A Study of the Variation of Electric Distance and Electric Strength with the Type of Voltage Stress and Portion of the Gap Covered By Flames

By

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I dedicate all of this hard work to my late father,

France Rachael Ndlovu

And my grandparents,

Simon Seven Ndlovu and **Boshiwe Emma Nkosi**

May your souls rest in peace, you raised a soldier!

I Sbongiseni Ndlovu declare that;

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I further would like to thank my family, friends and all the people who were continuously giving me motivation, inspiration, care, encouragement and support throughout my academic life.

Abstract

South Africa has a large network of high voltage substations and transmission lines (over 28 000 kilometers) across the country designed to supply power to households, industry and businesses, railways and mines. This transmission system must be strong and capable of withstanding the loss of any single circuit without loss of supply to key customers. Veld fires burning under or near high voltage transmission lines are a potential hazard capable of disrupting transmission and distribution of power. Forest fires under high voltage transmission lines reduce the breakdown strength of the air insulation due to the influence the heat and particles have on the electric field surrounding electrical conductors and insulators. The performance of the high voltage transmission lines is most likely to be affected by the occurrence of veld fires under these power lines. The fire under high voltage transmission lines generates heat and increases the temperature of the air surrounding the conductors and insulators. The increase in temperature due to the presence of the fire decreases the breakdown strength of the air insulation, this results in flashovers and undesirable power supply interruptions in the electrical transmission network. Due to the past experience of AC transmission lines tripping as a result of sugar cane fires that occurs under these lines during cultivation seasons, this study was initiated to provide an understanding of how burning can cause outages of transmission lines and give recommendations on how to prevent outages due to burning. This dissertation is a research based modeling aimed at giving an understanding of how the electric distance and electric strength vary with the type of voltage stress and the portion of the gap covered by flames. The study reviewed how different authors have conducted studies related to this dissertation and compared the results. The different failures due to burning occurring next to the transmission lines and contamination was grouped and analysed in terms of the time of occurrence, time of the day, season of the year and time of the day. The results shows that most of the faults on contamination occur on the DC lines and that the voltage level that’s affected the most is 220 kV. The time of the day analysis shows that most of the faults occur between 13:00 to 15:00, this is because the temperature around those times are very hot and temperature has a direct influence on the fire behavior.

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List of Abbreviations

A	Ampere
AC	Alternating Current
ACAR	Aluminum Conductor Aluminum-Alloy Reinforced
ACSR	Aluminum Conductor Steel Reinforced
ACC	All Aluminum Conductor
AFIS	Advance Fire Information System
DC	Direct Current
ESDD	Equivalent Salt Deposit Density
HP	High pressure
HV	High Voltage
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IVM	Integrated Vegetation Management
kV	Kilo Volt
kW	Kilo Watts
LI	Lightning Impulse
LIWV	Lightning Impulse Withstand Voltage
LTC	Long Time Creep
MV	Medium Voltage
MVA	Mega Volts Ampere
NFPA	National Fire Protection Association Fire Analysis
ROW	Right of Way
SI	Switching Impulse
STC	Short Time Creep
STP	Standard Temperature Pressure
V	Voltage
W	Watts

List of symbols

I_o - Initial photocurrent from the cathode

α - Primary ionization coefficient

γ - Secondary ionization coefficient

µ - Mobility of ions

ρ – Charge density

h – Plank's constant

σ - Conductivity

z – Atomic number

k – Boltzman constant

m – Mass of the electron

ύ – Velocity of the molecule

E - Electric field

p - Gas pressure

n_o - Initial number of electrons emitted by the cathode

n_a - Number of electrons that reach the anode

η - Attachment coefficient

x_c - Critical avalanche length

E_r - Radially directed space charge field strength

x - Avalanche progression distance

N_{cr} - Critical electron concentration in an avalanche

W_i – Ionization energy

u_i – Electronic concentration

n_e – Electronic mobility ratio

n_i – Ionic mobility ratio

D_e – Diffusion coefficient

D – Molecular diameter

δ - Relative air density

T - Actual temperature

p_o - 101.3kPA

T_o – 20^0C

CHAPTER 1- Introduction

1.1 Introduction

It has been reported that forest/veld fires near or under overhead power lines are a serious threat to the safe and reliable operation of power grids. The gap breakdown in forest fire relates to many factors such as flame the flame conductivity, temperature and particles. During veld fires, a large amount of smoke with carbon and ash is produced during the combustion of vegetation. This then causes the dielectric strength of the air gap to decrease drastically, as a result the breakdown voltage is decreased with the rising of the flame conductivity.

1.2 Background

Studies shows that the presence of fire under transmission power lines reduces the dielectric strength of the air around conductors and insulators [1]. This causes breakdown to occur at a value lower than it normally would under standard temperature conditions [2]. Over the past years industries such as Transnet and Eskom have experienced problem such as flashover voltage which are due to veld and sugar cane fires under transmission lines ranging from 132 kV to 400 kV [3]. In South Africa especially the northern coastal region of KwaZulu-Natal and in Mpumalanga where sugar cane farming is a major agricultural activity, farmers burn the sugar cane as a harvesting aid thus causing line failures [4]. Similar problems have been reported in other countries including Mexico, Brazil, Portugal and Canada, where agricultural fires have resulted in power outages [5]. These failures have led authors such as Lanoie and Mercure [6] in Canada, Robledo-Martinez et al in Mexico [9] and Sadurski and Reynders [3], Cowan *et al* [7] in South Africa to carry out studies to understand or rather investigate the effect of fire on the reduction of the insulation strength of air, thus the effect on the power line performance. This chapter entails fundamental background, feasibility study, objectives and the motivation behind the research conducted.

1.3 Problem definition

South Africa has a broad network of high voltage substations and transmission power lines across the country, which are put in place to supply power to industries and businesses, households, municipalities, railways and mines. The type of transmission used is strong and must be able to withstand the loss of any single circuit without loss of supply to key customers. The quality of supply from Eskom to large customers such as Transnet and Mines, and distributors such as municipalities is particularly important [9].

Veld fires and sugar cane burning near or under power lines are a potential hazard capable of disrupting the transmission and distribution power. The power lines mostly affected by such disruptions in the

Eskom network have been the transmission lines at 132 kV to 400 kV. In all cases including ring feeds, a system fault along a line causes a disruptive voltage-depression or voltage sag. These result in a voltage depression across all loads connected from this line including all the associated step-down transformers. Due to this, customers from an entire region may experience the disruption [9].

Veld fires and sugar cane fires are the major sources of fire related power supply problems. Sugar cane burning mainly occurs in KwaZulu-Natal and Mpumalanga whilst veld fires are found throughout South Africa [8]. Previous investigations show that the disruptions be it a short circuit or insulator flashing was due to the breakdown of the air around the conductors or insulators due to the proximity of the fire. Changes in the composition of the air around the conductors implies a change in corona activity around the conductors [9].

1.4 Research questions

The key questions to be addressed in this study are:

a) What are the characteristics or features related to smoke to cause a flashover on an insulator?
b) Which season, month, time of day and climatic condition is likely to cause flashover as a result of burning?
c) What are the environmental conditions that influences the flashover voltage?

1.5 Research objectives

The research aims to find out the threat caused by fires under or near transmission power lines. The empirical and theoretical findings of this research may be used in the design of insulation systems for HVDC or HVAC power lines, especially where the line is to pass through an area that is known to be prone to fires. Furthermore, with the recent increase in HVDC transmission systems, it further enforces the need for an in-depth understanding of air gap voltage breakdown characteristics under DC conditions.

Five major objectives that were set out:

a) To understand the characteristics or features related to smoke to cause a flashover on an insulator.
b) To analyse the faults caused by fires for different voltage levels.
c) To investigate the nature and properties of electromagnetic noise on power lines arising from the presence of fires under or near those lines.
d) To determine the conditions that influences the flashover voltage.
e) To determine at what temperature, which season and time of the day that’s likely to cause a flashover

1.6 Feasibility study

Cowan in 1991 [7] conducted a study with Eskom to establish the mechanism of insulation breakdown, the fault impedance and the extant of electromagnetic induced noise prior to flashover under HVAC voltages. The study was conducted because of the problems experienced on high voltage transmission lines in the coastal region of KwaZulu-Natal during sugar cane harvesting in which sugar cane is burnt as means of harvesting. These has resulted into flashovers and short circuit occurring that could potentially damage the transmission line and as a result of large fault current, severe voltage depressions would occur [7].

Figure 1-1 illustrates a sugar cane fire burning under a transmission line. It can be observed that the intensity and height of the fire flames can be such that they completely cover the three phases of an AC transmission power line. This would cause a severe deterioration in the dielectric strength of the air between the adjacent phases.

Figure 1-1: Forest fires under electrical power lines [10]

In studying the mechanism of insulation breakdown, the authors of [7] documented empirical observations which showed that the following factors influenced the probability of flashovers on an AC power line:

1) Fire intensity and duration (temperature),
2) The voltage gradient (i.e. transmission line phase spacing) and
3) Ash particles and smoke density.

Cowan et al., [7] further noted that the ambient temperature, humidity and other environmental conditions had little apparent influence. Additional data from previous years (1988-1990) was presented and it indicated the following findings:

1) 400 kV lines experienced 1.5 flashovers/100 km/annum while
2) 132 kV lines only experienced 0.3 flashovers/100 km/annum

3) 400 kV lines with 44 kV/m phase-to-phase and 47 kV/m phase-to-earth wire voltage gradient generally flash phase-to-earth while
4) 275 kV lines with 37 kV/m and 33 kV/m voltage gradients respectively flash mainly phase-to-phase

Laboratory studies showed that temperatures of 1100 ^{0}C reduced the dielectric strength of air from 2120 kV/m to 100 kV/m [7]. However, these results are only valid for small uniform air gaps and field observation indicated that the fire had to be intense and sustained for flashover to occur. For large and non-uniform gaps experienced in practice, the insulation breakdown was found to take place according to the streamer mechanism, rather than the classical Townsend mechanism thereby reducing the dielectric strength from the 110 kV/m stated above. Ash particles and smoke were observed to be assisting in the streamer breakdown thus reducing air dielectric strength even further.

The study concluded that the line-to-line and line-to-earth wire voltage gradient statistically predict where the flashover would occur. Thus to ensure less severe voltage depressions, the phase-to-earth wire voltage gradient must be greater than the phase-to-phase voltage gradient, thus forcing line-to-earth faults.

1.7 Research methodology

This study was conducted as follows

- Literature review on various aspects related to the research work
- Formulation of steps required for investigations
- Data collection of various phenomenon related smoke and flashover on insulators
- Analysing the results technically and scientifically
- Concluding the works and findings together with recommendations and future work

1.8 Research Layout

The dissertation entails seven chapters.

Chapter one entails the introduction to the work, background, objectives, feasibility study, questions relevant to the research work and the methodology adopted.

Chapter two gives a brief overview of how environmental factors affect or influence the flashover mechanism. This will give a deep understanding on how a flashover occurs. The chapter also classifies the different types of fires and discusses the role of weather in the start and spread of wildfires.

Chapter three gives a brief overview of the transmission line configurations that are likely to be affected or that can cause a flashover. The minimum clearance that must be adopted and insulation requirements are discussed in details.

Chapter four reviews different literatures on the effect of fire on the breakdown voltage of overhead power lines. Also discussed in this chapter is how different authors have conducted studies related to this thesis/investigation. The fire particles that initiates the flashover mechanism is discussed in details, the effect of increased temperature as a result of fires which then affects the breakdown strength of air is also discussed in detailed this includes thermal ionisation, combustion particles, dielectric strength and the flame conductivity theory. Also discussed in this chapter are measures employed to reduce outages due to burning in South Africa and other countries and risk assessment for fires.

Chapter five gives the methodology that was followed in the study.

Chapter six reviews detailed statistical analysis of outages as a result of burning. Also the chapter gives a brief discussion on the condition in which the faults occur, i.e. the season of the year, time of the day and environmental condition.

Chapter seven summarises the conclusion based on the study conducted and future work that can be conducted in aid of understanding the breakdown voltage as a result of burning.

