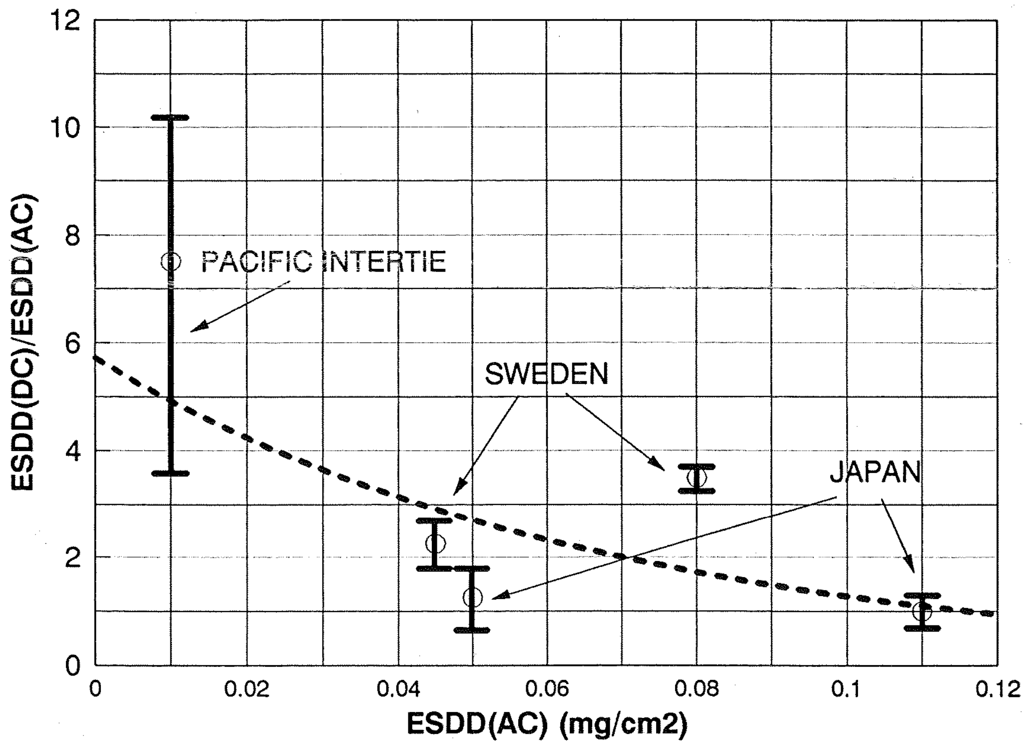


Figure 2 Ratio of ESDD collected on insulators energized with DC to that collected on insulators energized with AC (EPRI, 1982).

3.3 Birds

The notion that a bird can have any real influence on a transmission line has had to undergo many years of gradual acceptance up until only recently where any utility runs the risk of losing large amounts of revenue if the problem is not addressed adequately. The interaction of birds with the transmission system not only has a detrimental effect on the security of supply but also has a negative impact on the affected bird species population. Experience has shown that in South Africa, bird species such as storks, Bustards, cranes, flamingos and pelicans, Secretary Birds, Blue Cranes and the endangered Wattled Crane are all affected by the transmission line system (Vosloo H. F., 2004).

There are a number of ways in which the interaction between the birds and the transmission lines can take place. These include nesting activity, mid-air collisions and bird streamer faults (Vosloo H. F., 2004). Transmission towers often present themselves as ideal nesting spots for birds especially in areas of little to no vegetation. There are two possible effects that nesting activity can have on a transmission line: The first is that nests may fall and get lodged into insulators thus resulting in a flashover or, the increased bird activity around the nests may cause an unexpected rise in the contamination of the insulators through the excessive bird streamers present. Mid-air collisions are found to be associated with larger birds that have low manoeuvrability and have been previously understood to take place only on smaller reticulation systems. This however, has since been questioned after tests were carried out in the Karoo that show that the risk of collision increases with the voltage of the line (Vosloo H. F., 2004). Bird streamer faults however, pose as the biggest threat to transmission lines as they are the cause for most transmission line failures, especially on higher voltage systems up to 400 kV. The remainder of this report will only refer to bird streamer faults and not on nesting activity and mid-air collisions as it is believed that the latter causes are negligible for the lines that will be analysed.

Faults from bird streamers are generally only found to be caused by larger birds such as vultures and Blue Herons. Occurrence of these faults has been found to peak around 06H00 and 22H00 when there is high level of bird activity and also an increase towards the late summer months when the bird populations reach a maximum (Vosloo H. F., 2004). In order for a fault of this type to occur, it is not necessary that the streamer bridges the entire gap but rather creates a bridge sufficiently long enough for the breakdown strength of the air gap to be exceeded. The state owned utility, Eskom, has performed many insulator tests simulating bird streamer scenarios in order to understand the effect that bird streamers have on the line and also the possible mitigation methods as will be discussed later on (Naidoo, Ijumba, & Britten, 2006). Figure 3 below shows a laboratory setup used to simulate bird streamer faults on outdoor insulation using an egg yolk and soap solution (Vosloo H. F., 2004).

Figure 3 Bird streamer simulations performed on outdoor insulation system (Vosloo H. F., 2004).

3.4 Fire

It is sufficiently understood the provisional requirements that should be met for a line to not be affected by fire, however, it is not so well understood the actual mechanism by which a fire induced flashover occurs (Vosloo H. F., 2004). A number of theories exist which attempt to explain how flashovers are induced from fires of which three of them are briefly described below, namely the Reduced Barometric Model, Particle Initiated Flashover Model and the Ionisation Model.

3.4.1 Reduced Barometric Model

Developed by West and Mc Cullum (1978), this theory postulates that the flashover voltage depends on the temperature and humidity as per the following relationship:

$$Vs = Vt\,(H / D)$$

Where Vs is the flashover voltage under standard conditions, Vt is the flashover voltage under actual conditions, H is a humidity factor and D is the relative density of the air (Vosloo H. F., 2004). This equation may be further simplified by replacing D with its equivalent pressure (P) and temperature (t) relationship and assuming a negligible humidity factor (since a fire won't combust with excess humidity). Taking these two changes into account, one ends up with the following relationship (Vosloo H. F., 2004):

$$Vt = Vs\,(0.392P / (273 + t))$$

From the above equation, one can see that the flashover voltage is inversely proportional to the temperature and directly proportional to the pressure.

3.4.2 Particle Initiated Flashover Model

This theory is based on the idea that fire induced flashovers occur as a result of the presence of particles between the conductors and earth brought about by the presence of the flame. Initially studied by Sadurski (1977), the research was first brought into light due to the concerns Escom had over the “severe problems experienced with veld and sugar cane fires” (Vosloo H. F., 2004). Sadurski’s experiments revealed that one may experience no flashover with a flame spanning the entire length of the air gap and that a flashover may occur when only 60% of the gap is filled with particle filled flames (Sadurski, 1977). Table 1 below gives a summary of his experiments.

Table 1 The effect of floating particles and flashovers for various line voltages (Vosloo H. F., 2004).

Nature of the Flame	**Portion of the Gap Bridged**	**Line Voltage kV**								
		400	275	220	132	88	66	44	32	22
Clean	100%	Y	N	N	N					
With Floating Particles	100%	Y	Y	Y	Y	Y	Y	Y	N	N
	80%	Y	Y	Y	Y	Y	N	N	N	N
	70%	Y	Y	Y	Y	N	N	N	N	N
	60%	Y	Y	N	N	N	N	N	N	N
	50%	N	N							

One can clearly see from the above table the relationship that exists between the flashover voltage and the span with which the air gap is breached with the particle inclusive flames. However, no explanation could be given for the 400 kV flashover from the clean flame hence one can immediately deduce that more is involved than just the particle theory for flame induced flashovers.

3.4.3 Ionisation Model

The ionization model, as the name states, is based on the idea that the flashover voltage is dependent on the number of ions generated during the combustion process. There are two main sources of ions, the first being the oxidation process of the burning material which creates H3O+ ions and CH3+ ions and the second being the generation of ions through increased thermal activity (Sukhnandan. A, Oct 2002). As the flame temperature increases, so does the production of ions through mutual collisions with other ions thus increasing the effective conductivity of the flame. With an increased conductivity, one can then expect a higher chance of a flashover occurring. This theory is far easier to digest since it is well known that flashovers that occur from lightning are as a result of ions present in the lightning path.

The above three theories give one valuable insight into fire flashover mechanism. Although all are completely different, there is no reason to suspect that one is less correct than the other. It would be safe to say that the true answer lies in a combination of all three theories in which case, it is clear that additional research is required in order to fully describe the fire flashover mechanism.

4 FAULT MITIGATION METHODS

4.1 Lightning

Lightning, by its statistical nature, is very difficult to design for and in general, a designer will accept that no lightning mitigation parameters will ever be completely ‘lightning proof’. An example of where this may be found is in the fact that critical flashover voltages do not represent the absolute maximum voltage that may be experienced for a flashover to occur but rather a voltage level where there is only a 2% chance of experiencing a higher lightning peak voltage (The Practical Guide to Outdoor High Voltage Insulators, September 2006). Figure 4 is commonly referred to for any insulation design since it allows one to gain a visual image of where the probability of failure lies and thus assists the designer in designing for the required strength of insulation according to the required specifications.

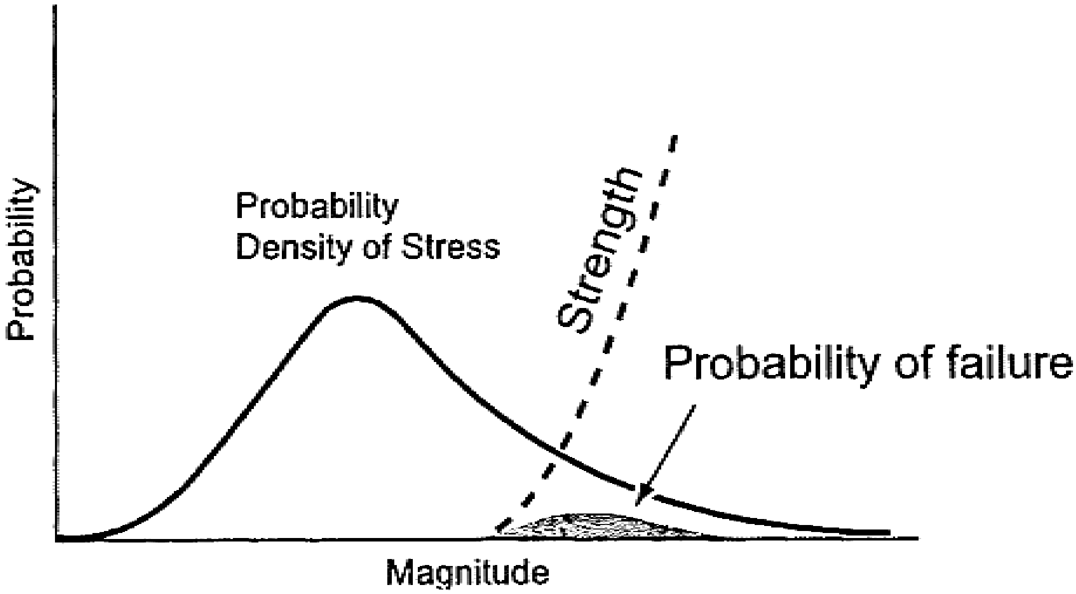


Figure 4 Graph showing the statistical procedure for determining insulation failures (EPRI, 2005).

There are four methods by which one can reduce the probability of a flashover caused by lightning. These include proper insulation design, appropriate shield wire design, effective tower earthing and the installation of surge arrestors on the line. Each of these methods is briefly discussed below.

Insulation strength requirements are designed according to the Critical Flashover Voltage (CFO) or otherwise known as the V_{50} voltage. The CFO is the value at which 50% of the strikes experienced by the line will result in a flashover occurring (EPRI, 2005). As one would expect, by increasing the number of insulators, one decreases the chance of a flash over occurring since the probability of reaching a voltage of higher magnitude decreases. Figure 5 shows the relationship between the length of insulator used and the CFO voltage.