Chapter 2: Environmental factors influencing the flashover mechanism

Weather is the state of the atmosphere surrounding the earth at certain area. The atmosphere is a gaseous mantle (mostly oxygen and nitrogen) encasing the earth and rotating with it in space. The weather is never static, it is dynamic, changing day-by-day, hour-by-hour and even minute-by-minute [10]. The weather patterns and environmental factors that may affect the performance of a transmission power lines includes pollution, lightning occurrences, rainfall patterns and forest fires. South Africa is characterised by two main seasons, namely winter and summer. These weather conditions are a main factor responsible for faults in transmission lines. Birds, lightning, fire and pollution were identified as the four most significant individual causes of faults. These four causes altogether represent about 89% of all faults [11].

Eskom transmission system or network is spread across South Africa in different regions in terms of biomes. The concept biomes describes the type of vegetation present in an area such as grasslands and forest as shown in Figure 2-1. These biomes may affect the performance of a transmission power line in several ways. It has been reported that one of the more serious effects is the number of line faults as a result of forest fires through the burning of savannah type grass [12]. This chapter discusses the role of weather in the start and spread of wildfires and in the use of prescribed fires.

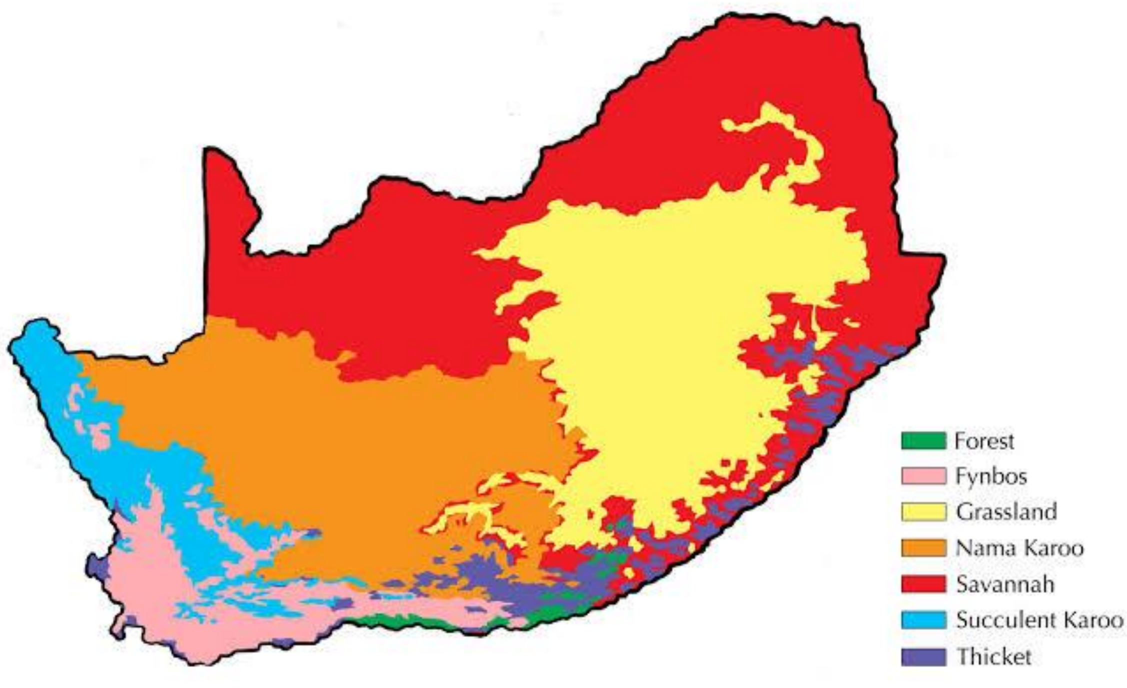


Figure 2-1: Biomes of South Africa [12]

2. 1 Wildfire chemistry

2.1.1 How does fire start?

Fire needs fuel, oxygen and heat to ignite and spread. Wherever forests grow, the fuel for forest fires are provided by continued biomass production along with the resulting fuel load that vegetative growth. Oxygen is created in abundance through the process of photosynthesis, so it is all around us in the air. A source of heat is needed to provide the exact chemistry combinations for a flame. When natural combustibles such as wood, leaves and grass reach 572^0, a gas in the steam given off reacts with oxygen to reach its flash point with a burst of flame. The flame then preheats the surrounding fuels resulting in other fuels heating up and the fire growing and spreading. If the spreading process is not controlled, then this will result into a wildfire or uncontrolled forest fire [13].

2.1.2 Flame length

The heat generated by the fire is a continuous "plasma" frequently releasing large pockets of heat from the main body of the flame. Depending on the environmental elements, flames of a sugar cane fire may reach the conductors from many meters away. Sugar cane fires have been visually recorded with flames reaching heights of several meters above the earth wires on a triangular line configuration. With no wind present, the vertical heights obtainable from a continuous flame should therefore not be underestimated. Recordings have captured flames at heights of 25 to 30 meters [13].

Figure 2-2 shows a parabolic shape of a flame height. From the graph, it can be seen that at the beginning

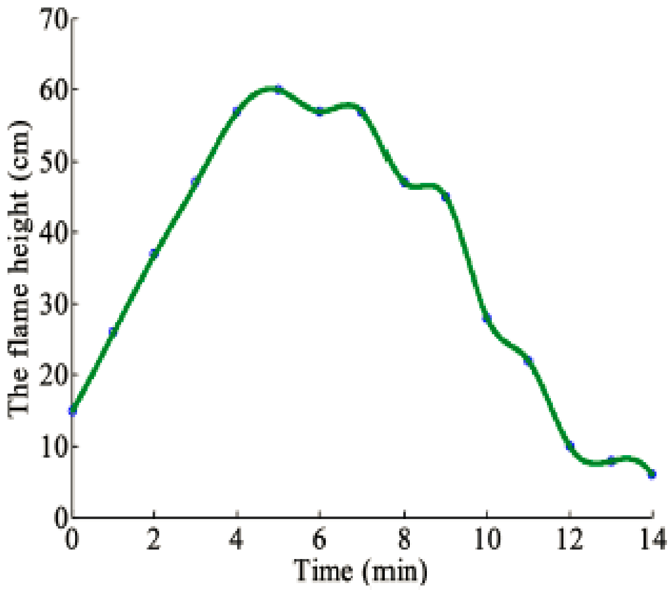


Figure 2-2: The flame height curve in different times [14]

2.1.2 Classes of fire

According to [15] fires are grouped in classes in relation to the combustion materials which have ignited. There are mainly 6 classes of fire namely:

- Class A- Ordinary combustibles

These are the most common fires; they involve combustible solid materials such as wood, plastic, paper, cloths and pieces of clothing. They can occur anywhere and can spread quickly as long as there are enough combustible materials, oxygen and heat to sustain it [15].

- Class B- Flammable liquids

These fires can be incredibly dangerous. They involve flammable liquid substances such as oil, paints, alcohol, kerosene, petrol and solvents. These types of fires can occur in any area where flammable liquids are stored or used such as garages, construction sites, hospitals, laboratories and warehouses. Flammable liquids have a low flash point so they can burn easily when an open flame or other ignition point is introduced. A match or spark can ignite the vapors of a flammable liquid, so proper storage is required to minimize the chances of class B fire occurring [15].

- Class C- Flammable gases

These type of fires involves various flammable gases such as hydrogen, butane and propane. The gases are highly volatile and pose a major fire and explosion risk, and therefore require secure storage in sealed containers such as gas cylinders. The concentration of flammable gases in the air will dictate the potential fire hazard and even small or isolated leaks of these gases can lead to quick ignition if an open flame or igniter is introduced [15].

- Class D- Flammable metal objects

Metal based fires are not highly common as all metals are not flammable. These kinds of fires are characterized by the presence of burning metals. The main risks for class D fires is smaller deposits of metal such as shavings or powders. Combustible metals include potassium, magnesium, calcium titanium and lithium [15].

- Class E- Electrical fires

These are type of fires caused by electrical equipment in a form of faulty wiring, broken electrical appliances, frayed cables, overloading sockets and short circuits. The fires can be very common with potential hazards present in virtually every commercial or industrial setting [15].

- Class F- Cooking oils, fats and vegetable oils

These kinds of fires are more common in restaurants and commercial kitchens. They involve fat, oil or grease cooking at extremely high temperatures. Most often, they occur when pans containing oils are left unattended [15].

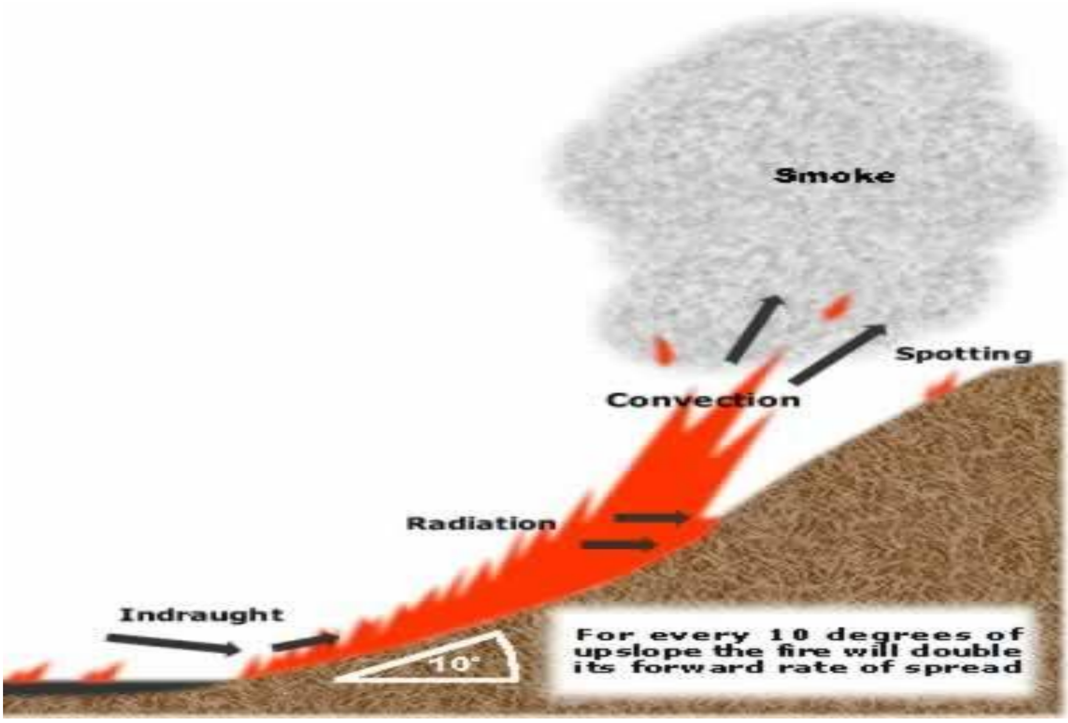


Figure2-3: How firestorms form [15]

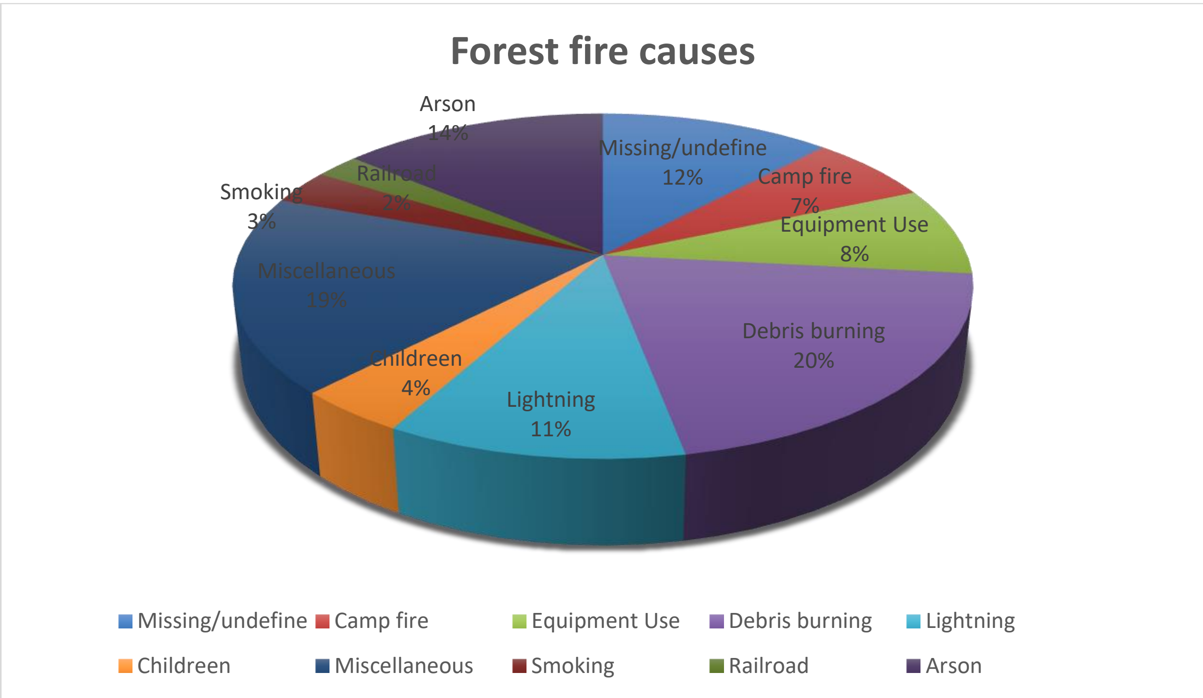


Figure2-4: Top 10 causes of forest fires [13]

2.3 Lightning

Lightning has been reported to be the cause of most of natural fires. This happens where little or no rain accompanies a stormy weather disturbance. Lightning randomly strikes the earth an average of 100 times each second or three billion times every year and has caused some of the most notable wildland fire disasters in the western United States. Table 2-1 gives the number and percentages of fires ignited by lightning at various times throughout the day. This is from a study to investigate how lightning cause fires in Canada [16]. From the Table 2-1 it can be seen that that 70% of the lightning fires were started between 12:00 noon and 22:00 in the evening, 84% started between 06:00 in the morning and 22:00 in the evening [16].

Table 2-1: Ignition time of lightning fires [16]

Time (hrs.)	Number of fires	Percentage (%)
00:31 – 04:30	311	10.2
04:31 – 08:30	205	6.6
08:31 – 12:30	304	9.8
12:31 – 16:30	1029	33.4
16:31 – 20:30	819	26.4
20:31 – 00:30	415	13.5

The Coastal regions of South Africa do not experience high lightning activities compared to the Central and Northern regions. Most of the identified problematic lines fall within lightning incidence areas. Figure 2-5 shows the lightning ground flash density maps of South Africa. It is notable that there are Eskom Transmission Network running through these regions with high lightning density and if there is wildfire due to lightning they are affected [16].

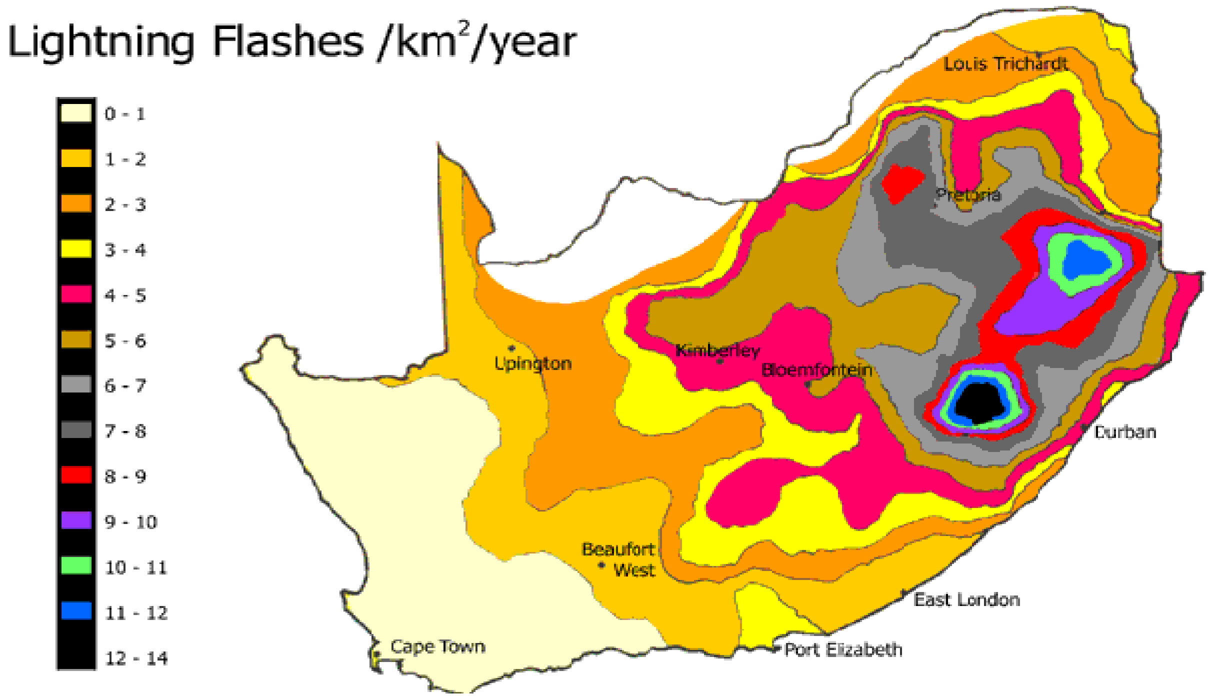


Figure 2-5: Lightning map of South Africa [16]

2.4 Relative humidity

Moisture in the form of water vapor is always present in the atmosphere. The amount of moisture that is in the atmosphere affects the amount of moisture that is in the fuel. Relative humidity is the term used in prescribed burning to express the amount of moisture in the atmosphere. It is the ration of actual water vapor in the atmosphere compared to the amount of water vapor that would saturate the atmosphere at that temperature. When the relative humidity is 40%, it means that the atmosphere contains 40% of the moisture that it could contain at the same temperature [10].

The lower the relative humidity, the more readily a fire will start and burn. Moisture in the fuel absorbs heat and reduces the fire’s intensity before it is converted to steam and driven off. Relative humidity fluctuates widely during each 24-hour period. It will generally be the highest in the early morning hours before daylight and the lowest during the early afternoon. This is called the diurnal cycle. This is because relative humidity changes with temperature. When air is warmed, it expands and as a result, will hold more moisture. As temperature changes, relative humidity changes but in the opposite direction. As temperature goes up, relative humidity goes down and vice versa [10].

2.5 The effect of wind

Wind has a strong effect on the fire behavior due to fanning effect on the fire. Wind can change direction and intensity throughout the day as shown in Figure 2-6. This change can be very abrupt surprising the burner that is not alert. Abrupt changes generally occur during the afternoon when atmospheric conditions are most unstable. Wind is important to the prescribed burners fire fighter because of three influences it has on fire behavior:

- Supply oxygen for combustion process
- Reduce fuel moisture by increasing evaporation
- Exerts pressure to physically move the fire and heat produced

Wind increases the supply of oxygen, which then results in the fire burning more rapidly. It also removes the surface fuel moisture, which increases the drying of the fuel. Air pressure will push flames, sparks and firebrands into new fuel. By pushing the flames closer to the fuel in front of the fire, the fuel is preheated quicker because of the increased radiant heat. More of the fuel is then available for combustion since it is dryer and can reach ignition temperature quicker [10].

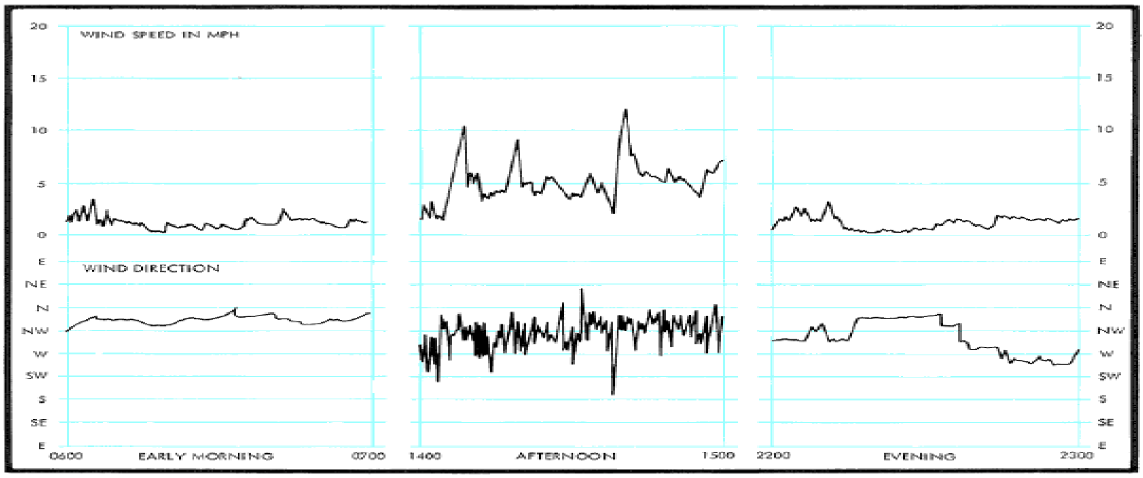


Figure 2-6: Wind speed throughout the day [10]

Wind changes the speed, direction of fire which can then influence the intensity of the fire. High winds will cause the head of a fire to move rapidly, cause the wind to crown into the top of trees and jump barriers as shown if Figure 2-7. This then makes it easier for the fire to reach overhead conductor and insulators damaging them. Wind also influences prescribed fire smoke dispersal which will the contaminate insulators and cause them to flashover.

Effect of wind on vegetation

- Fire is more intense at edge of openings
- Friction slows down speed next to the surface
- Causes turbulence and eddies
- Increases evaporation by blowing away the moist air next to fuel

Wind as little as 10 mph can cause rapid fire progression in a structure [10].

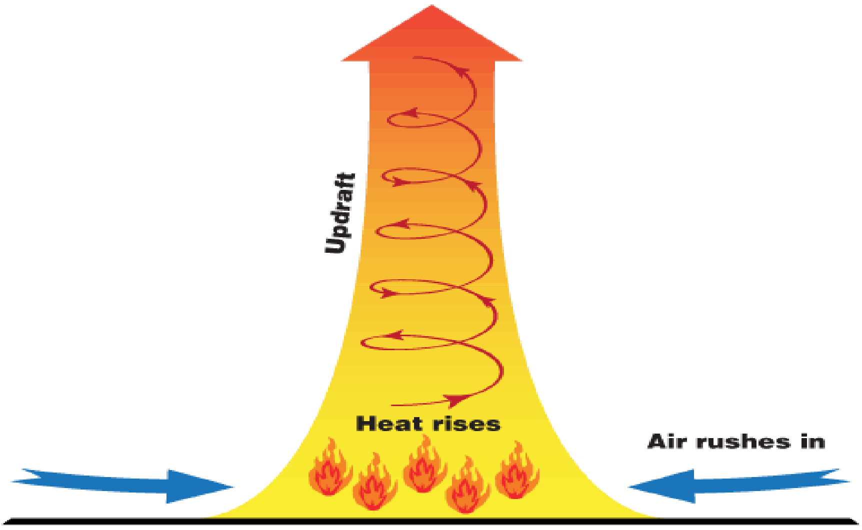


Figure 2-7: Formation of firestorms due to wind [10]

2.6 Temperature

Air temperature has direct influence on fire behavior because of the heat requirements for ignition and continuing the combustion process. Heat from the sun is transferred to earth by radiation. This heat warms up the surface of the earth and the atmosphere close to the surface is in turn warmed by heat reflecting from the surface. This is the reason that the temperature above the surface is cooler than at the surface of the earth [10].

Forest fuels receive heat by radiation from the sun. As a result, less heat is required for ignition. The differential heating of the earth surface is the driving force behind most of the influences on the atmosphere. The sun emits short wave energy rays known as radiation. When striking a solid object such as trees or grass, the object get warmed. The surface absorbs some of the heat and reflects some in long-wave radiation that is absorbed by the water vapor in the air, thus raising its temperature as well [10].