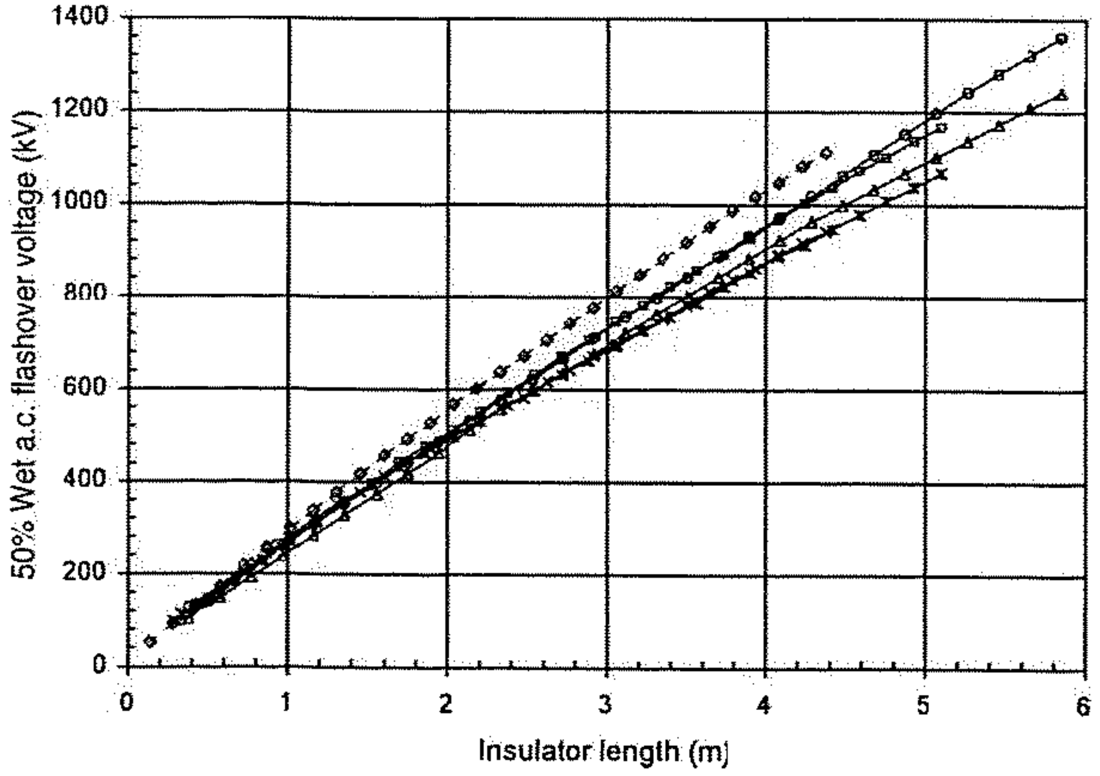
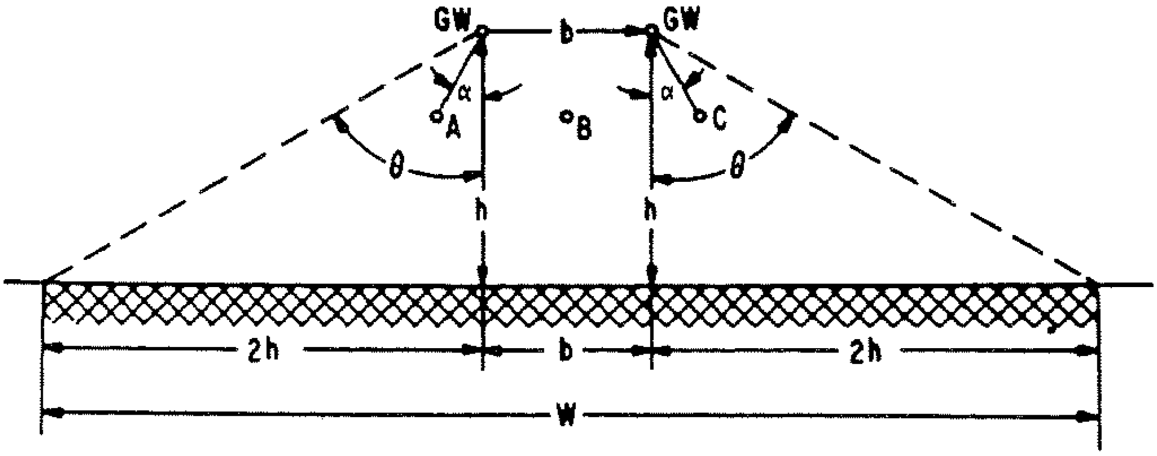


Figure 5 Wet AC flashover voltage for various cap and pin type insulators (EPRI, 2005)

Shield wires, as the name suggests, are there to 'shield' the conductors from lightning strokes. In addition to providing lightning protection, they also assist in providing mechanical strength for the servitude. These wires are always situated above the conductors in positions that would attempt to optimize the lightning coverage area around the conductors. The number and positioning of the shield wires is dependent on the ground flash density with additional cover been designed for areas with a high ground flash density. Very rarely are more than two shield wires ever installed since the anticipated financial losses from not having an additional earth wire would not exceed the installation cost of an additional earth wire.

A key parameter which one looks at for any shield wire design is that of the shield angle. This is the angle that is formed from the earth wire to the conductor as can be viewed in Figure 6. A variation in the shield angle will provide a different level of lightning protection but often at the cost of building a more expensive tower design. It has generally been accepted that an appropriate shield angle may be selected such that a flashover rate of 0.05 flashovers per 100km is achieved (EPRI, 2005). A CIGRE paper written by Corrales, Martinez and Barragán (2006), gives one an indication as to what kind of lightning performance improvements can be obtained through varying the shield angle. They simulated that by changing the shield angle from 25 to 3 deg for 22km 400 kV AC line, that the line should experience a 95% improvement in lightning failure rate.



θ = shadow angle (assumed 63½ degrees)
α = shield angle between shield wire and phase conductor
W = shadow width on earth's surface
GW = shield wire location
A, B, C = phase wires

Figure 6 Typical cross section of AC transmission line indicating shield wire location parameters (EPRI, 1982)

Back flashovers, caused by induced voltages occurring on the towers, can be reduced by improving the footing resistance of the tower. A reduced tower footing resistance will lower the induced voltage level caused by the lightning thus decreasing the chances of a flashover to the conductors occurring (Peter & Vajeth, 2005). Typical tower footing resistances range from 0 to 25Ω. Problems arise when one is required to provide good earthing measures for the towers over rocky or impenetrable terrain. Achieving the desired resistance levels under these conditions would either require large amounts of additional metal placed in the ground or that the ground be treated with certain chemicals that would improve the conductivity of the soil (EPRI, 2005). Both measures are costly to implement with the latter not been desirable due to the possible environmental impact.

An alternate method of reducing the possibility of lightning faults is to use Lightning Surge Arrestors (LSA's). LSA's offer a robust, efficient, and cost-effective method for reducing line outages and can be used on all voltages up to 800 kV (EPRI, 2005). Transmission Line Arrestors (TLA's) are a recent development but operate on the same principal as regular LSA's found in substations. The basic principles of operation involve the use of metal-oxide (usually Zn-O is used) layers to create a nonlinear resistor which will only conduct a substantial amount of current given the presence of an abnormally high voltage such as that experienced by a lightning or switching impulse. Three main variations are available which include the gapless, shunt-gapped and series-gapped arrestors. The main difference, as the name implies, is the inclusion of an air gap either in series or parallel or not at all. This air gap changes the operating characteristics of the LSA and can be used to determine at what over voltage the surge arrestor should operate (EPRI, 2005). TLA's are used for the protection against both shield failure faults and backflash faults. In the event where poor tower footing resistance is present, the TLA would limit the voltage difference between the tower and the conductors sufficiently enough to prevent a flashover from occurring. A typical installation of TLA's (as can be seen in Figure 7) requires careful analysis, through the use of complex computer simulations, and knowledge of the tower footing resistance, lightning ground stroke density, span length, conductor geometry, insulation level and the performance goals (EPRI, 2005). TLA's can be used to replace the shield wiring as a lightning protection system or add an extra layer of protection to an already existing installation. For EHV lines, TLA's are normally placed close to the substations only (EPRI, 2005).

Figure 7 A Typical installation of TLA's on an overhead line (Vosloo H. F., 2004).

The probability of either an AC or DC line experiencing a lightning fault given the same level of protection is expected to be the same. But even though the strike rate to the lines may be similar, the response of either system will be different. Without discussing the details of how the systems reacts to lightning faults, one can mention that in the event that an AC fault occurs, all three phases will be lost whereas with the DC system, both poles can operate independently of each other thus depending on the configuration, only a portion of the power would be temporarily lost (EPRI, 1982).

4.2 Contamination

The best method by which a designer can minimize the number of contamination faults on the line is to ensure that the correct type and length of insulator is selected. There are two types of insulators from which one can choose, namely, ceramic or polymeric (also referred to as Non-Ceramic Insulators (NCI)). Ceramic insulators, constructed either from toughened glass or porcelain, have proven to be the most durable and can be found in the majority of installations worldwide. Both materials have inert surfaces which allows for good surface arcing resistance and both are extremely strong in compression (Kuffel, Zaengl, & Kuffel, 2004). One of the main problems experienced by ceramic insulators is that of vandalism with people shooting the glass sheds to observe them shatter.

Polymeric insulators have not been as widely used but have been gaining popularity over recent years. Historically, problems with u.v degradation, tracking and erosion were experienced but as materials and manufacturing techniques improve, these problems are becoming less significant to the point where performance matches that of ceramic insulators (Kuffel, Zaengl, & Kuffel, 2004). Polymeric insulators offer superior water handling capabilities due to the extremely hydrophobic surface. Having a hydrophobic surface greatly reduces the chance of a continuous water surface from occurring thus reducing the leakage currents present and the associated dry-band arcing process (Kuffel, Zaengl, & Kuffel, 2004). This entails that polymeric insulators offer improved contamination performance and are thus often installed in areas of expected high pollution.

The length of the insulator is determined by the creepage distance[2] (also known as leakage distance) which in turn is dependent on the anticipated contamination levels. A higher contamination level will

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[2] Creepage Distance is the distance along the surface of an insulator where it is expected the leakage current will flow. Specified in mm/kV, the value is obtained by measuring the entire length of the insulator string and dividing by the operating voltage.

require a greater creepage distance in order to perform to the required specifications. Table 2 shows standard creepage distances for both AC and DC systems for varying levels of contamination. It is interesting to note on the table the higher creepage distances specified for the DC systems as one would expect based on the findings discussed under 3.2 .

Table 2 Standard creepage distance for both AC and DC systems as defined by the IEC standards (EPRI, 2005)

IEC 60815		**IEC TS 60071 – 5**
Severity Withstand Levels SDD [mg/cm2]	**Specific AC Creepage Distance [mm/kV]**	**Equivalent DC Creepage Distance [mm/kV]**
0.03 - 0.06	16	27.2
0.10 - 0.20	20	34
0.30 - 0.60	25	42.5
> 0.60	31	52.7

Since exact modelling of the contamination levels for a new line can be difficult or impractical (given that a line may experience a number of different micro-environments which yield varying contamination levels), especially in areas where no existing lines can be used as a reference, one may encounter problem areas where faults caused by contamination exceed the acceptable level. A variety of methods exist that allow one to reduce the number of contamination faults on the line and that may be applied to both AC and DC systems.

- Insulator addition / replacement

If excessive contamination flashovers are experienced by the line, the easiest method for reducing the number of faults would be to add additional insulation (not applicable for single piece insulators) or to replace the existing insulation with a more suitable level of protection as discussed above. This however is not always possible and is largely limited by the tower configuration (The Practical Guide to Outdoor High Voltage Insulators, September 2006).

- Insulator Cleaning
    - Hand washing

Hand washing may only be performed on an outage and is very labour intensive. Regular detergents and de-greasing agents may be used but thorough rinsing must be performed prior to energizing the line since these substances are highly conductive (The Practical Guide to Outdoor High Voltage

Insulators, September 2006). Hand washing is very effective in removing stubborn deposits which would normally never be removed through regular wetting.

  - Spray washing

Spray washing may be performed online and presents a quicker, less labour intensive cleaning method. The following considerations must be taken into account when performing spray washing (The Practical Guide to Outdoor High Voltage Insulators, September 2006):

- Nozzle Pressure: Sufficient spacing between the water droplets must be maintained in order to keep the resistance between the hose and the conductors to a safe level.

- Water Conductivity: Water must be of a low conductivity to reduce the risk of flashovers occurring.

- Washing Apparatus Earthing: The apparatus must be sufficiently earthed for safety purposes (This however is not possible in the event that helicopter spray washing is performed).

  - Fixed spray washing

Fixed spray washing systems are permanently installed spray systems only used on strategic equipment. These systems are not favoured due to their high capital costs and high maintenance requirements.