Temperature is the most important weather factor affecting fire behavior. Temperature affects relative humidity. Fuel temperatures also affect fire's rate of spread. Warm fuels burn faster because less heat energy is used to raise the fuels to their ignition temperature. Fuels exposed to sunlight will be warmer than the fuels in shade, also drier. Hence, fuels not shaded by an overstory will generally be warmer and drier resulting in a more intense fire. Fires also burn more intensely in the afternoon when the temperature is the highest resulting in higher fuel temperatures [10].

2.7 Stability of the atmosphere

Atmospheric stability is the air's tendency to resist vertical movement. If the atmosphere is unstable, vertical movement of air is encouraged and this tends to increase fire activity. Parcels of air masses with different temperatures are continually mixing trying to reach the same temperature. The more the temperature difference in the atmosphere, the more unstable the conditions and the more movement both horizontally and vertically. Fire will burn more intensely because of the unrestricted updraft of the atmosphere and convective currents as shown in Figure 2-8. However, under stable conditions, fires burn slowly and the smoke column doesn't rise very far. It is of note that the earth's surface is not heated uniformly by the sun, as a result the conditions are unstable [10].

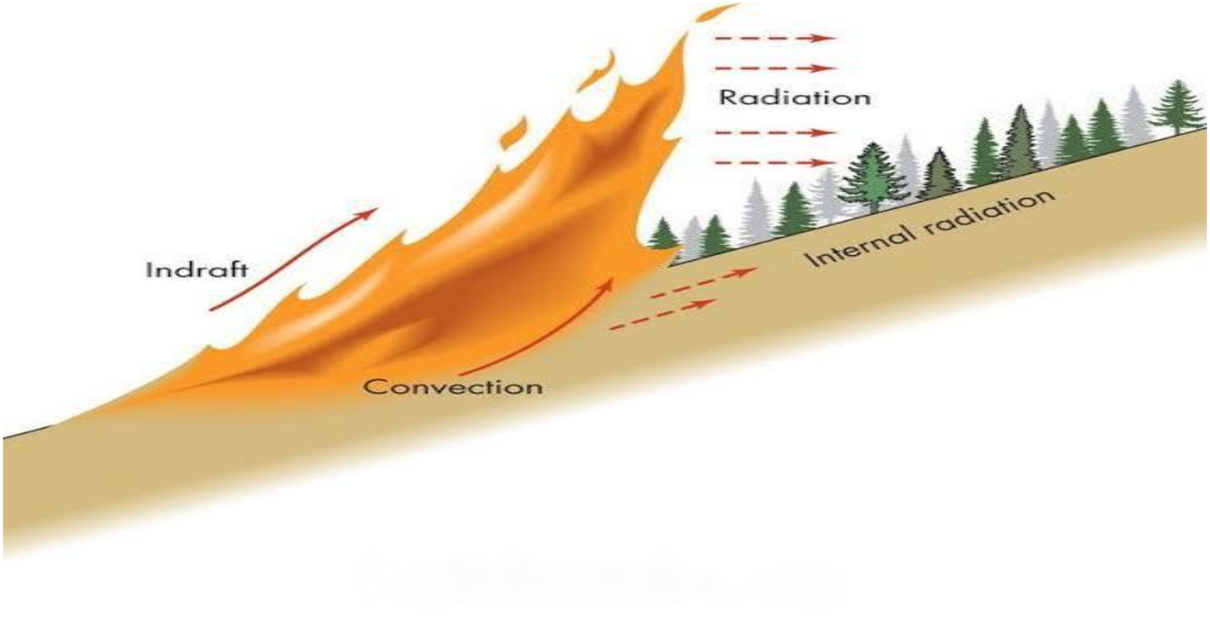


Figure 2-8: Wild fires on slopes [10]

2.8 Precipitation

Precipitation (rain or snow) has a direct and immediate effect on fuel moisture and relative humidity. Temperature usually drops as well and the winds become calm. When the atmosphere becomes saturated, precipitation usually occurs if more moisture is added. Precipitation will quickly dampen the surface of fuels to the point that fires cannot ignite and no wildfires will occur [10].

The patterns of rainfall is a big factor in determining the fire season. In the Southern Africa, fire season starts in fall and generally slacks off during December and possibly January, as the climate turns cold, with rains, calm winds and overcast skies. In the Southern Africa, the last two weeks of February and the first two weeks of March are suitable for late dormant season burns. As the rains lessen in the early spring and the winds increase, the fire season is again high until late April. As the vegetation grows and greens up, prescribed burning conditions may deteriorate. However, if a winter drought occurs and continues into spring, fires will readily burn on into the summer because of large amount of dry fuel and low fuel moisture. These fires may be difficult to control and do more damage due to burning deeper into the litter and consuming larger fuel size [10].

2.9 The 24-hour cycle (or the Diurnal cycle)

Early afternoon is generally the peak burning period when fires will burn most intensely, spread most rapidly and tend to exhibit erratic fire behavior. This is because all of the weather elements are at the point where their influence on fire behavior is the greatest [10].

- Temperature is the highest
- Wind direction is most variable
- Fuel will be the driest

- Relative humidity is at its lowest point
- The atmosphere is the most unstable
- Wind speed is at its maximum

Radiation from the sun is at its maximum when the sun is directly overhead. Because of a delay in its effect, the peak of the burning period is generally around 13:00 to 14:00 in the afternoon depending on latitude and daylight savings time [10].

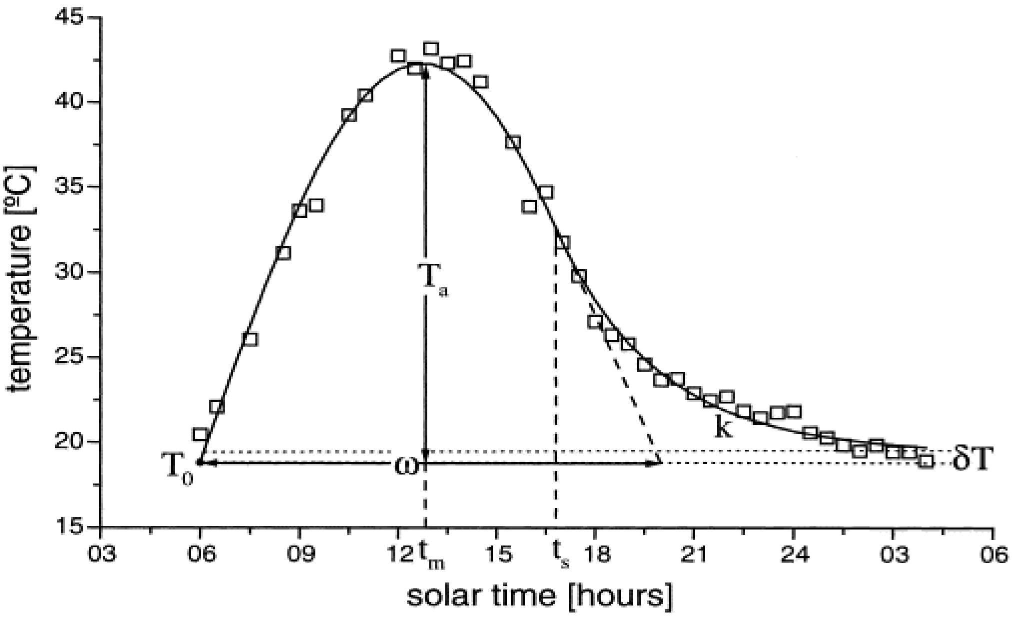


Figure 2-9: The Diurnal cycle at different hours of the day [10]

2.10 How forest fire causes outages of transmission lines

It has been reported that forest/veld fires near or under overhead power lines are a serious threat to the safe and reliable operation of power grids. The gap breakdown in forest fire relates to many factors such as flame the flame conductivity, temperature and particles. During veld fires, a large amount of smoke with carbon and ash are produced during the combustion of vegetation. This then causes the dielectric strength of the air gaps to decrease drastically; as a result, the breakdown voltage is decreased with the rising of the flame conductivity [16].

In South Africa especially the northern coastal region of KwaZulu-Natal and in Mpumalanga where sugar cane farming is a major agricultural activity, farmers burn the sugar cane as a harvesting aid thus causing line failures. Same problems have been reported in other countries such as Mexico, Brazil and Canada, where agricultural fires were resulting in transmission line failures. These failures have led to authors such as Lanoie and Mercure [6] in Canada, Robledo-Martinez et al in Mexico and Sadurski and Reynders [3], Cowan *et al* [7] in South Africa to carry out studies to understand or rather investigate the effect of fire on the reduction of the insulation strength of air thus the effect on the power line performance.

Studies shows that the presence of fire under transmission power lines reduces the dielectric strength of the air around conductors and insulators. This causes breakdown occurring at a value lower than it normally would under standard temperature conditions. A tall fire column is necessary to produce hot ionized gases (discussed in the later chapters) sufficiently close to the conductors to cause flashovers.

The majority of the fire-induced flashovers occur at mid-span. Past experience has proved that it is not necessarily just long grass that can cause a flashover when it burns underneath or near a power transmission line but the probability at flashover also depends on various factors including [17]:

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

The above mentioned factors can influence the probability of a line to ground flashover. As said earlier that the air density between the conductors and the ground changes as a result of veld fires [17]. Over the past year's Eskom has experienced problem such as flashover voltages that are due to veld and sugar cane fires under transmission lines ranging from 66 to 400 kV. Annually Eskom records almost 3000 to 6000 fires near the transmission lines with a rate of 100 to 150 of fire-induced flashovers per annum [3]. Previous research by Eskom has shown that fire under transmission lines produces enough ionized air to cause about 20% of the total number of flashovers [17].

2.11 Conclusion

Extreme weather conditions, or conditions favorable to the ignition and spread of wildfire, are driven by three factors: wind speed, relative humidity, and fuel moisture. When wind speed is high, relative humidity is low, and fuel moisture content is low, weather conditions are considered to be extreme. Low humidity and fuel moisture content increase the flammability of fuel sources. High wind speeds can affect both the intensity and extent of a wildfire by providing oxygen to, and on the other hand acting to spread a fire. The extreme weather percentile rankings are based on the number of days during the fire season that a site experiences extreme weather conditions.

Chapter 3- Line Configuration factors

3.1 Transmission Lines

The purpose of a transmission line towers is to support conductors carrying electrical power and one or two conductors at suitable distances above ground level and from each other. The construction of the transmission line including the type of voltage, voltage level, phase-to-phase and phase-to-earth clearances, type of conductors and type of insulators plays an important role in any flashover mechanism occurring on the system. The Eskom transmission network is spread across South Africa for them to be able to deliver power to customers at the agreed quality [17]. Table 3-1 below gives an indication of the total length of in service lines per category.

Table 3-1: Eskom transmission line length per voltage level [17]

Voltage rating (kV)	Length (km)
765	870
533 (DC monopolar)	1035
400	15187
275	7409
220	1239

Table 3-1 shows that the longest lines are 400 kV system followed by 275 kV system. Moreover, there are relatively lines with short length at other voltages which are not particularly problematic. The configuration of a transmission line tower depends on the following factors [17]:

- The length of the insulator assembly
- The location of ground wires with respect to the outermost conductor
- The mid-span clearance required
- The minimum clearance of the lowest conductor above ground level.
- The minimum clearances to be maintained between conductors and the tower

3.1.1 Minimum conductor clearance

Transmission lines are designed to conform to the electrical clearances recommended by statutory laws. Figure 3-1 illustrates the effects of conductor sag, due to the conductor material elongation, from various factors, on the minimum required conductor to ground clearance. Apart from thermal elongation, a transmission line sags due to the conductor weight or force exerted, the tension, and wind or ice loading. The maximum sag is calculated to ensure that clearance to ground and to other conductors is maintained at the different loading conditions. The final sag, resulting from operating the conductor at its maximum temperatures, determines the minimum electrical clearance to ground and conductor blowout to minimize electromagnetic field exposure to the public in the vicinity of the power line [20].