  - Dry cleaning

Dry Cleaning is only performed in countries with little to no water available. It involves blasting the surface of the insulators with a dry, abrasive material such as corn cobs or walnut shells. The main disadvantage of using this method is that the mess that is left behind may pose as a fire hazard if not properly removed (The Practical Guide to Outdoor High Voltage Insulators, September 2006).

- Silicone Rubber (SIR) Coatings

A popular method of increasing the performance of an insulator or when increasing the voltage rating of the insulator, is to coat the insulator with RTV Silicone rubber which in turn, increases the hydrophobicity of the insulator thus allowing it to perform similar to a polymer type insulator. A coating, 0.3 To 0.5 mm thick, may last for over 10 years and re-application is possible with minimal surface preparation. Figure h shows how one would apply the coating using a spray gun to coat the entire insulator surface.

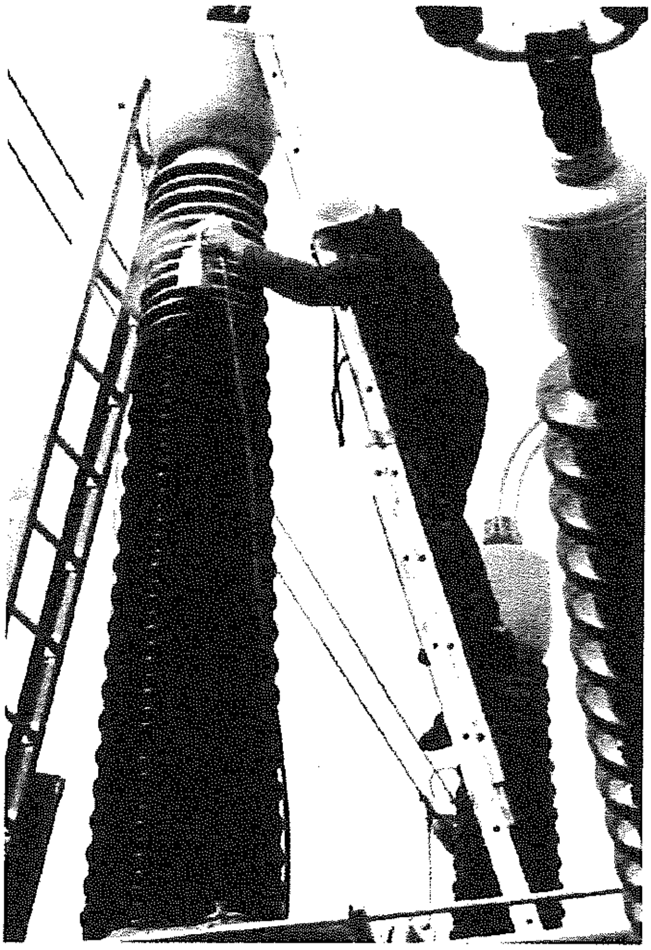

Figure 8 SIR Coating applied to HVDC bushing (The Practical Guide to Outdoor High Voltage Insulators, September 2006)

- Shed Extensions

Shed extensions are used to increase the creepage distance of the existing insulator. Installation of the shed extensions involves attaching polymeric disc-shaped devices onto the perimeters of the insulator sheds. The biggest disadvantage of this method is caused by the difference in surface characteristics of the polymeric shed extensions against the ceramic insulators. The difference in hydrophobicity causes an uneven field distribution and permanent dry-bands may form which will result in premature partial discharge activity resulting in a flashover and damage to the shed extensions.

- Insulator Upgrading

This involves an engineering study which takes into account all of the above mentioned measures to provide a permanent, maintenance free solution to the contamination flashover of substation insulators that cannot be easily replaced. It involves assessing what the current installation consists of, determining the expected contamination levels for that area and performing the necessary changes to the insulators which includes any of the above mentioned methods.

It is important to remember that in any polluted environment, without the proper maintenance procedures in place, a flashover will always occur (Kuffel, Zaengl, & Kuffel, 2004). Only the time for which it occurs may be altered by using the methods described above.

4.3 Birds

It is estimated that the cost of line faults caused by birds to Eskom is approximately R25 Million per annum (Vosloo & van Rooyen, 2001). A number of fault mitigation methods have been proposed however, often the cost of implementation would not prove to be economically beneficial to the utility. At present, there has only been one method of bird fault mitigation that has been successfully implemented of which South Africa has embarked on the largest project of its kind in the world (Vosloo H. F., 2004).

Bird guards present an effective and simple way of dissuading birds from perching on critical locations along the towers thus decreasing the chances of a flashover over occurring either through direct contact with the bird or the bird streamers. Figure 9 shows the installation of the bird guards on a 345 kV transmission line. The exact placement of the bird guards is dependent on the tower design. Generally, the guards will be placed near or above the phase conductors so that the birds will be discouraged from landing at those points thus minimizing the number of streamers around the conductors.

Figure 9 Installation of bird guards above phase conductor (Vosloo H. F., 2004)

Eskom has embarked on a number of large scale projects for the installation of the bird guards on its transmission system (Vosloo H. F., 2004). Initially, bird guards were only fitted to the closest 70 towers to the substation however, it was later found that the majority of bird faults occurred outside that 70 tower bracket. It was therefore decided that placement of the bird guards should depend on bird species population distribution along the lines and the risk associated with each bird species (Vosloo H. F., 2004). Due to the relative newness of the project, not much historical data is available however, noticeable improvements can be seen on lines that have been fitted with the bird guards as can be seen in Figure 10.

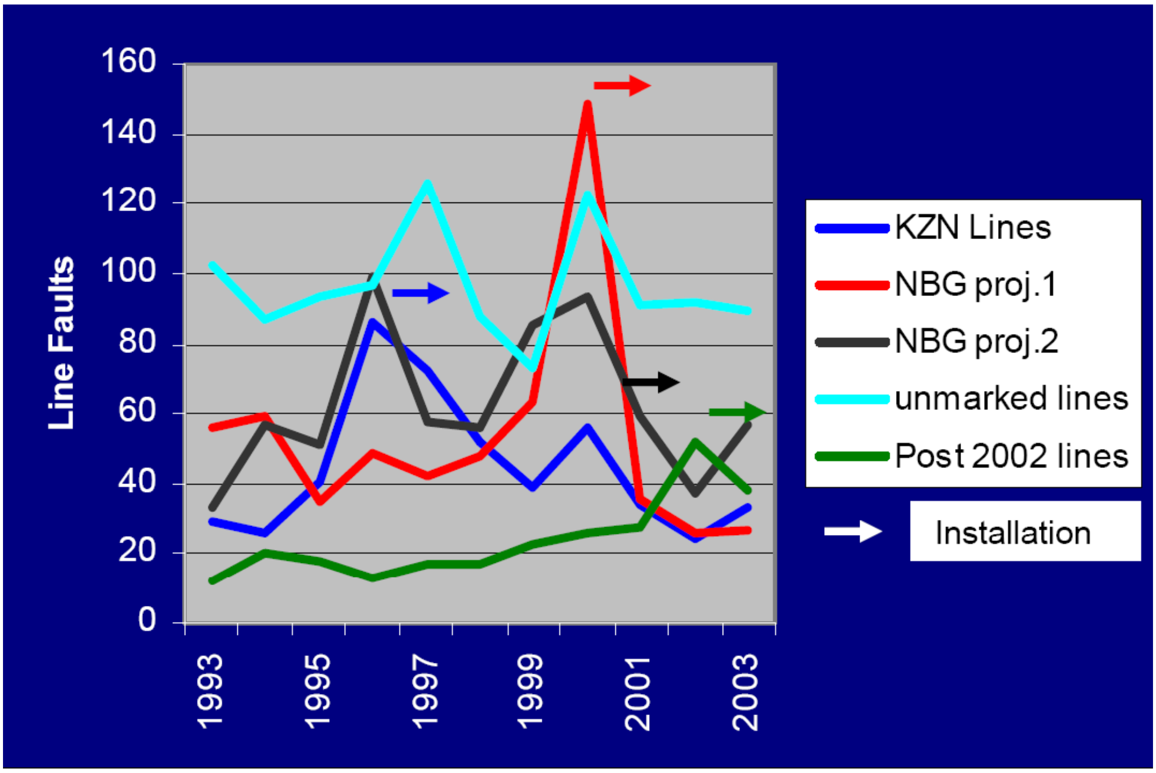

Figure 10 Graph indicating number of annual line faults pre and post bird guard installations (Vosloo H. F., 2004)

4.4 Fire

The prevention of fires below the servitudes is an unrealistic objective as fires are a natural phenomenon often required for the long term survival of vegetation. Humans are largely responsible for the starting of fires whether it be intentional or through pure negligence. Training and awareness programmes may be implemented in order to reduce the number of unintentional fires however, this is not sufficient to control the risk of fires under the servitudes.

It is in the utilities best interests to rather manage the risk of fire than to try and prevent it from occurring. State owned utility, Eskom, has implemented a detailed Environmental Management Programme (EMP) of which the purpose is to facilitate the management of servitudes in a sustainable manner in keeping with legislation, company policies and sound business practices, to ensure the safe, sustainable and optimal operation of the transmission grid (The Fundamentals and Practice of Overhead Line Maintenance, September 2006). As part of the EMP, the utility would include an Integrated Vegetation Management (IVM) programme of which the main focus would be to control and maintain all vegetation related aspects that may influence the servitude[3]. The mitigation of fire risks falls under the IVM and is discussed further below.

The first step in controlling a risk of fire fault would be to identify the vegetation types that occur within South Africa and determine their respective fire risk to the servitudes going across them. The following groups of vegetation have been identified and classed according to their fire risk (The Fundamentals and Practice of Overhead Line Maintenance, September 2006):

- Alien Invasive plants
- Densifiers
- Reeds
- Grasses
- Commercial Forests
- Sugar Cane
- Fynbos
- Karoo
- Indigenous Forests

The fire risk of these groups is determined by the plant structure, moisture content and quantity of material available as fuel (The Fundamentals and Practice of Overhead Line Maintenance, September 2006). Having identified the vegetation groups which may be encountered, and also determined their respective fire risk, the appropriate vegetation clearance methods may be put in place which will reduce the risk of fire affecting the servitudes. These methods include the following (The Fundamentals and Practice of Overhead Line Maintenance, September 2006):

- Manual methods – If selective vegetation removal is required.
- Mechanical methods – When large scale with complete vegetation removal is required.
- Biological methods – The planting of lower fire risk vegetation to outgrow the existing vegetation below the servitudes.
- Chemical methods – The use of herbicides to remove certain plant species below the servitudes.

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[3] As part of the IVM, one would also take cognizance of the expected weather and climatic conditions since this would have a direct influence on the FDI and hence should be monitored and managed accordingly.

- Intentional burning – The controlled burning of the area below the servitudes (performed at night when there is a low FDI[4]).

An important concept which forms part of the IVM would be that of a 'Fire Critical Zone'. The 'Fire Critical Zone' is that area underneath the servitude that, if not kept clear of excessive vegetation, will pose as a direct fault risk on the line. The focus of this area lies at the mid-span length with a decreasing area of coverage towards the towers. It is found that for a 400 kV line, a clearance of 3m from directly below the outer most conductor is sufficient in reducing the fire risk but with an additional safety margin added, the accepted clearance distance for a 400 kV line is 5m (refer to figure below for a visual illustration on both the 400 kV and the 765 kV lines) (The Fundamentals and Practice of Overhead Line Maintenance, September 2006). This is based on the thinking that the electric field gradient should be between 20 and 25 kV/m in order to prevent a fire fault from occurring. From the two scenarios shown in Figure 11, one can utilize a linear relationship to determine the required clearances for other voltage levels (The Fundamentals and Practice of Overhead Line Maintenance, September 2006).