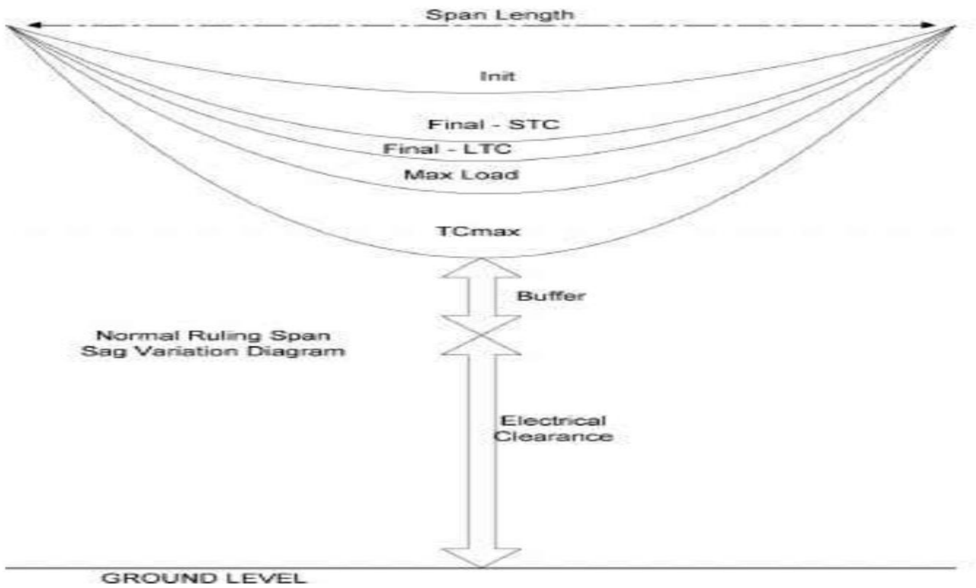


Figure 3-1: Factors affecting the sag characteristics of conductors [26]

3.1.2 Conductor to ground distance

In case of any disturbance on the mid-span of overhead ground wires, the critical condition occurs at the mid-span during the propagation of surge current and mid-span flashover may occur from ground wire to conductor, before the current is discharged through the tower. In this case, the flashover may be due to the ionization of gases, which will then create a path between the conductor to the ground. The mid-span clearance between the earth wires and the conductor is therefore, kept more than the clearance at the tower. The usual practice in this regard is to maintain the sag of ground wire at least 10% less than that of the conductor, under all temperatures conditions in still wind at the normal spans, so as to give a mid-span separation greater than that at the supports [20].

During a disturbance in the mid-span, on one of the ground wires, when two ground wires are used, it is preferable if the disturbed ground wires flashes over to the second ground wire instead of the conductor. The mid-span clearance may vary with the span length. Increased spans increases the mid-span clearance [20]. Table 3-2 shows the design span adopted [20].

Table 3-2: Minimum clearance at different voltage levels [20]

Nominal system voltage U_n (kV)	Minimum phase to earth clearance (m)
66	0.8
132	1.5
220	1.9
275	2.4
400	3.2
765	5.5
533 (DC)	3.7

The minimum conductor to ground clearance at mid-span (D) can be determined by:

$$D = D_{basic} + D_{el} + D_{sag} \quad (3.1)$$

Where : D_{basic} is the basic clearance

D_{el} is the electric distance required

D_{sag} additional clearance to compensate the increase of conductor sag due to the increase of temperature.

3.1.2 Spacing of conductors

The spacing of conductors is determined by taking into account mechanical and electrical parameters. The material and diameter of the conductors should also be considered when deciding the spacing. Usually, conductors will swing synchronously (in phase) with the wind but with long spans and small wires there's always a possibility of the conductor swinging non-synchronously and the conductor and the maximum sag at the center of the span are factors taken into account in determining the distance apart at which they are strung [20]. Table 3-3 shows the minimum clearances safe for conductor spacing [20].

Table 3-3: Standard clearances for safe access and conductor spacing [17], [20]

Nominal system voltage (kV)	Minimum height of live parts above fixed accessible surfaces (m)	Minimum busbar clearance height (m)	Minimum vertical work safe by clearance (m)	Minimum horizontal work safety clearance (m)
66	3,07	4,07	3,07	4,43
110	3,54	4,54	3,54	4,90
220	4,54	5,54	4,54	5,90
275	4,54	5,54	4,54	5,90
400	5,84	6,84	5,84	7,20
765	6,32	7,45	6,32	7,80

3.1.3 Maximum sag of lower conductor

Sag and tension of a conductor is determined by the size and type of conductor, climatic conditions of the region and the span length. The maximum sag for conductor span occurs at the maximum temperature and still wind conditions. The maximum value of sag is taken into consideration in fixing the overall height of the steel tower structure. In cases where transmission line are prone to snowfall, the maximum sag may occur at 0^0 with the conductor loaded with ice. The maximum working tension under stringent loading condition shall not exceed 50% of the ultimate tensile strength of the conductor. Therefore, sag-tension computation made for final stringing must ensure that factor of safety of 2 and 4 is obtainable under respective loading condition [20].

3.1.4 Height and location of ground wire

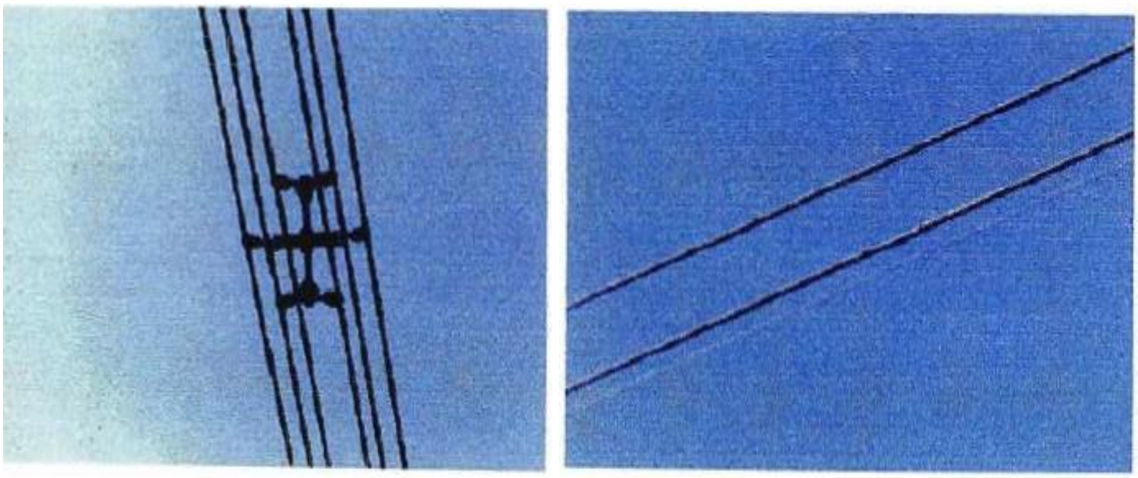
Ground wire provides protection against direct lightning stroke. In intercepts, the direct lightning stokes and conducts the charge to the nearest ground connections. For the case of this study, the ionized air create a path for current flow between the phase wire and the ground wire, thus creating a short circuit which results in breakers tripping and causing a power outage. The height and location of overhead ground wires shall be such that the line joining the ground wire to the outer most conductor shall make angles of approximately 20 to 30 degrees with the vertical, this angle is called the shield angle. On extra high voltage lines wide conductor spacing, the use of two earth wires provides better protection. Table 3-4 indicates the shield angle for different voltage levels [19]. For voltages exceeding 230 kV, the shielding angle often controls the required vertical and horizontal separation between the ground wire and conductor [21]

Table 3-4: Shielding angles for different voltage angles [19], [21]

Nominal system voltage (kV)	Shielding Angle (^{0})
66	30
110	30
220	25 to 30
275	25 to 30
400	20
765	10 to 12
533 (DC)	15

3.1.5 Types of conductors

Overhead power lines suspended by towers uses various types of conductors. These include Aluminum Alloy conductors which are divided into different types such as All Aluminum Conductor (ACC), Aluminum Conductor Steel Reinforced (ACSR), Aluminum Conductor Aluminum-Alloy Reinforced (ACAR) and bundle conductors. The most common used conductors are the ACC and ACSR which both has different properties [23], [24]. The Eskom transmission system uses different conductor types depending on the voltage application.



(a) (b)

Figure 3-2: Hexagonal Bundle Conductor (a) and Twin bundle conductor (b) [taken by author]

3.1.6 Insulators

3.1.6.1 Types of insulators

The standards and regulations indicate that the insulators utilized in the overhead electrical lines can be made of porcelain, glass or another material of adequate characteristics to their function. The most used insulators until some years ago were manufactured with porcelain, glass or soapstone. Due to their dielectric characteristics and their facility of casting, all the insulators have been manufactured for many years with these materials. However composed materials do a hard competence to the traditional one [26].

Porcelain is constituted essentially with kaolin and quartz of first quality. The insulators are cooked to 1400 ºC and later they are covered with a layer of enamel of silicate, boil subsequently to obtain a glazed in hot, doing them waterproofs and slippery, complicating in this way the adhesion of humidity and dust. Glass is manufactured melting to temperatures among 1300 ºC and 1400 ºC, a mixture of salicylic acid with oxides of calcium, sodium, barium, and aluminium. The glass used in the insulators is a calcium glass alkaline, obtained by a special procedure by mean of abrupt cooling off through a cold air current during the process of fusion. In this way, a hard glass is obtained, of high mechanical resistance and with good stability for the changes of temperature [26].

Related to compose materials, the families of polymeric material more usual are rubber or rubber of silicone and propylene ethylene rubbers (generally EPDM). Several components are added to these materials to improve their properties [26].

The main dielectric material used in outdoor insulation is air, as it is self-restoring. However, there is a need to support the conductor carrying the high voltage under various often strenuous environmental conditions. This is the role of the outdoor insulator and is critical for the performance of the transmission and distribution systems. Outdoor insulators should have the following properties:

- High dielectric strength
- Mechanically strong
- High insulation resistance
- High puncture resistance
- Non-porous
- No internal impurities

An outdoor insulator needs to be able to insulate under power frequency conditions and be able to hold the required mechanical load over time. The type of material used for outdoor insulator is important as the material should not only have high dielectric strength but should be capable of performing under severe environmental conditions, in the case of this study the focus is on the effect of forest fires and pollution contamination as a result of forest fires over a long period of time. Outdoor insulators are broadly categorised into ceramic (porcelain and glass) and non-ceramic (polymeric) insulators, they all react differently when exposed to different environmental conditions [25], [27], [28].

The most common type of insulators used on the transmission system in South Africa is glass discs insulators. 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, for 533 kV/mm lines it is between 23 and 27 mm/kV and for 765 kV it ranges from 16-31 mm/kV depending on the pollution site severity. Anti-fog insulators are installed in limited areas. In areas where pollution is present, such as industrial or marine pollution, it has become the practice to install composite insulators [31].

Composite insulators can take wind and rain, and have a good self-cleaning performance under wind and rain, so need checking for pollution only once every 4 to 5 years, and require less time for the maintenance. Since the core and rod has higher extension strength, composite insulators can result in very light overall weight [29]. Composite insulators consist of at least two insulating material, one for providing electrical properties and the other proving mechanical properties [30].

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 1980s a large number of non-ceramic insulators have been installed on the Eskom system [31].

During burning, the particles produced such as ash and soot pollute the insulators. Although the impact of the pollution is not during the burning period but in the long run the insulator will flashover as a result of the pollution from burning. Section 3.1.6.2 describes the flashover mechanism due to pollution [25].

3.1.6.2 Pollution flashover mechanism

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

STEP 1: Pollution is deposited on the insulator surface. Previous research has shown that the most important mechanism of pollution deposit is through the movement of air. Most common types of pollution are bird pollution, marine pollution (salt), agricultural pollution, industrial pollution and as a result of particles deposited from burning (which is the key focus of this study). The solid layer deposit generally consists of a soluble component and non-soluble component [25].

STEP 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, these electrolyte will have a conductivity dependant on the type of soluble deposit and its concentration [25].

STEP 3: Once the insulator is covered with the electrolyte layer, current will then start to flow across the insulator surface. Due to the corresponding Joule heating losses in the electrolyte layer the water will evaporate in some areas (high current density areas) creating dry bands. Under these conditions the electric field distribution of the insulator is highly interrupted (most of the voltage appearing across the dry bands) and normally the dry bands will spark over [25].