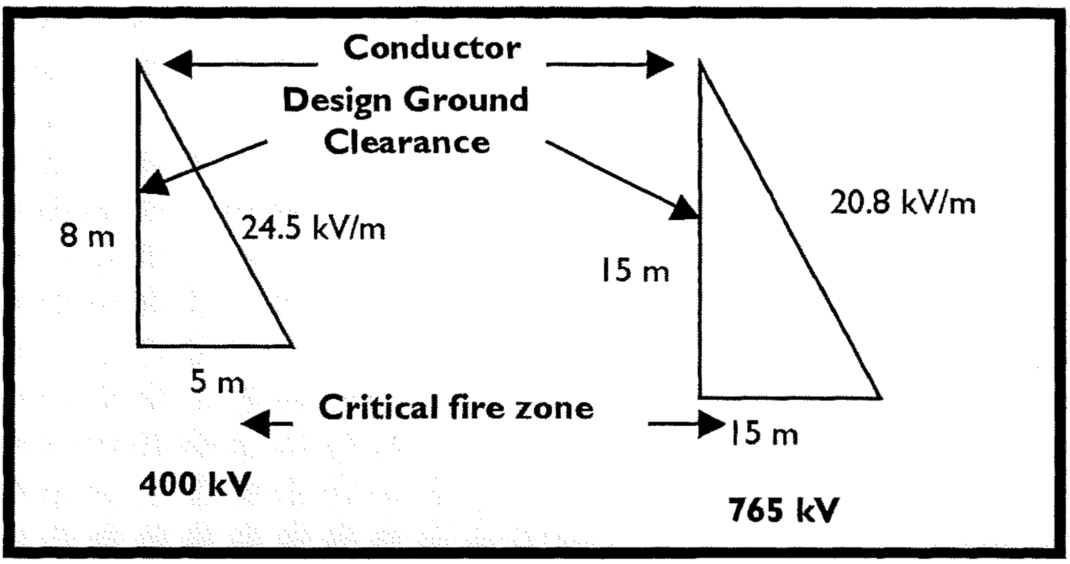

Figure 11 Critical fire zones for a 400 kV and 765 kV line (The Fundamentals and Practice of Overhead Line Maintenance, September 2006)

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[4] A Fire Danger Index (FDI) is a numeric index that it based on air temperature, relative humidity and wind speed. Some models may make provision for conditions of fuel such as fuel moisture or the effect of recent precipitation . Refer to Appendix C for a typical example of a FDI table (Vosloo H. F., 2004).

As with the contamination faults, unless proper maintenance procedures are carried out regularly, fire faults will occur.

5 SOURCE DATA ANALYSIS AND COMPARISON

The most accurate results that one may achieve upon comparing the performance of both AC and DC transmission systems would be based on the comparison of two adjacent, infinitely long, similarly rated lines that cover all the required terrain types and that have similarly recorded fault data spanning over many years. This, however, does not exist and hence one must find the most suitable grounds for comparison when selecting the appropriate AC and DC lines based on what is data is available.

Since one of the intentions of this report was to assist in the design of the proposed Westcor HVDC line, it was decided that only DC lines within a similar expected terrain should be selected for comparison, ie: only those found in Africa / Southern Africa. In selecting a HVDC line within Africa, only two options were available, namely, the Inga-Shaba System in Zaire (1700km; ±500 kV Monopoles) and the Cahora-Bassa System (1414km; ±533 kV Monopoles) going from Zambia to South Africa (EPRI, Transmission line reference book HVDC to ±600kV). Only data for the Cahora-Bassa System was available thus that was the line selected to be used for the comparison. This line however, presents itself as a suitable candidate for comparing with the Westcor HVDC link due to the similar environmental conditions that will be experienced by both lines (Kohlmeyer, Feb 2008). For the AC System, line fault data was available for all the transmission lines rated between 88 kV and 765 kV within South Africa dating from 1993 up until 2006 (Vosloo H. F., 2004).

It was decided to use the 400 kV AC lines to compare with the ±533 kV DC line for the following reasons:

- The 400 kV represents the closest AC voltage rating available to the DC line.
- A large amount of data on the 400 kV lines is available.

This section starts off by describing how the source information was arrived at for both systems. A brief discussion is then had over where possible inconsistencies in the data lie which may result in a negative impact on the findings.

5.1 Source Data Analysis

5.1.1 DC

The Cahora-Bassa DC link between Zambia and South Africa has been in operation since 1979 (EPRI, Transmission line reference book HVDC to ±600kV) and is used to transmit power between the Cahora-Bassa hydroelectric dam (Songo) and Apollo substation 15 km outside Johannesburg. The line has a nominal capacity of 1920 MW but is rarely operated at that rating for various reasons which include power unavailability at the hydro-electric dam and political instability. Two monopole lines are installed that lay approximately 5 km away from each other for the entire distance, the path of which can be seen in Figure 12. Appendix D contains basic line information about the DC transmission line.

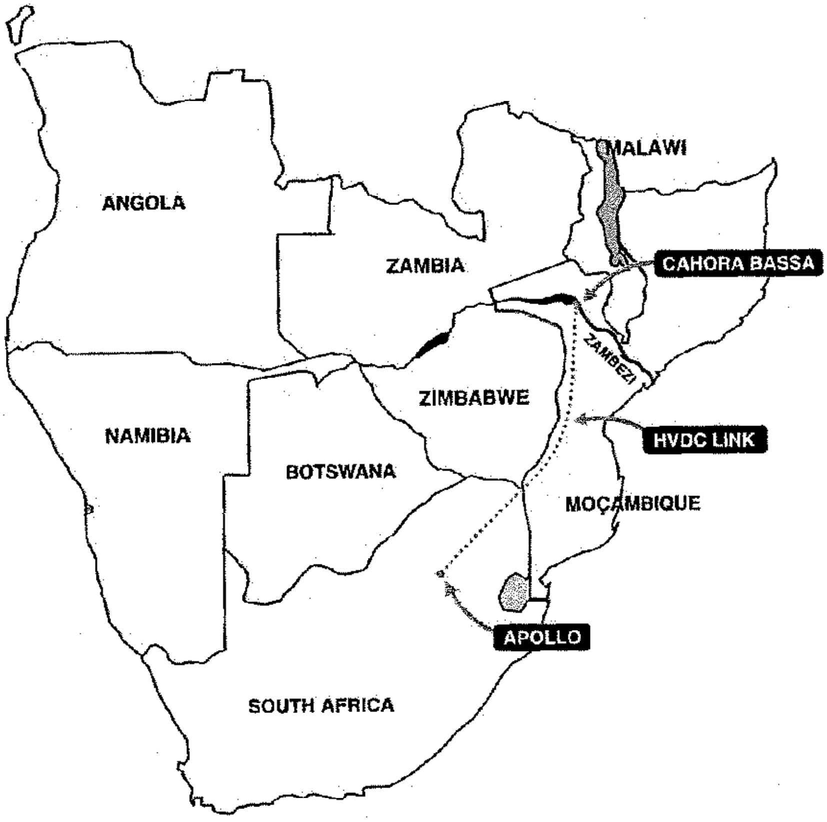

Figure 12 Map showing path of Cahora-Bassa DC link (Raynham, June 2004)

Eskom has been closely monitoring the performance of the line since it was commissioned and has constantly employed the latest line analysis techniques in the hope of finding ways of improving the performance of the line (Kohlmeyer, Feb 2008). It is from one of these reports that the information analysed has been extracted from.

The report classifies line faults into the following categories: Lightning, Fires, Pollution (Contamination) and Unknown. A brief description as to how these faults have been determined and classified may be summarised as follows:

- All the line faults were recorded using fault locators positioned along three points along the line (namely Apollo; Songo and Pietersburg). A fault is only recorded as a line fault when more than one of the fault locators is triggered by a travelling impulse. During 2007, a total of 201 faults were detected of which 20 did not have a corresponding distance value and 23 could not be positively identified (Kohlmeyer, Feb 2008).
- Lightning faults were detected using a system known as the Lightning Localizing System (LLS). This system, which replaces the previous Lightning Positioning and Tracking System (LPATS), is able to detect, with an accuracy of 100%, the position of lightning strikes to within 500m based on specialized satellite imagery. The accuracy of the system decreases closer to the South African Borders to 93% for strikes within 1km of the line. The system however, does not detect lightning strikes outside the South African border (Kohlmeyer, Feb 2008). With this technology, one is able to see over any required period, the number of strikes that occurred within a specified location. All major transmission lines within South Africa are constantly monitored using this technology and valuable insight as to where additional lightning fault mitigation methods are required can be determined. Figure 13 and Figure 14 below depicts how the information is displayed.

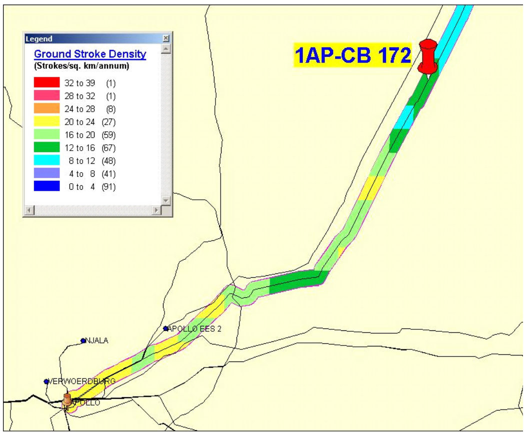

Figure 13 Unfiltered strike information around the DC line (Kohlmeyer, Feb 2008).

Figure 14 Refined strike data depicting the Ground Stroke Density around the line (Kohlmeyer, Feb 2008).

- Fire faults were determined using a combination of two methods. A ‘time of day’ analysis was performed on the data based on the knowledge that fires primarily take place around the late Autumn months and peak at around 13H00 (Vosloo H. F., 2004). In addition, specialised satellite imagery known as ‘MODIS’, which is a provider of detailed satellite imagery used in a number of applications worldwide (Horrocks), was used in identifying the occurrence of fires. This technology allows one to gain information into the location and time of when fires occur across the world. Figure 15 is an example of how the information is presented to the viewer. In addition, recently developed technology known as ‘AFIS – Web Fire Mapper’ (jointly developed by Eskom and CSIR) is able to indicate the time and location of fires within Southern Africa along with other data such as roads, distribution and transmission lines, national parks, rivers and cities (AFIS - User Guide). A 50% probability of detection is expected for fires in the order of 100m^2 but under certain conditions which include a homogenous surface, no other nearby fires and no heavy smoke or cloud cover, one can expect a detection of fires approximately 50m^2 in size (AFIS - User Guide).

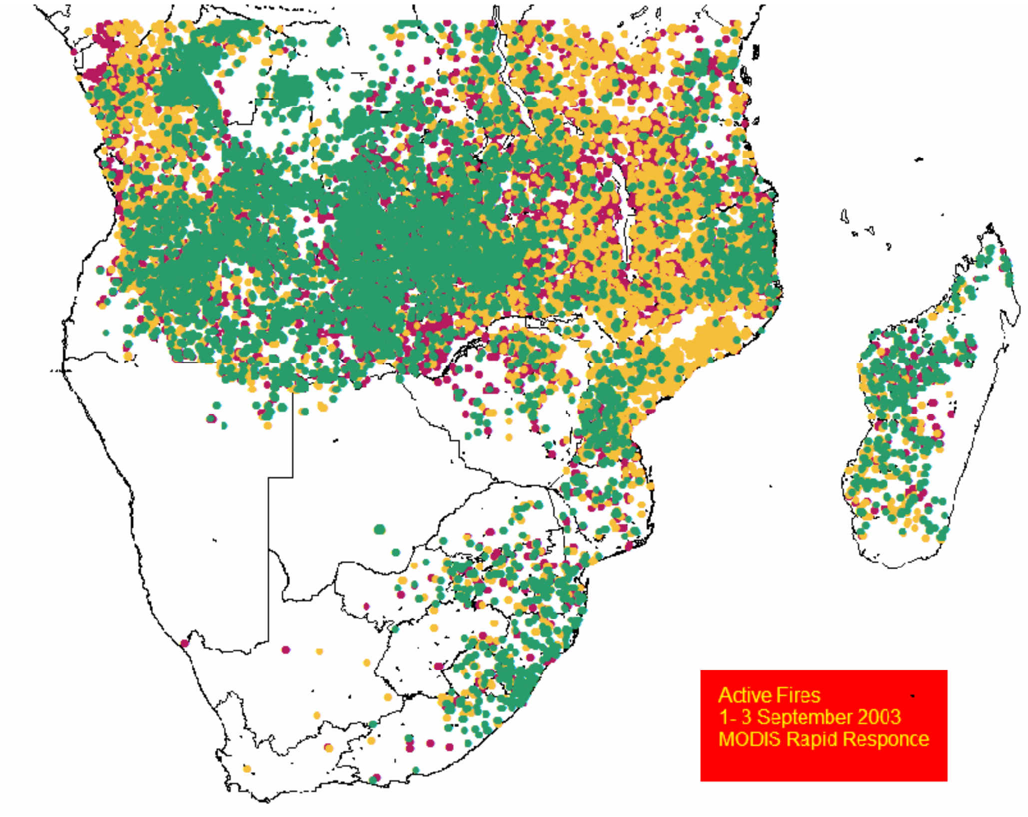

Figure 15 MODIS Fire data showing map of Southern Africa and fire locations for three days. Daily time differences are depicted by the three different colours (Vosloo H. F., 2004).