STEP 4: If the conductivity of the wet surface layer is high enough the dry bands arcs may develop into a flashover of the insulator [25].

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 reabsorption 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 [22], [23], [24].

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 [25]. 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 [32].

The various phases are 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. This is because 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 [32].

The extent to which the DC line attracts more contamination than the AC line may be understood by observing Figure 3-3 below that 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 reaching a saturation' point of approximately 0.12 mg/cm point, both systems will contain equal amounts of contamination [32]. This is also tabulated in Table 3-5.

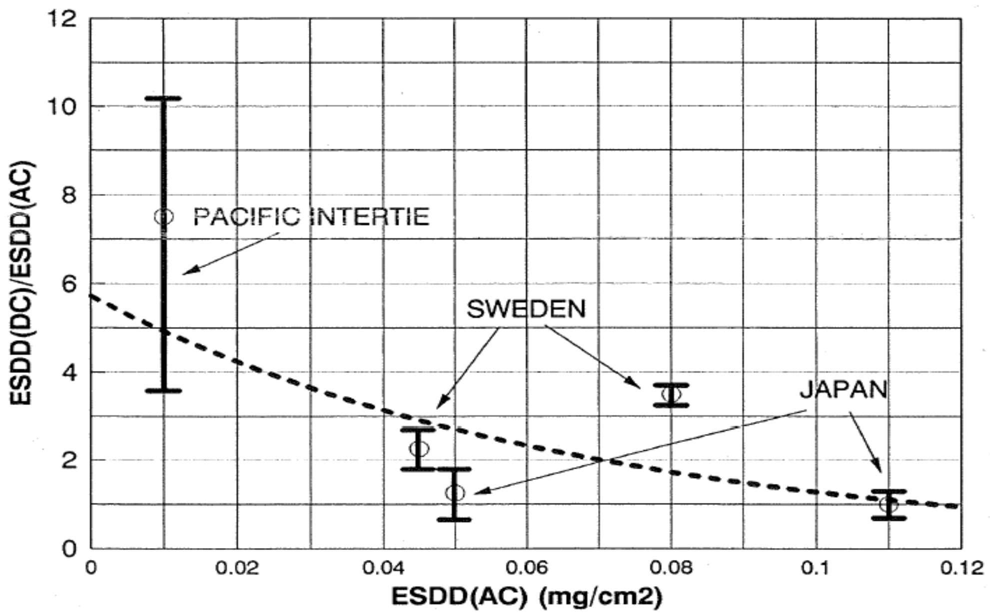


Figure 3-3: Ratio of ESDD collected on insulators under DC and AC voltages [32]

3.1.6.3 The contamination of insulators due to burning

Outdoor insulators are being subjected to various operating conditions and environments. Contamination on the surface of the insulators enhances the chances of flashover. Under dry conditions the contaminated surfaces do not conduct, and thus contamination is of little importance in dry periods. In cases when there is light rain, fog or dew, the contamination on the surface dissolves. This promotes a conducting layer on the surface of the insulator and the line voltage initiates the leakage current. High current density near the electrodes results in the heating and drying of the pollution layer. An arc is initiated if the voltage stress across the dry band exceeds the withstand capability. The extension of the arc across the insulator ultimately results in flashover. The contamination severity determines the frequency and intensity of arcing and thus the probability of flashover [18]. Figure 3-4 shows the picture of a contaminated silicone rubber insulator. It can be seen that the pollution level is high enough for causing a change in the natural colour of the insulator.

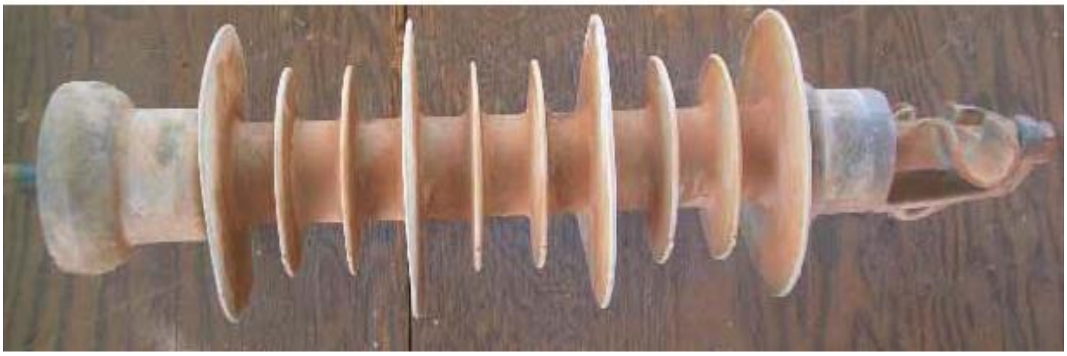


Figure 3-4: A picture of a contaminated insulator [18]

During burning, the air gets heated up which creates air turbulence with strong winds and formation of whirls with a great number of particles carried by air such as dust, soot, and debris that deposit on the insulators surface. Sugar cane fields are frequently manured with a by-product obtained from the fermentation of the sugar cane syrup that could increase the conductivity of the local earth and consequently of the dust carried by air [18]. Table 3-5 shows the equivalent salt deposit ESDD of several insulators units taken from chains coming from sugar cane culture regions.

Table 3-5: ESDD values of some insulators from regions with sugar cane culture [18]

Type of Insulators	ESDD (mg/cm)			Pollution
	Top	Bottom	Average	
TL 138kV CESP	0,0070 0,0034	0,0070 0,0035	0,0070 0,0036	Very light
TL 138kV CPFL1	0,0014 0,0025	0,0035 0,0053	0,0176 0,0144	Not significant
TL 138kV CPFL2	0,0016 0,0012	0,0105 0,0030	0,0070 0,0022	Not significant
Furnas substi.	0,0016 0,0012	0,0135 0,0061	0,0112 0,0056	Not significant
Furnas substi.	0,017	0,085	0,057	Average
TL 230kV CHESF	0,0200 0,0200	0,1500 0,0900	0,0900 0,0600	Average
TL 400kV CESP	0,0070 0,0034	0,0070 0,0035	0,0070 0,0036	Average
TL 500kV CESP	0,0100 0,0080	0,0400 0,0300	0,0300 0,0200	Light

Figure 3-5: A picture of a flashing over insulator [18]

3.1.6.4 Flashover mechanism of insulators

During wet atmospheric conditions like light rain or fog the contamination layer on the surface of the insulator gets wet and promotes leakage current flow along the surface. The heat dissipated due to the flow of leakage current evaporates the moisture on the surface of the insulator. This evaporation leads to the formation of areas termed as “dry bands.” Dry bands tend to form near the surface of the insulator parts where the diameter is the smallest, because of the high current density in those parts. A concentration of voltage stress is formed around the dry bands as the surface resistance of the dry bands is much higher than the conductive contaminated surface film. Subsequently the dry band will break down causing an initial partial arc over the surface. After the formation of a partial arc the propagation of the arc further depends on if $E_p > E_{arc}$, that is the arc will propagate if the voltage gradient ahead of the arc, which is the voltage gradient of the pollution layer, is greater than that of arc gradient. This is due to the fact that ionization of the path ahead of the arc by the increasing current at every instant enables the arc to proceed. When the arc propagation across the contaminated layer bridges the whole insulator a flashover will occur. The flashover triggers a power arc that results in the interruption of power supply and may damage the insulator temporarily or permanently, depending on the severity of flashover [33-36].

3.1.7 Types of towers in use

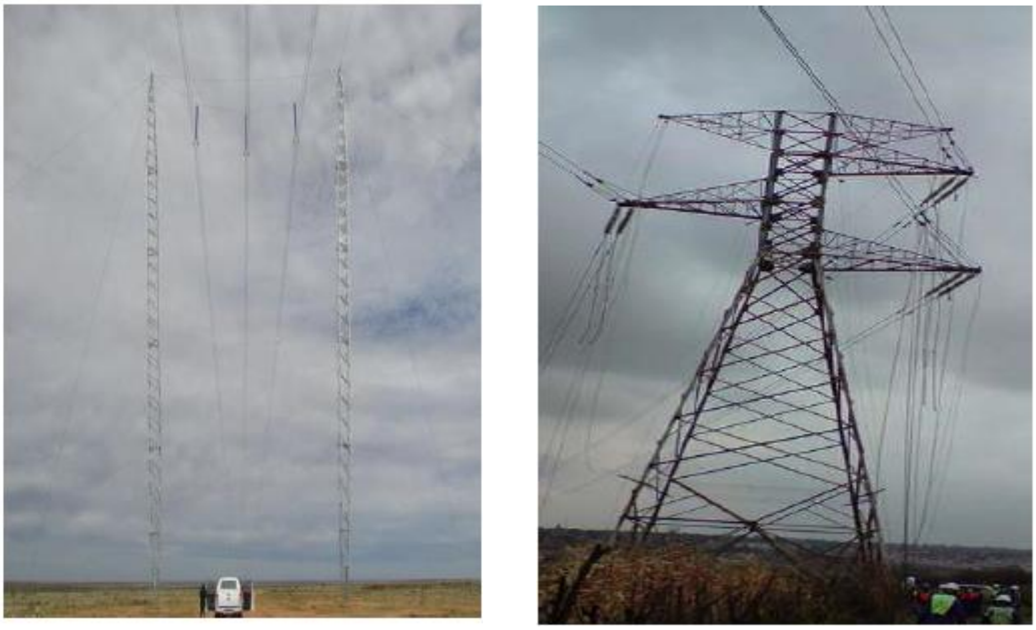
There are four types of towers in use by Eskom transmission, which are; the Self-supporting strain, Compact cross-rope suspension, Delta structures and Guyed-Vee. However, the most commonly used structure is the Guyed due to the following reasons [37]:

- Less expensive

- Easy to transport and install.
- Easier production and logistics
- They have a good overall stability and can withstand large axial pressure.

(a) (b)

Figure 3-6: Self-supporting tower(a) and Guyed-Vee tower (b) [37]



(c) (d)

Figure 3-7: Cross rope suspension tower (c) and Delta structure tower [37]

3.2 Electrical discharge in air

Air serves as an insulating medium in the power system industry. It has two major advantages which are; Occurring in abundance and the self-restoring capability after a breakdown [31]. Impact ionization is the most important process in air discharge. Electrodes at high voltage in a gaseous medium induces an electric field that causes free electrons to accelerate to the anode. During the migration process, they collide with neutral air molecules causing excitation of gas atoms and ionization of floating particles. There are a number of collisions that occur between the free electrons and air molecules along the mean free path in the direction of the electric field [31].

The energy imparted during the collision is large enough to force out an orbiting electron, thus causing a positive ion to be produced and left behind, while the new electrons together with the original electrons proceed along the field and the collision process progressively continues to happen. The effectiveness of ionization depends upon the energy that charged particles gain as they accelerate under the effect of the electric field. In an electric field, the head of an avalanche is built up of electrons while the tail is clouded with positive ions as shown in Figure 3-8. This happens because electrons have higher velocities than the positive ions that might appear virtually at standstill in the time an electron takes time to reach the positive pole [38]. Previous research [17-19] has concluded that the mobility of ions in the drift zone is independent of the field strength when the velocity due to the field is considerably less than the average thermal velocity of air.

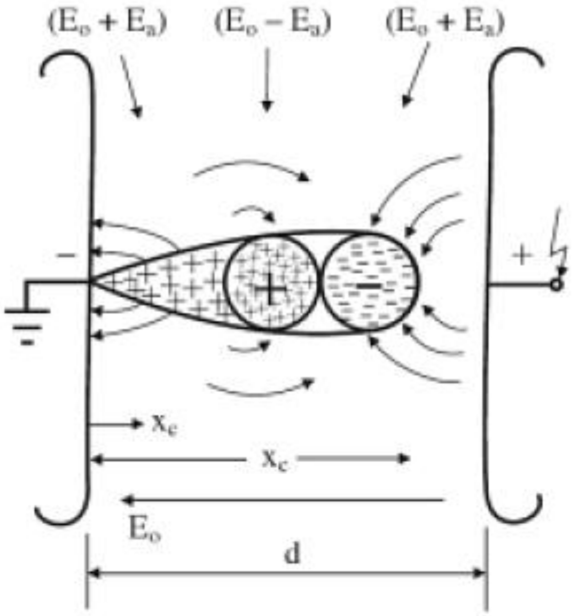


Figure 3-8: Development of an electron avalanche in a uniform electric field [38]

Partial discharge may occur under non-uniform field [39]. Non-uniform fields like in point-plane, point-point, sphere-plane gaps or in coaxial cylinders, the field strength and the effective ionization coefficient vary across the gap. For a streamer to be initiated at the high voltage electrode and for it to bridge, the two conditions have to be satisfied; one for the streamer inception and the other for streamer propagation [40].