- Contamination faults were identified using relative humidity measurements and a ‘time of day’ analysis. Only faults occurring when the relative humidity exceeded 80% and peaking after sunset and before sunrise were classified (Kohlmeyer, April 2007). Relative Humidity measurements were readily obtained from the South African Weather Services.
- No Bird Streamer faults were identified on the line. The reasoning for this is discussed under 6.3 .
- Faults were classified as ‘Unknown’ if they did not fit the criteria for any of the above mentioned classifications.

The report makes available, to the best of its ability, a complete breakdown of the cause of line faults however, it should be noted that the causes of line faults is based on a number of estimations and even the author of the report states “The majority of line faults recorded on the Cahora-Bassa lines have not been positively identified” (Kohlmeyer, Feb 2008).

5.1.2 AC

It is in the utilities best interests to record and analyse all line faults so that improvements can be made on either existing lines or proposed new lines. A comprehensive data base that lists the cause, date and location of all line faults from August 1994 up until December 2006 was made available for use in this report. The information available for AC line faults is substantially larger than that of the DC line since the data covers all the standard voltages from 88 kV to 765 kV and also due to the total length of servitudes installed in South Africa being far greater than that of the DC line. Each identified fault was classified into five causes, namely: fire, lightning, birds, contamination and unknown. A brief description as to how these faults have been determined and classified may be summarised as follows:

- The identification of fire faults was accomplished using the same method as that described for the DC line. In addition to using the ‘AFIS – Web Fire Mapper’, often times Eskom would be informed by farmers or landowners of fires in the vicinity of the servitudes (Vosloo H. F., 2004).
- Lightning fault identification was also performed in the same manner as that of the DC line.
- Bird faults were identified through visual inspections and a ‘time of day’ analysis. A physical inspection of the line suspected to be caused by a bird fault would either have the carcass of the bird beneath the servitude or the bird streamer could be observed on the line. In addition,

one expected that faults caused by birds peak after sunset and before sunrise and more frequently during the late summer months (Vosloo H. F., 2004).

- Contamination faults were identified using both visual inspections and a ‘time of day’ analysis. A visual inspection after a fault has occurred would reveal some form of burn marks on the insulators. In addition, high risk areas for contamination faults would be known before hand (such as coastal environments, heavy industrial areas, etc) which would assist in the identification of the fault. As with the DC line, a time of day analysis was also performed with expected peaking times before sunrise and after sunset expected.
- Faults classified as ‘Unknown’ include mechanical failures, fires in equipment such as transformers and human errors (Vosloo H. F., 2004). It also includes faults that could not be identified due to inaccessible fault location, visibly hidden burn marks or the absence of post fault investigations. In addition, where no reasonable explanation could be found, faults were then classified under this heading (Vosloo H. F., 2004).

It is practically impossible to accurately identify and classify all faults that occur on the transmission system without investing substantial amounts of time and money into the fault investigations. However, over time and through the experience and knowledge gained, fault classification becomes easier and more accurate thus allowing for a more reliable data base from which to analyse.

5.2 Source Data Comparison

Since data has been taken from two different sources, it is important to understand where the possible ‘pitfalls’ or differences may exist when comparing the data. Without identifying and understanding these inconsistencies, the reader may be lead into having an incorrect perception as to how these lines perform against each other. The major sources of inconsistencies are briefly discussed below:

- From the DC contamination faults, it is understood that no actual inspections were carried out on the line to confirm whether the cause was actually contamination or not. The faults were only classified based on the relative humidity and time of day measurements which is less accurate than the physical inspections carried out for the AC lines. It is also estimated to be a gross over-assumption of the number of actual faults caused by contamination occurring on the line.
- The accuracy of the TWS (Travelling Wave System) fault locators used on the DC line has been questioned for high impedance faults (such as fire faults) (Kohlmeyer, April 2007).

- For the DC line, 62% of the faults were classified as ‘unknown’ until the data was filtered using the ‘time of day/season’ analysis and also the relative humidity measurements (Kohlmeyer, Feb 2008). This is a large portion of faults that could not be positively identified.
- The AC data base was compiled from a number of sources (approximately 18 different people supplied the relevant source data) thus further inconsistencies may exist within these different sources.
- The lightning fault data was obtained from the LPATS system for both AC and DC lines. This system however, is only operational within South African borders thus the DC line readings may be affected since the majority of the line is outside South African borders.

Although the data may contain inconsistencies, the author believes that it is still acceptable to compare the two sources of data against each other bearing in mind how the data was compiled.

6 FAULT TYPE COMPARISON AND 765 KV ESTIMATIONS

By looking at the number of faults for each fault type on the AC and DC systems, one will be able to get an understanding as to the relative influence that the fault type causes on the line. It is then from these findings that recommendations or predictions can be made on both existing lines and proposed lines above 765 kV. The primary comparisons are those taken between the 400 kV AC data and the ±533 kV DC data with reference made to the existing 765 kV AC lines. Lower AC voltages have been used to shows trends in line performance. Table 3 below shows a breakdown of the percentage of total faults for each system.

Table 3 Fault type breakdown for the 400 kV AC, 765 kV AC, and the 533 kV DC lines.

Fault Type	**400 kV AC** (Vosloo H. F., 2004)	**765 kV AC** (Vosloo H. F., 2004)	**DC (CAHORA BASSA)** (Kohlmeyer, Feb 2008)
FIRES	26%	19%	49%
CONTAMINATION	3%	2%	31%
LIGHTNING	17%	43%	8%
BIRD STREAMERS	38%	0%	0%
OTHER / UNKNOWN	16%	32%	12%

6.1 Lightning

For the DC line, a total of 5 lightning faults were recorded using the TWS system for 2007. Using this figure, the average number of faults per 100km per year is 0.35 (Note: This has only been based on the data obtained for one pole since it is believed that the other pole will behave in a similar manner (Kohlmeyer, April 2007)). In comparison with the AC data for a similar a voltage level, one can see that the values are similar with the AC lines exhibiting a slightly higher value of approximately 0.4 faults / 100km.year based on the straight line trend shown in Figure 16[5].

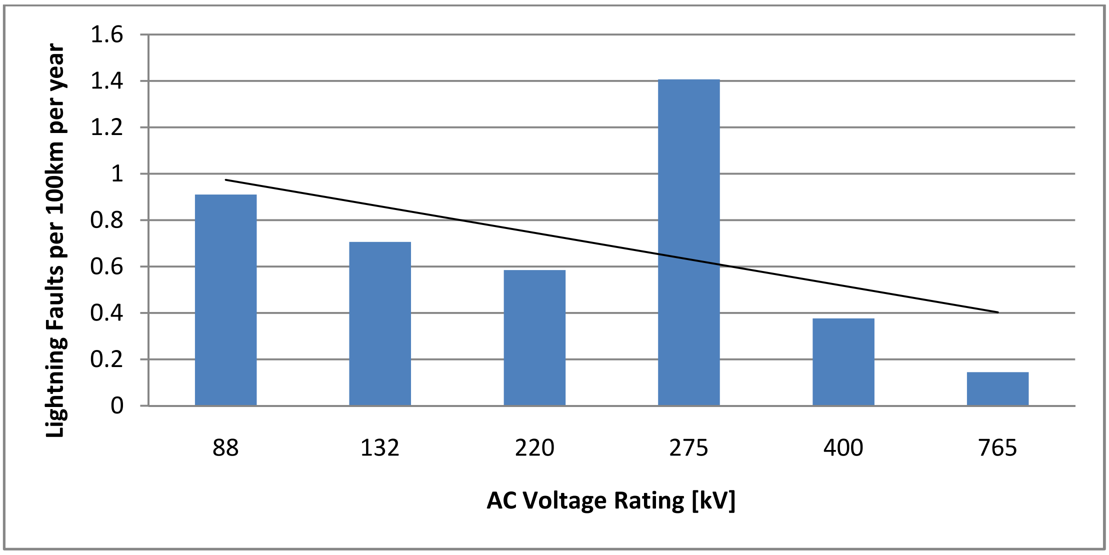

Figure 16 AC lightning faults per 100km per year for varying voltage levels with added trend line.

As the voltage of the line increases, it is also expected that the occurrence of lightning faults should decrease due to the increase in strike distance of the line. The EPRI AC Transmission Line reference book (1982) quotes: “because of the large air gaps and insulator lengths, lines above 800 kV (AC) should be practically lightning-proof, provided that attention is paid to proper shield angles and that the footing resistances are maintained below 50Ω”. The reasoning behind this statement is discussed below:

The lightning impulse strength (or the V_{50} voltage) is 520-560 kV/m for the positive polarity and 605 kV/m for the negative polarity[6] (EPRI, 2005). When looking at the 800 kV AC line, the minimum strike distance, as specified by the National Electric Safety Code (NESC 2002), is 4 m thus requiring

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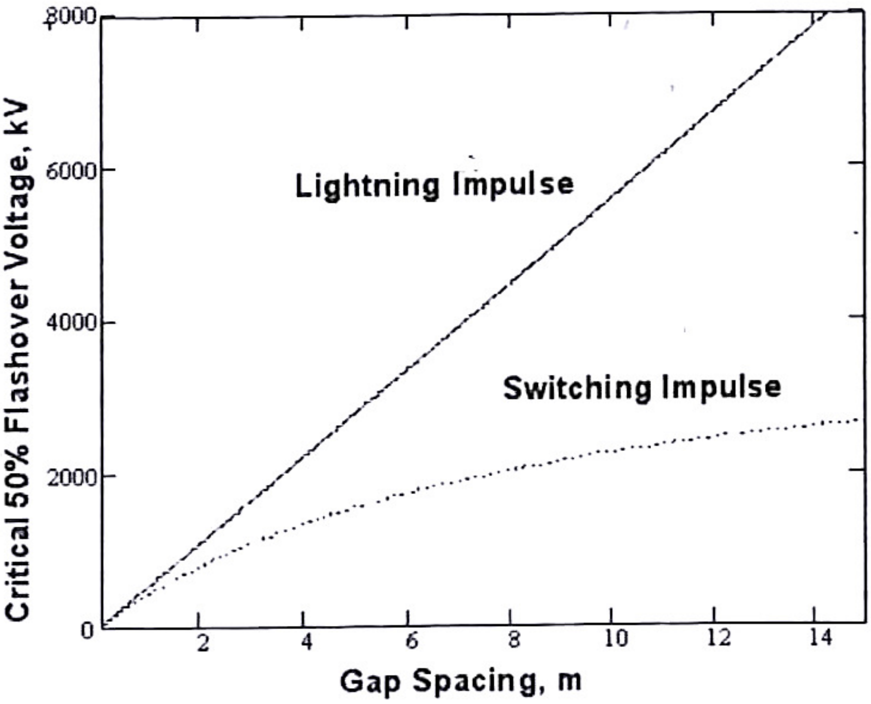
[5] Even though the AC and DC lightning faults per 100km correspond to each other, the average values of 0.35 and 0.4 are still far above the recommended value of 0.05 as stated by EPRI which was discussed under 3.1 .

[6] These values are only applicable under Standard conditions which is defined as: Temp - 20˚C; Pressure – 760mm of Hg; Relative Air density of 1 and Absolute humidity – 1.1 grams of water/m^3 of air (EPRI, 2005).

a voltage of approximately 2 MV to be generated on the line before there is a 50% chance of a flashover occurring. For a 400 kV line, the minimum strike distance is 2.03 m which then requires a V_{50} value of 1,228 kV. The respective critical currents[7] for these lines is 16 kA and 8 kA from which it is safe to say that there is a greatly probability of the lightning stroke current exceeding 8 kA rather than 16 kA (An average line impedance of 250Ω was used for the calculation (Kuffel, Zaengl, & Kuffel, 2004)). Although this does depend on what the surge impedance of the line is, one can still say that the probability of a lightning flashover will decrease with an increase in the strike distance due to the large voltages required for breakdown.

This does not mean that protection from over-voltages becomes less apparent at higher voltages since as we increase the voltage, the risk of switching impulse flashovers increases (refer to **Error! Reference source not found.**). Up until present, South Africa has had no failures on the 765 kV lines caused by switching failures (EPRI, 2005), but as the 765 kV network expands and the voltage levels of 1 MV anticipated for the Westcor HVDC link, switching surges will play a vital role in the performance of the line.



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[7] The critical current, which is defined as the lightning stroke current that results in a flashover of the conductor, is calculated using the following formulae: $I_c = 2.V_{50} / Z$. (EPRI, 2005)

Figure 17 Comparison of lightning and switching impulse strength (EPRI, 2005)

6.2 Contamination

The contamination faults constituted 31% of the total faults on the DC line thus it is important to see where the possible causes for such a high percentage may lie. Comparison of the contamination faults was not easily performed due to the variations in the number of insulator discs and type used on the DC line. A summary of how the insulation varied along with the number of contamination faults (only for 2007) for the entire length of the Cahora-Bassa line is shown in Figure 18.

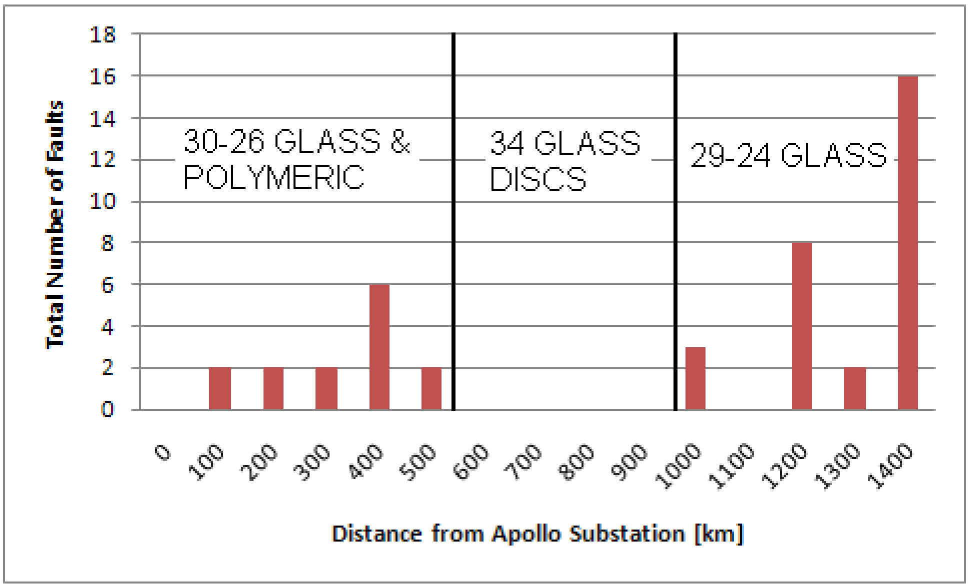

Figure 18 DC Contamination fault distribution along the DC line with variations in insulation (Kohlmeyer, Feb 2008).

Through a refinement of this data, one can then obtain the fault / 100km.year values for each of the three sections as shown in Figure 19.

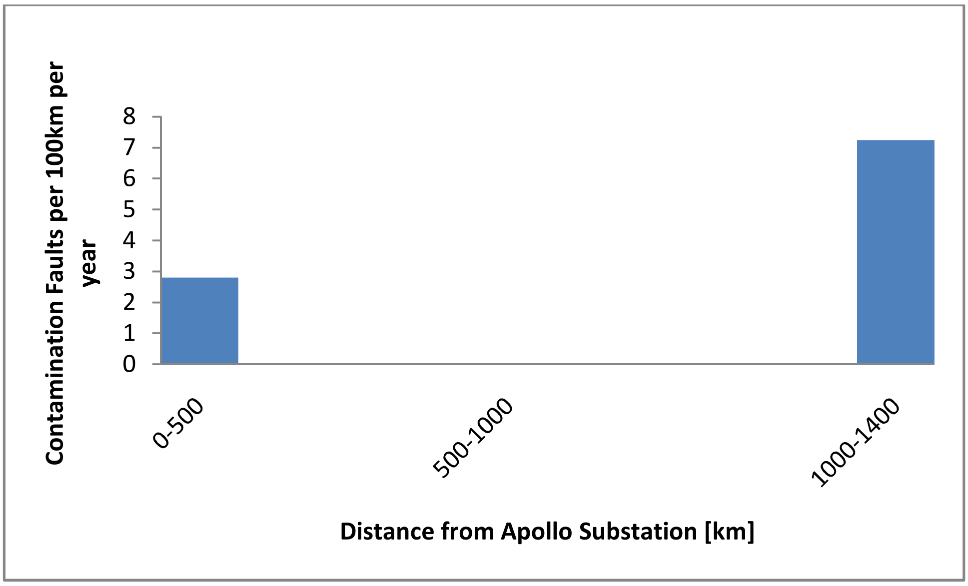

Figure 19 DC Contamination faults per 100km per year for the different sections of insulation.

From observing Figure 19, it is clear to see the difference that is made by varying the number of discs on the insulator string which results in a change of the creepage distance of the insulator. Parts of the line that contained the least amount of insulator discs revealed the greatest faults per 100km whereas no faults occurred in the section that contained a high number of insulators discs. This is not to say that no faults will occur given a certain creepage length but rather that only no faults occurred for this period of measurement and that the possibility of faults caused by contamination does still exist. For now, a weighted average for all three sections will be used. This value turns out to be 3.041 faults / 100km.year.

Contamination faults only account for 3% of the total faults on the 400 kV AC line. The average faults per 100 km per year for the 400 kV line is 0.066 which represents a value 46 times smaller than that of the DC value. This should be a clear indication that the number of contamination faults occurring on the DC line is far greater than should be expected. A meaningful comparison with such as large difference in results is not possible.

Figure 20 shows the contamination fault frequency for all the AC ratings. With the exception of the 132 kV voltage, one can observe a generally decrease in the trend line as the voltage rating increases. This is what one should expect since the longer the insulator string is, the less likely a contamination fault will occur.

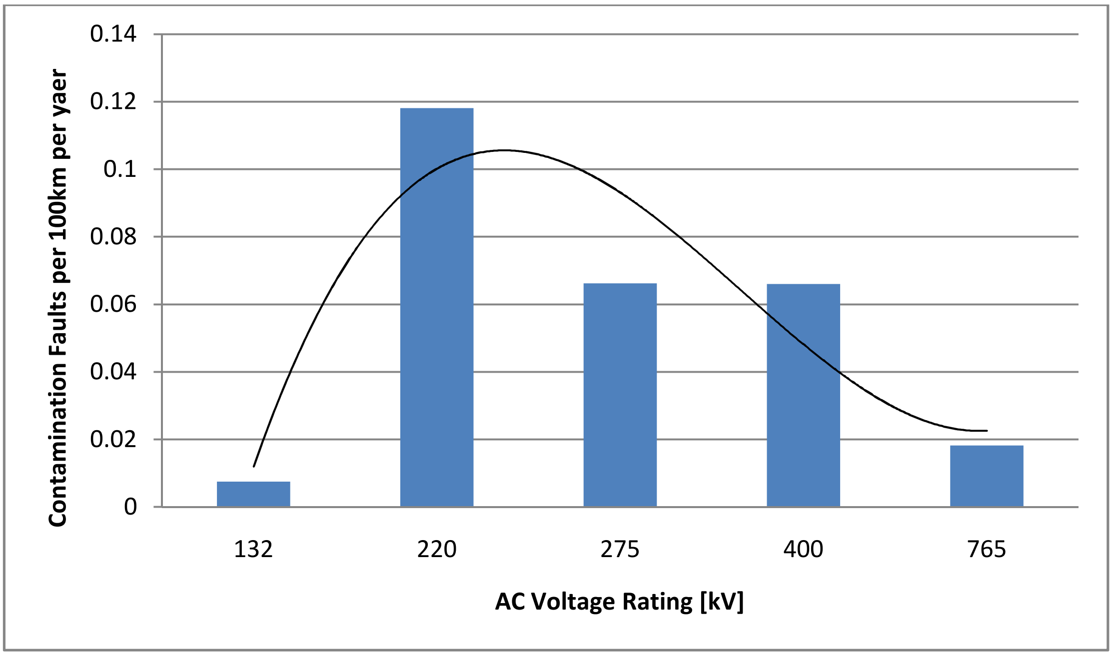

Figure 20 AC Contamination faults per 100km per year for varying voltage levels with added trend line.

6.3 Birds

When looking at the percentage allocation of bird streamer faults for both the 400 kV AC and the DC lines, it is clear that not only are bird faults the greatest cause of faults on the AC system (38%) but also that they are responsible for none of the faults on the DC system. Confirmation of this fact is shown in Figure 21, which clearly shows the edge of the ‘cliff’ at 400 kV. Based on this, one can say that there is a clear difference in the line between 400 kV and 533 kV that prevents any bird faults from occurring on the higher voltage ratings.

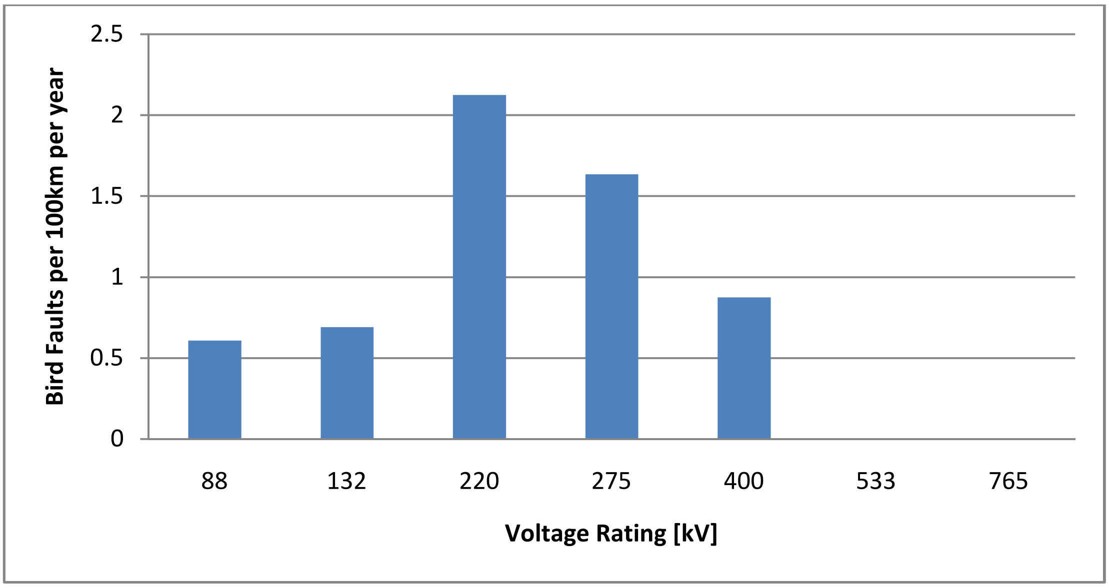

Figure 21 Bird streamer faults per 100 km per year for both AC and DC systems.

The reasoning behind this data 'cliff' was explained by Bologna (Bologna, Britten, Kohlmeyer, & Vosloo, 2007) in his report that investigated the cause of 'unknown' faults on the Cahora-Bassa line. This explanation may be summarised as follows: Previous research has shown that 400 kV lines containing an air gap of 4.2 m are not affected by bird streamers whereas lines that have an air gap of 3.2 m are (Vosloo & van Rooyen, 2001). This means that the maximum length of air gap to allow bird streamer faults to occur lies somewhere in the middle. When looking at the Cahora-Bassa line, the smallest air gap occurs between Apollo and Pafuri where the air gap length is only 4.16 m (this is equivalent to 26 glass discs each contributing 160 mm) (Bologna, Britten, Kohlmeyer, & Vosloo, 2007). In addition, research done by Eskom indicates that the length of a vulture streamer is approximately 2.4 m (Piper). With the flashover strength for a positive DC voltage known (400 kV/m, the negative voltage is higher thus not taken into consideration), one can then proceed to calculate what line voltage would be required for a breakdown to occur:

The effective air gap with the streamer in the circuit is = 4.16 m – 2.4 m = 1.76 m

The voltage required to bridge the air gap is then = 400 kV x 1.76 m = **704 kV**

This voltage is clearly higher than the rated 533 kV hence no bird streamer faults are expected for this line (Bologna, Britten, Kohlmeyer, & Vosloo, 2007).

Based on these findings alone, one can safely say that no bird related faults are expected to occur for both AC and DC transmission lines above 765 kV.

6.4 Fire

Fires have been identified as the cause of 26% for AC line faults and 49% for DC line faults. The percentage for the DC faults initially seemed too high but upon further investigation, the reason behind the 49% was discovered and a more realistic value of 9% may be used to compare.