If the field is non-uniform, an increase in voltage will first cause a discharge in the in the gas to appear at points with highest electric field intensity, which are sharp points or where electrodes are curved or on transmission lines. This form of discharge is called corona discharge and can be observed with a bluish luminescence. This phenomenon is always accompanied by a hissing noise, and the air surrounding the corona region becomes converted into ozone. Corona is responsible for considerable loss of power from high voltage transmission lines, and it leads to the deterioration of insulation due to the combined action of the bombardment of ions and of the chemical compounds formed during discharges.

3.2.1 The streamer mechanism applied to high temperatures

Climatic parameters (air pressure, air temperature, solar radiation and precipitation) influence electrical discharge in air, which results in a dependence of the breakdown voltage on these parameters. The focus of this section seeks to elaborate the influence of temperature on the streamer breakdown in air, pressure and humidity. To incorporate the influence of temperature on the breakdown mechanism, it is convenient to introduce the 'relative gas density', δ which is a dimensionless quantity. This quantity takes care of the effect of temperature on the mean free path of electrons in the gas at constant pressure and expressed as [42]:

$$\delta = \frac{\rho}{760}\frac{293}{273+T} = 0.386\frac{\rho}{273+T} \tag{3.1}$$

Where: ρ is the gas pressure in Torr

T is the Temperature in 0C

Temperature influences the electrical discharge in air by means of the motion of the particles [42]. As the temperature in the air gap is increased, the mean free path of the particles also increases linearly with the corresponding increase in temperature. The electron and ion concentrations in the air gap rise with the result that the distortion of the electric field by the field of the space charge of positive ions increases [41].

3.3 Types of faults caused by fires

It is worth mentioning that, there have been so many cases of failure as a result of veld fire in proximity with high voltage power line conductors [3], [5], [9. Hence, it is said that smoke, which could be likened to a fault on the power line, creates a path between the live high voltage conductor and the earth conductor (phase-to-phase and phase-to-ground fault), which in turn causes a short circuit between the two conductors. Consequent to this abnormal situation, it ends up damaging the overhead wires and causing failures, which end up interrupting the flow of power [7].

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 [17].

3.4 Corona and fires

As the induced noise is a function of corona activity, the generation of fire-induced corona noise is dependent on the generation of corona. Corona is a phenomenon caused by the partial electrical breakdown or ionization of the air surrounding high voltage electrical conductor or fitting when energized, it occurs in both AC and DC [43]. If the conductor surface electric field becomes greater than the critical breakdown electric field for ionization to occur, ionization starts and results in the generation of streamers which in turn, if the high local field persists, results in corona formation [44].

The field around a conductor is dependent on many factors. The most significant factors are firstly, the applied voltage, and secondly the conductor and conductor bundle diameters. Increasing the applied voltage increases the local electric field. Reducing the diameter of the conductor or the overall bundle diameter whilst maintaining a constant applied voltage will also increase the electric field around the conductor or bundle of conductors [44].

These parameters are taken into account when transmission lines are designed for high voltage or transmission of large amount of power. For any particular operational line these parameters are constant. The additional parameters which change and cause an increase in the local electric field and hence an increase in the corona to above designed levels are those factors which change the air density and introduce high local fields due to near-point charges [44].

Atmospheric air is composed mainly of 78% nitrogen, 21% oxygen, 0.93% argon, 0.033% carbon dioxide, water vapor and other particles (such as dust and pollen). The electronegative nature of oxygen molecules sustains the corona discharge. Oxygen molecules easily capture free electrons and form negative ions, which aid the electron avalanche process. The avalanche process creates what is known as space charge that tends to move away from the source. Corona discharge is accompanied by audible noise, energy loss, visible light, radio interference noise, ionic current flow, mechanical vibrations and chemical reactions [44].

Fires introduce particles into the electric field. During veld fires there are elements formed such as carbon which also influence corona since carbon is a molecule with a low ionization potential. The particle becomes charged and forms part of high localized field. The breakdown voltage of air is directly proportional to the density of the atmospheric air present in between the power line conductors [44].

Humidity and dust (in the case of fire the dust particles include smoke, ashes and soot) increases the presence of particles in natural air, which causes the number of ions present around the conductor to increase. This further increases the space charge resulting in a lower on-set voltage [45].

Each particle and air density pocket contributes to the development of a higher local field and lower critical field respectively, with resulting growth in the streamers occurring and developing into corona regions. The further the corona regions develop, the smaller the gap becomes between the highly stressed conductors and either ground or the other phases. The result is a growing electric field at the head of the corona region and sufficient criteria for a self-sustaining passage of ionization until flashover occurs [46].

3.4.1 Fire a catalyst of corona and voltage breakdown

3.4.1.1 Flame temperature

Fire has the fundamental component of high temperatures. The temperatures of the sugar cane fires in the proximity of the conductors has been estimated to be in the region of 110°C to 250°C. Flame temperatures have been measured up to 800°C and 1200°C, but it appears that no accurate measurements have been made to date. In limited measurements made in this project with advanced thermal detecting visual equipment, temperatures greater than 162 C were recorded at the conductors in a genuine sugar cane plantation fire. Further temperature recordings should be made to capture more information about the actual temperatures under which corona is being generated at the conductors. It is however, not expected that the temperatures would be high enough for thermal ionization to play any major role in the corona process. The work done by K. Compton [47] showed that temperatures of over eight hundred degrees are required to reduce the breakdown strength of air by even a small amount with the assistance of thermal ionization.

3.4.1.2 Particles

The presence of carbon-based particles in sugar cane fires is another factor which will severely influence the electric field about the conductors. The distortions caused by conducting particles to electric fields are well understood [48]. In the proximity of the conductors the particles become dipoles, ionized by the electric field and becoming part of the field lines emanating from the high voltage conductors.

The increased local field due to the particle will start the process of ionization by electron impact, and provided the electric field is high enough, the gap between conductor and particle will be bridged with streamers then emanating from the particle. Should there be sufficient particles in the gap between electrodes, the bridging affect from conductor to particle to particle will finally result in the bridging of the entire gap.

The final bridge to flashover may not necessarily be a particle bridge but rather the increased electric field stresses across the reduced gap between the last particles (front of the leader) and the other electrode. More research is being carried out in this field to determine the process by which particles bridge the gap and the requirements for such a flashover to occur due to the sugar cane particles [49].

3.5 Conclusion

The above-mentioned factors influence the flashover mechanism. It is very important to understand the configuration of the transmission line to be able to understand how flashovers occur, and the factors influencing the flashover mechanism on a transmission line. The chapter also summarizes the type of faults that are caused by fires on a transmission line and the effect of corona discharge.

CHAPTER 4: Literature Review

The primary objective of this research study is to investigate the effect of fire on the flashover voltage of power lines or rather transmission lines and insulators. By doing so, we can be able to reduce the number of failures that are experienced by industries such as Eskom and Transnet as a result of veld fires on the power network. The approach taken in order to achieve all the objectives set for this study was firstly to perform an intensive study of existing literature related to the effect of fires on overhead electrical conductors and insulators. The intention behind the literature study is to review different literatures on the breakdown voltage of overhead power lines. Also, get an understanding on how different authors have conducted studies related to this dissertation. The fire particles that initiates the flashover mechanism is discussed in details, the effect of increased temperature as a result of fires which then affects the breakdown strength of air is also discussed in detailed, this includes thermal ionisation, combustion particles, dielectric strength and the flame conductivity theory.

The first investigations on the effect of fire under electrical transmission lines were published in the early 1970’s by different authors [4], [6], [9]. Industries such as Eskom (South African power utility) has experienced flashover problems caused by veld and sugar cane fires under voltage ranging from 132 to 400 kV transmission line [39]. In the Northern coastal region of KwaZulu-Natal where sugar cane farming is a major agricultural activity, farmers burn the sugar cane crops as a harvesting aid thus causing outages [4]. Similar problems have also been reported in other countries such as Mexico, Canada and Brazil [5], [9], [6].

As a result, various authors in South Africa such as Sukhnandan and Hoch [4], [15], Cowen *et al* [7], Sadurski and Reynders [3], Robledo-Martinez et al. in Mexico [9], Lanoie and Mercure in Canada [6] and Fonseca *et al.* in Brazil [5] have carried out studies to understand the effect of fire on the reduction of the performance of transmission lines. However, these have been conducted under AC voltages, except in [6] where studies were also conducted on a 450 kV experimental bipolar DC line and [40] where studies were conducted on a 60 kV DC voltage line [40].

Literature review conducted by Fonseca *et al.* [5] has shown that for AC transmission lines with rated voltages of up to 500 kV, the faults are said to be mainly due to conductor-to-ground short circuit at mid-span or phase-to-phase short circuit depending on the line configuration. The research work that ivestigates the performance of overhead transmission line under agricultural fires is of critical importance so there can be enough evidence to support that the occurrence of fires under transmission lines cause a number of power outages. This further need to be verified by comparing the result obtained and published by similar research works and should consider some other associated factors as well such as the amount of flame, the breakdown gradient, the pressure drop and other important factors that could cause a flashover [5].

Tian Wu *et al.* [40] investigated the insulation of wire-plane gap under fire conditions. The authors highlighted that the gap discharge under mountain fire conditions is affected by high temperatures, flame conductivity (electrons and ions) and large fire particles (smoke, and ash). They also studied the characteristics of leakage current in DC applied voltage of different vegetation flames and the effect of flame conductivity on wire-plane breakdown characteristics. The study concluded that the conductivity of three kinds of vegetation flame was quite high while the breakdown voltage decreased with the rise in flame conductivity [40].

In the literature [40] and [59] conducted similar investigations to study the dielectric characteristics under fire conditions but the test in [59] was performed under both AC and DC breakdown characteristics with the same objectives and three different typical vegetation. The authors of [59] also highlighted that the gap breakdown in forest fire relates to factors such as particles, flame temperature and conductivity. However, the studies don't tell how much smoke, flame temperature or rather particles can cause a flashover. The authors in [59] raised a very important point about the gap breakdown which has an evident effect of polarity characteristics under DC voltage, the breakdown voltage of positive polarity is said to be smaller than that of negative polarity. The study concluded that the AC breakdown voltage is lower than that of DC positive polarity under the same test conditions.

Studies in [60] found similar findings to [59] where tests were performed under both AC and DC voltages. The authors in [60] simulated the influence of forest fire particles on the breakdown characteristics of air gap using a conductor plane configuration. The experimental results of the literature shows that carbon were formed between flame and conductor by the action of electric field, which was also found in [59]. The gap's insulation strength was found to have decreased by about 40% of that of pure air under AC voltage, but for DC voltages, the breakdown voltage was reduced only by about 29% of that in the air gap under negative DC voltage. This shows that behavior of the gap breakdown is not the same under AC and DC applied voltages, hence a need to investigate this effect to understand which one behaves better.

The work done by Cowan [7] in 1991 with Eskom (South African power utility) was to establish the mechanism of insulation breakdown, the fault impedance and the extent of electromagnetic induced noise prior to flashover. The work was motivated from problems experienced on high voltage lines in the coastal region of Kwazulu-Natal where sugar cane burning is used for aiding harvesting. According to the authors, the flashover that would occur could potentially damage the transmission line equipment and as a result of large fault currents, severe voltage depressions would occur [7]. In investigating the mechanism of insulation breakdown, the authors of [7] documented empirical observations which showed that the following factors influenced the probability of flashovers for AC lines:

- The fire intensity and duration,
- The transmission line phase spacing (i.e the voltage gradient) and,
- The smoke density and ash particles.