After looking at the breakdown of where the fire faults occurred along the DC line, it was clearly observed that the majority of faults occurred on the Mozambique side (refer to Figure 22). Based on this information, it is questionable as to whether any vegetation clearance was being performed on the Mozambique side which was causing the substantially high number of fire faults (Bologna, Britten, Kohlmeyer, & Vosloo, 2007).

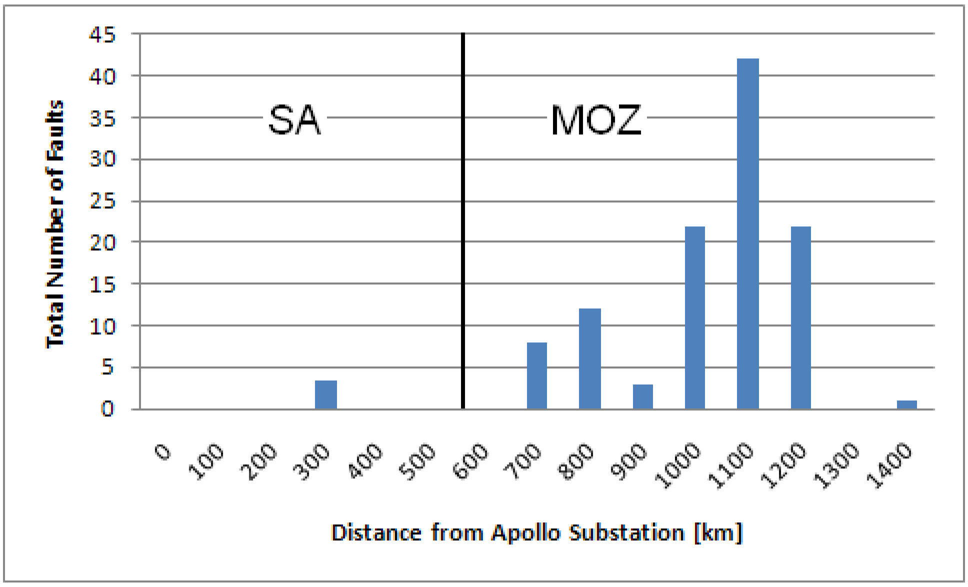

Figure 22 Fire fault locations on the DC line (Kohlmeyer, Feb 2008).

If one were to look at only the South Africa side of the line, where proper line maintenance was carried out, then the fault rate would be approximately 0.58 faults / 100km.year. This represents a satisfactory result.

Based on recommendations made by Eskom for transmission line vegetation clearance distances, and as was discussed under 4.4 , a Fire Critical Zone distance of 23 m should be implemented for the DC line in order to maintain a 25 kV/m electric field strength from the line to the furthest cleared point (calculated using basic trigonometry with a mid-span height of 8.5m). This was not done as a Fire Critical Zone of only 5 m was maintained for the line (Kohlmeyer, Feb 2008). Given the satisfactory performance of the line, the recommendation of maintaining an electric field strength of 20 to 25 kV/m may be questionable for the case of DC lines.

The fire fault rate for the 400 kV AC line is 0.661 faults / 100km.year. This value is slightly above that of the DC line is supported by the fact that the clearance of the 400 kV line is slightly less than that of the DC line (approximately 3.5% lower). It is however, contradictory to the idea that a low field gradient should be maintained in order to minimize the fire risk since the voltage increase in the line is 25% more for the DC. A possible explanation may simply lie in the fact that the data looks at lines in varying locations which are subject to different fire risks.

It was initially thought that fire faults would very seldom occur on the 765 kV AC lines but the data reveals that a total of 7 faults from August 1994 till December 2006 had actually resulted from fires. This value makes sense if one looks at the electric field grading for the line. At the mid-span clearance, the field gradient is 461/15 = 30.6 kV/m, which exceeds the assumed fire flashover withstand gradient of between 20 and 25 kV/m (EPRI, 2005). From this, one can say that 765 kV lines are inherently exposed to fire faults. Special note of this fact should be taken when looking at the proposed Westcor line which passes through some extremely high fire risk areas and also through areas where lack of servitude maintenance, as experienced on the Cahora-Bassa line, may easily be encountered. Generally speaking, the 765 kV lines within South Africa have performed satisfactorily against the risk of fire faults with only a 0.0635 faults / 100km.year value recorded (refer to Figure 23 for a relative look as to how all the AC voltage levels performed under fire faults).

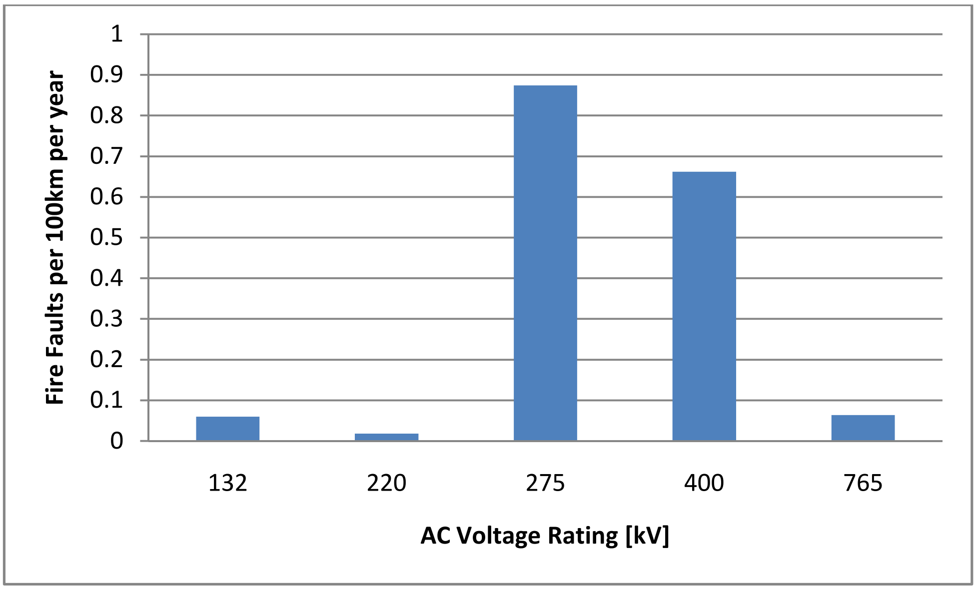

Figure 23 AC fire fault rate per 100 km per year for varying voltages.

7 SUMMARY

All the findings discussed within this report may be best summarised by looking at the fault ratings per 100 km per year for each fault type. This will allow one to gain a good understanding into not only the relative effects that each fault type has on the line, but will also help in identifying where either data analysis methods may be incorrect or where a focus on performance improvements are required.

Figure 24 below shows the fault rate for each fault type for the 400 kV AC, 765 kV AC and ±533 kV DC lines. The data presented in this graph represents exactly how it was obtained from the source information. Since it is known that the number of fire faults that occurred on the DC line is over-inflated for reasons that were discussed earlier, a figure which is more reflective of how the line should perform was inserted to reduce the distortion in the graph. The revised graph can be seen in Figure 25.

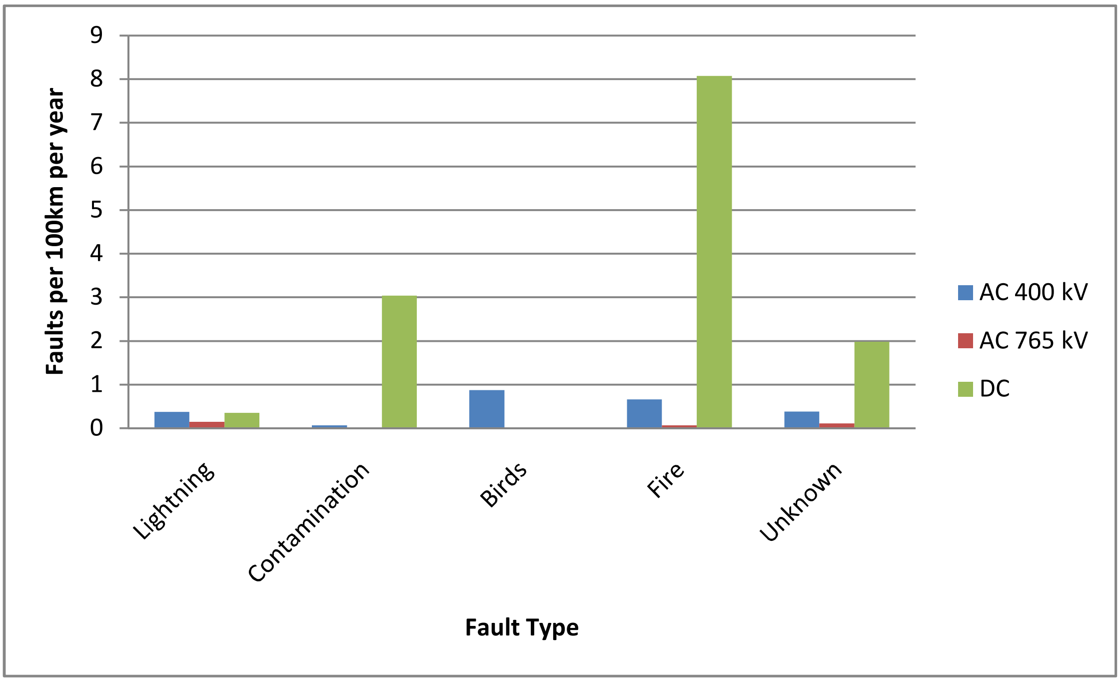

Figure 24 All fault type rates per 100km per year for the 400 kV AC, 765 kV AC and the 533 kV DC lines.

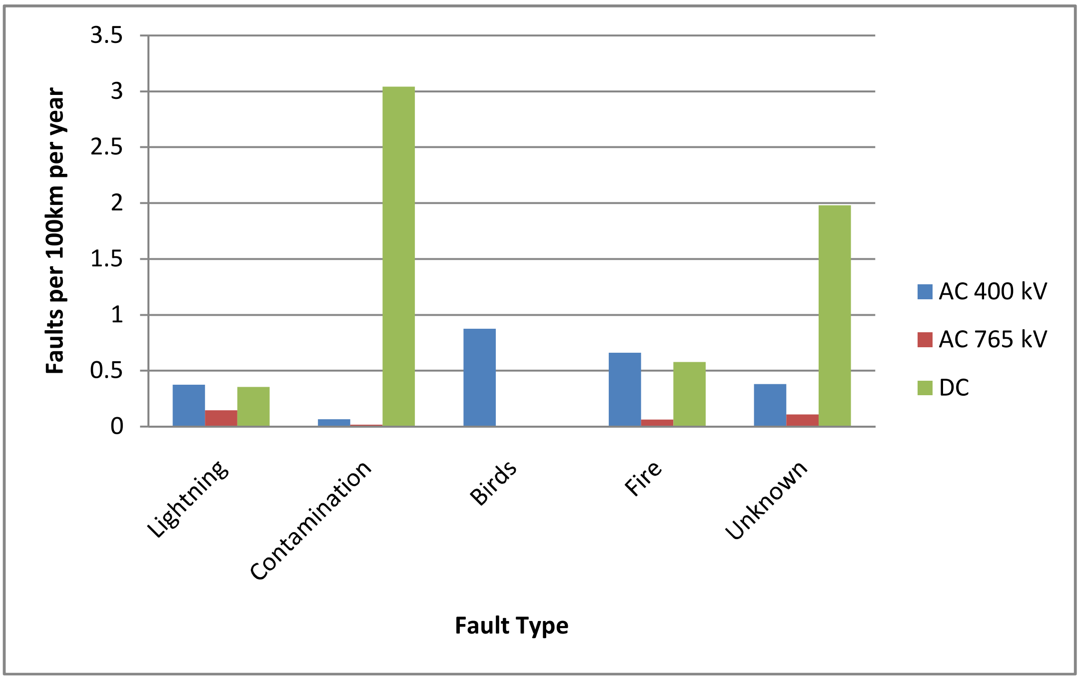

Figure 25 All fault type rates per 100 km per year for the 400 kV AC, 765 kV AC and the 533 kV DC lines with the modified DC fire fault rate.

The ‘Skyscrapers’ in Figure 25 are sets of data that have either been incorrectly recorded or where a genuine problem in the performance of the line exists. The most prominent skyscrapers include the

‘DC Contamination’, ‘DC unknown fault ratings’, ‘AC 400 kV Bird faults’ and ‘AC 400 kV and 533 kV DC Fire faults’.

Based on Figure 25, Table 4 summarises the behaviour of all the fault types for each voltage analysed and predicts what can be expected for higher voltage lines along with any recommendations that can be made.

Table 4 Findings and predictions summary for each fault type.

Fault Cause	Data Summary	Predictions / Recommendations
Lightning	Lightning performance for all three lines has been satisfactory and within expectations.	Current design practices have proven to be succesful for the AC line thus should be continued with no additions. The use of TLA’s can further improve the performance of future EHV lines.
Contamination	Contamination faults for the DC line represent the highest value over all fault types and voltage ratings. It is recommended that the method by which these are classified be re-looked at. In addition, it is proven how the performance improves with an increase in the number of discs thus this should be implemented for the entire line. Otherwise, the performance of the AC lines yields excellent results.	It is expected that pollution faults will become less apparent for higher voltages due to the increase in insulator length (but not disappear completely). In addition, further improvements can be made with the current advances in insulator design and materials specifically that of polymer insulators.
Birds	It has been shown that faults caused by birds only occur up until 400 kV afterwhich, due to the increase in air gap, no bird faults are experienced.	It is expected that no bird faults will occur on lines exceeding 765 kV.
Fire	Barring the data from the Moz DC line, fire faults are still within acceptable levels if not slightly elevated. This may be reduced by simply increasing the vegetation clearance distance for the 400 kV AC and the 533 kV DC lines.	One must still consider the electric field gradient in the design of lines for higher voltages as these lines are still susceptable to fire faults. In addition, it is still not clear if DC and AC lines should be treated differently with regard to this. Further investigation is still required for the exact mechanism of fire faults.
Unknown	A high number of the DC faults are still classified as ‘unknown’. A more rigorous approach should be taken to reduce the level of uncertainty as carried out with the AC lines. In addition, more	Proper fault recording equipment should form part of the initial design and installation of new EHV lines since knowing the performance

	accurate equipment may be installed to reduce the level of uncertainty in the fault measuring equipment for the DC line.	of these lines is imperative.

8 CONCLUSION

This dissertation has successfully compared the 400 kV AC lines within South Africa with the ±533 kV Cahora-Bassa DC line based on data from two different sources. First, all the relevant fault types were identified and explained along with standard methods of how to reduce/minimise the effects of these faults. The dissertation then proceeded to compare the data for each system after establishing how the source data was obtained and after identifying where possible inconsistencies in the data may exist.

It was found that in instances where line fault data was recorded differently between the AC and DC systems, that the data could not be realistically compared. This is clearly evident in the results for the Contamination fault type.

Based on the existing data, the following performance improvement recommendations are made:

- Proper vegetation clearance procedures should be carried out on the Mozambique side of the DC line to reduce the number of fire faults occurring on the line.
- The number of insulator discs used on certain sections of the DC line should be increased to improve the contamination performance of the line.
- Bird faults occurring on the 400 kV AC line could be reduced through in increased use of bird guards.
- The method of fault identification should be common for both AC and DC systems. It is further recommended that the fault identification methods used on the AC system be carried out due to the higher number of positively identified faults.

Based on the analysis of the existing data and the understanding of the fault types and their corresponding mitigation methods, the following predictions and recommendations are made regarding AC and DC systems exceeding 765 kV:

- Current design methods used to reduce lightning faults are satisfactory and should be used for higher voltage levels. Further improvement may be achieved through an increased use of LSA's in critical lightning areas.
- Current contamination fault mitigation methods employed should prove sufficient to meet the performance requirements of lines greater than 765 kV.
- Bird faults will not occur for lines over 765 kV.
- Fire faults, although expected to be minimal, should still be taken into consideration. This is especially true in the case of the Westcor project where, as seen with the DC Mozambique line, a lack of maintenance could lead to an abnormally high number of fire faults occurring.
- Due to the high performance requirements of lines above 765 kV, it is recommended that line fault identification equipment should be included in the initial line design and feasibility studies to allow for constant monitoring of line faults and hence quicker solutions to be met.

This research may be extended for the use in the establishment of transmission line performance standards with respect to fault type based on the type and location of the line within Southern Africa.

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APPENDIX A: Westcor Project

APPENDIX B: ESDD Table

Table 5IEC Contamination Severity Table (Kuffel, Zaengl, & Kuffel, 2004)

Pollution Level description	**ESDD [mg/cm2]**	**Examples of Typical Environments**	**Min. Leakage distance**
Very Light	0 – 0.03	Areas without industries and low density of houses equipped with heating plants. Areas with low density of industries or houses but subjected to frequent winds and /or rainfall. Agricultural areas. Mountainous areas. Note: All these areas shall be situated at least 10 km to 20 km from the sea and shall not be exposed to winds directly from the sea.	16 mm/kV
Light	0.03 – 0.06	Areas with industries not producing particularly polluting smoke and/or with average density of houses equipped with heating plants. Areas with high density of houses and/or industries but subjected to frequent winds and/or rainfall. Areas exposed to wind from the sea but not too close to the coast.	20 mm/kV
Moderate	0.06 – 0.1	Areas with high density of industries and suburbs of large cities with high density of heating plants producing pollution. Areas close to the sea or in any case exposed to relatively strong winds from the sea.	25 mm/kV
Heavy	> 0.1	Areas generally of moderate extent, subjected to conductive dusts and to industrial smoke producing particularly thick conductive deposits. Areas generally of moderate extent, very close to the coast and exposed to sea-spray or to very strong and polluting wind from the sea. Desert areas, characterized by no rain for long periods, exposed to strong winds carrying sand and salt, and subjected to regular condensation.	31 mm/kV

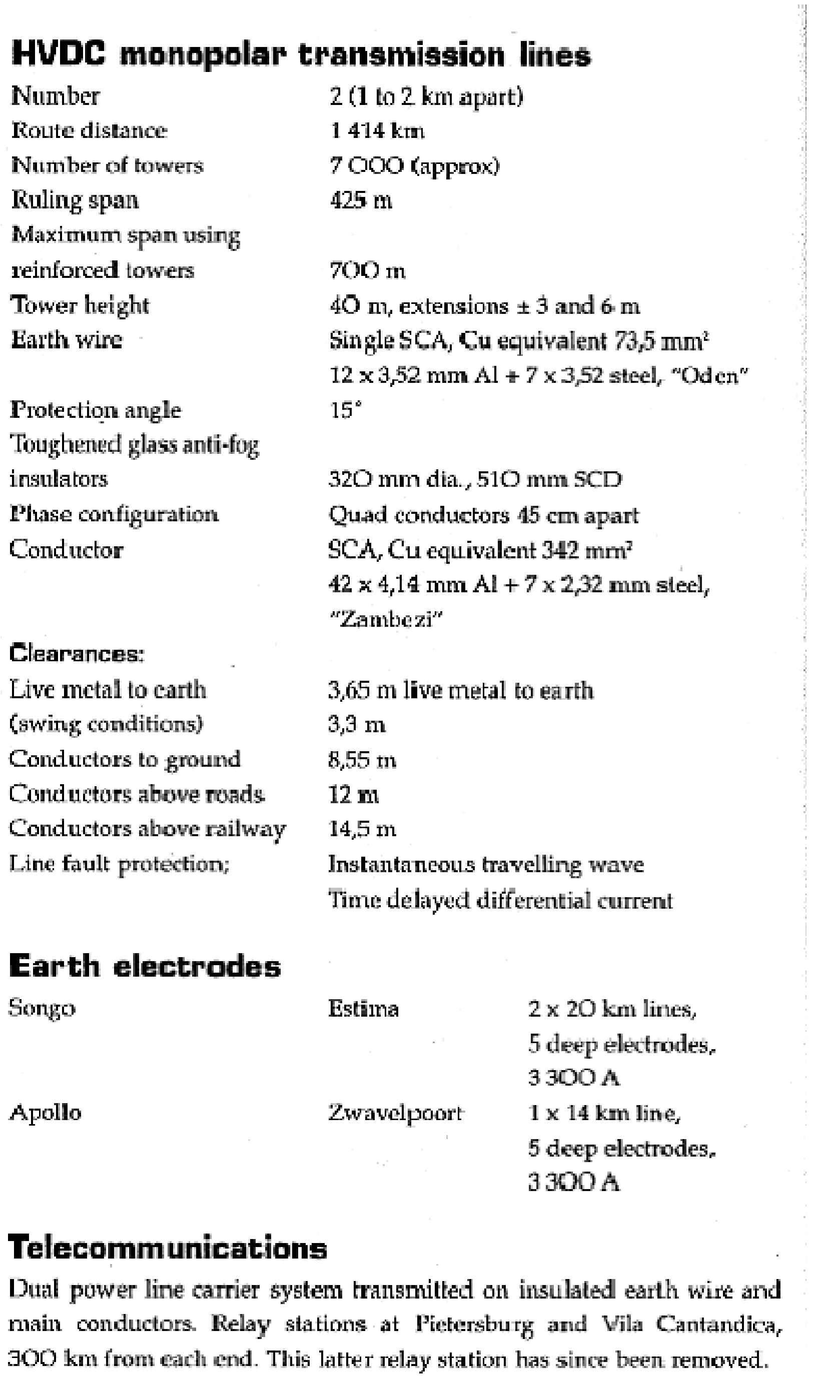
APPENDIX C: A Typical FDI Table

Table 6A typical fire danger index (Vosloo H. F., 2004)

Fire Alert stages	Blue	Green	Yellow	Orange	Red
Fire Danger Index	0-20	21-45	46-60	61-75	76-100
Fire Behaviour Flame lengths (m)	Safe 0-1 m	Moderate 1-1,2 m	Dangerous 1,2-1,8 m	Very Dangerous 1,8-2,4 m	Extremely Dangerous 2,4 + m
Fire Control Guide	Fires are not likely to start. If started they may spread very slowly or may go out without aid from suppression forces. There is little flaming combustion and intensity is low under all conditions. Control is readily achieved and little or no mopping up is required.	Ignition may take place near prolonged heat sources (camp fires, etc.), spread is slow in forests, moderate in open areas. These are light surface fires, with low flames. Control is readily achieved by direct manual attack and with minimum forces. Difficulty may be experienced on exposed dry slopes and some mopping up will be necessary.	Extreme caution should be taken when controlled burning is carried out. Aircraft should be called in at the early stages of a fire	Ignition can occur readily, spread may be fast in the forests though not for sustained periods. Grass fires could outstrip forces with a spread of approximately 7 km/h. Fires may be very hot with local crowning and short to medium range spotting. Control will be very difficult, requiring indirect attack methods with major assistance necessary. Mopping up may require an extended effort.	Ignition can occur from sparks. Rate of spread will be extremely fast for extended periods. Fires will be extremely hot with a dangerous heat effect on people within 10 m of the fire and there may be extensive crowning. Fire whirls and "long range" spotting. Control may not be possible by frontal attack during the day and fire fighters should limit their actions to containing lateral spread, until the weather changes. Damage potential total and mopping up operations may be very extensive and difficult. Full assistance necessary throughout.

APPENDIX D: Cahora-Bassa Line Information

(Raynham, June 2004)



HVDC monopolar transmission lines

Number	2 (1 to 2 km apart)
Route distance	1 414 km
Number of towers	7 000 (approx)
Ruling span	425 m
Maximum span using reinforced towers	700 m
Tower height	40 m, extensions ± 3 and 6 m
Earth wire	Single SCA, Cu equivalent 73,5 mm^2 12 x 3,52 mm Al + 7 x 3,52 steel, "Oden"
Protection angle	15°
Toughened glass anti-fog insulators	320 mm dia., 510 mm SCD
Phase configuration	Quad conductors 45 cm apart
Conductor	SCA, Cu equivalent 342 mm^2 42 x 4,14 mm Al + 7 x 2,32 mm steel, "Zambezi"

Clearances:

Live metal to earth	3,65 m live metal to earth
(swing conditions)	3,3 m
Conductors to ground	8,55 m
Conductors above roads	12 m
Conductors above railway	14,5 m
Line fault protection;	Instantaneous travelling wave Time delayed differential current

Earth electrodes

Songo	Estima	2 x 20 km lines, 5 deep electrodes, 3 300 A
Apollo	Zwavelpoort	1 x 14 km line, 5 deep electrodes, 3 300 A

Telecommunications

Dual power line carrier system transmitted on insulated earth wire and main conductors. Relay stations at Pietersburg and Vila Cantandica, 300 km from each end. This latter relay station has since been removed.