The authors further noted that there are other environmental factors such as ambient temperature and humidity which had little influence. However, in this literature it was proven by laboratory tests that temperatures of 1100 ^{0}C reduced the dielectric strength of air from 2120 kV/m to 110 kV/m for small and uniform air gaps but for large and non-uniform gas experienced in practice, the temperature that could reduce the dielectric strength was not specified. For large and non-uniform gaps experienced in practice, the insulation breakdown was found to take place according to the streamer mechanism, rather than the classical Townsend mechanism thereby reducing the dielectric strength from the 110 kV/m stated above. Ash particles and smoke were observed to be assisting in the streamer breakdown thus reducing air dielectric strength even further. The study concluded that the phase-to-phase and phase-to-earth wire voltage gradient statistically predict where the flashover will occur [7].

The study drew a conclusion that the phase-to-phase and phase-to-earth wire voltage gradient statistically predict where the flashover will occur. Thus to ensure less severe voltage depressions, the phase-to-earth wire voltage gradient must be greater than the phase-to-phase voltage gradient [7].

It was reported that Eskom records 3000 to 6000 fires annually near high voltage transmission lines with a rate of 100 to 150 of fire-induced flashovers per annum [3]. Research done previously by Eskom shows that fire under or near transmission lines produces enough ionized air to cause about 20% of the total number of flashovers [4]. R Event [58] carried out a study to investigate the detection of fire under high voltage transmission lines and studied the high frequency characteristics of corona and electrical discharge generated by fire.

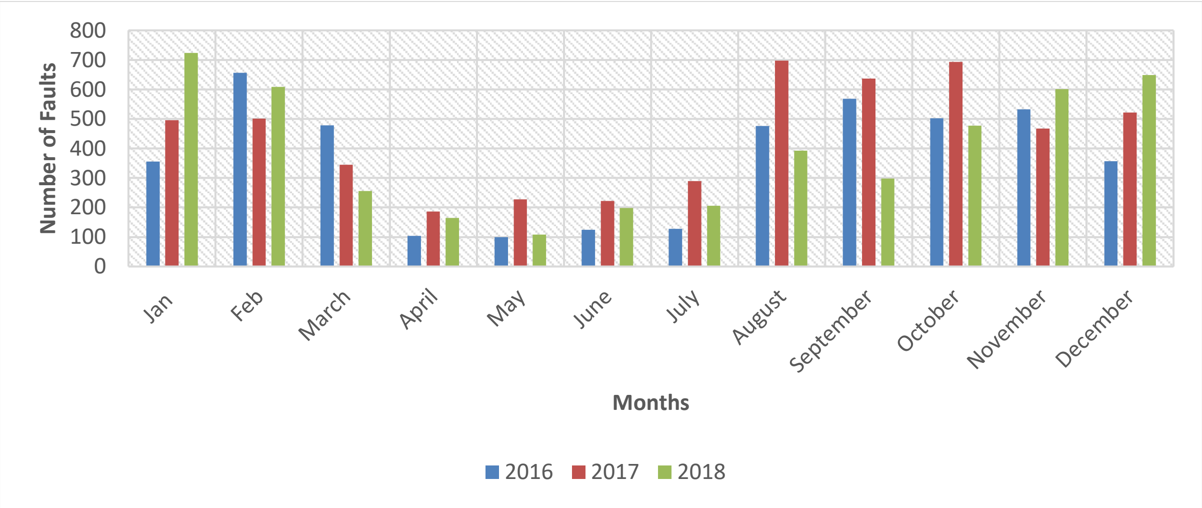


Figure 4-1: Fire related faults reported for a period of 12 months [4]

In overhead power transmission, the greatest need is to transmit maximum power to consumers with reduced losses, minimal infrastructure degradation and minor environmental impact at low costs. Insulation systems in high voltage power transmission lines are designed for a certain level of electric field strength. Since air is used as the main insulating medium in high voltage transmission [4], a safe operating distance between adjacent conductors and a safe operating distance from the ground fault must exist. This will minimize the possibility of interruptions due to insulation failures on the transmission system.

Table 4-1: Minimum clearances for voltages [4]

Nominal system voltage U_n (kV)	**Highest equipment voltage U_m (kV)**	**LIWV (kVpk)**	**Minimum phase to earth and phase to phase clearance (mm)**
11	12	75	500
22	24	125	500
33	36	170	500
50	55	250	500
66	72.5	325	630
110	123	550	1100
220	245	1050	2100
400	420	1425	3400 (phase-earth) 4200 phase-phase)

4.1 Voltage breakdown characteristics of air gaps

The breakdown of air is the transition of a non-sustaining discharge into a self-sustaining discharge. The buildup of currents in a breakdown is due to ionization in which electrons and ions are created from neutral atoms or molecules and their migration to the anode and cathode respectively. Townsend and Streamer theory are the present two types of theories which explains the mechanism of breakdown under different conditions of pressure, nature of electrodes, temperature, electrode field configuration and availability of initial conducting particles. Normally air medium is widely used as an insulating medium in different electrical power equipment and overhead line as its breakdown strength is 30kV/cm [7].

Earlier investigations showed that the disruptions were due to breakdown of the air about the conductors due to the proximity of the fire [3]. Changes in the composition of the air about the conductors implies a change in the corona activity about the conductors. This was confirmed by some preliminary tests using spectral measurements on the power line carrier performed by [6].

4.2 Participles initiating discharge mechanism

Veld fire is a kind of diffusion flame and the voltage ingredients produced by solid vegetation are mutual diffusion and reaction. Particles such as ashes, smoke and soot are generated within the gap in the presence of fire. The amount of particles generated depends on the source of fire. Should the smoke and particles in the flame be exposed for a relatively long time in the environment above 1000 Kelvin, which can be burned completely and the particles out of the reaction zone will become ash and smoke. In most cases of the actual veld fires accidents, the vegetation does not generally burn incomplete. Hence, large amounts of ash and particles may be produced and the triggering discharge of particles and ash has a multiplier effect in the line gap due to the function of the thermal buoyancy of flame [60].

(a) (b)

Figure 4-8: Picture of ash (a) and smoke (b) [57]

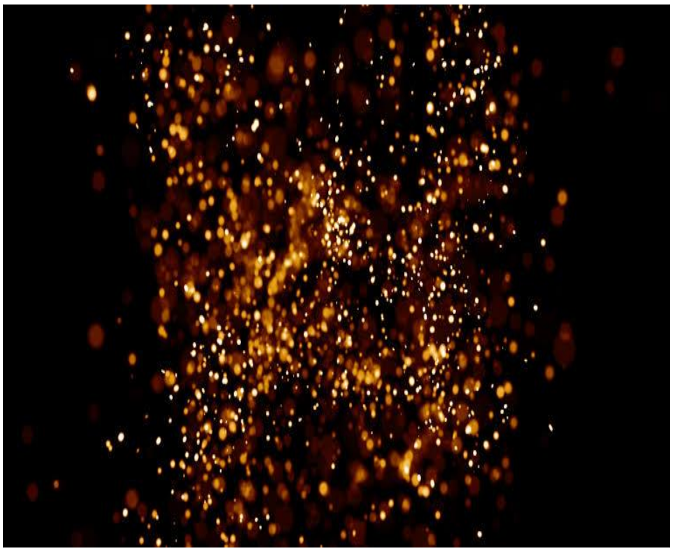


Figure 4-9: Picture of fire particles [57]

Ions and electrons in the fire transfuse large quantity of charge in the discharge channel which accelerates partial discharge to transfer into steady arc discharge. When discharge activated by particles and formed blue electric arc, if adequate current shall not be transfused into channel, then the electric arc shall extinguish at current zero crossing or the lowering of flame height. If the flame conductivity is high enough to provide sufficient current, then it shall promote partial discharge transfer into electric arc [60].

4.3 Dielectric strength at power frequency of air insulation

Dielectric strength is the voltage that a material can withstand for a given wall thickness before dielectric breakdown or electrical discharge through a material occurs [62]. The study conducted in [61] proves that flashover voltage of air insulation drastically decreases in the presence of fire when compared with to the value at ambient temperature. Table 4-2 shows the flashover voltage for power frequency voltage obtained in tests performed in Mexico for a 3m conductor plane gap configuration under different temperature and fires of different sources. The results shows that the flashover voltage is minimum when the gap is bridged by flames of sugar cane leaves.

Table 4-2: Dielectric strength at power frequency for a conductor-plane gap configuration [18]

Gap Conditions	Flashover Voltage kVrms/cm
Without fire, t=15ºC	2.5
Without fire, t=100ºC	1.9
Without fire, t=120ºC	1.7
Fire with Gasoline	1.0
Fire with alcohol	0.8
Fire of sugar cane leaves	0.5

Table 4-2 shows that the flashover voltage depends on the quantity of floating particles within the gap. The significant reduction in the flashover voltage for sugar cane is due to the large amount of combustions. This was proved in South Africa where a reduction of 50% was achieved on the flashover voltage for electrodes tested with a clean gap flame and later with flame particles [18].

The flashover voltage of air insulation at high temperature, as occurs during fire conditions is reduced drastically when compared with values at ambient temperature. The dielectric strength is dependent on the type of voltage stress (AC, DC and impulse) and on the proportion of the gap covered by flames. At high temperature, the flashover voltage of an electrode configuration is reduced due to the decrease of the relative air density within the gap [18].

4.4 Behavior of air insulation at high temperature

The most common gaseous insulator at atmospheric pressure is air. Air is an excellent insulator at normal temperature and pressure. Various natural phenomena such as cosmic radiation, gamma rays and radioactive substances on earth give rise to natural ionization of air. This ionized air produces charge carriers such as free electrons and ions that inhibit the air ability to be a good insulator. Thus, positive and negative ions are mainly found in atmospheric air as a result of these natural ionization processes.

Air remains almost electrically neutral due to an equal number of positive and negative ions but susceptible to the occurrence of electrical discharge [31]. In the presence of an electric field the positive and negative ions produced by natural ionization start moving and cause an electric current to flow in the air. The processes primarily responsible for the breakdown of gas are ionization by collision, photo-ionization and secondary ionization. The process of attachment plays an important role in insulating gases [63].

Air has two major advantages which are occurring in abundance and the self-restoring capability after a breakdown [31]. The insulation strength of air is decreased by the reduction in air density due to the temperature increase caused by the fire. The only factors that influence the breakdown strength of air are humidity and temperature. However, the humidity correction factor, H is not considered in the presence of fire and assumed to be 1, hence the flashover voltage is given by the expression [65].

$$V_s = V_t \frac{H}{\delta} = \frac{V_t}{\delta} \tag{4.1}$$

Where:

V_s is the flashover/breakdown voltage under standard conditions.

V_t is the flashover/breakdown voltage under actual temperature conditions.

H is the humidity factor (assumes to be 1 in the presence of fire)

δ is the relative air density and affects the flashover voltage the most, expressed as follows:

$$\delta = \frac{0.392P}{273+T} \tag{4.2}$$

Where:

P is the constant barometric pressure in mmHg

T is the temperature in ^{o}C

Authors in [18] cited that the reduction of the dielectric strength of an insulator due to increase in temperature can be approximately determined by the following equation:

$$V_t = V_s \frac{0.392P}{273+T} = \frac{V_s}{\delta} \tag{4.3}$$

Equation (4.3) shows that flashover voltage is directly proportional to the barometric pressure and indirectly proportional to temperature. This theory presumes that a reduction of air density is caused by the heat from fires and results in a reduction in the insulation strength of air. Results from field measurements shows that at constant barometric pressure and temperature of 900^{o}C, the air density can be reduced to 0.25 of its normal value [31].

4.4.1 Millimetric experimental tests

For characteristics of discharges in high temperature air, a study by [64] was conducted to measure the breakdown voltage under uniform electric field air gaps. The study confirmed the validity of Paschen's Law for millimetric air gaps for temperatures of air up to 1200^{0}C. Paschen Las states that at higher pressures, the breakdown characteristics of a gap are function (not linear) of the product of the gas pressure (p) and gap length (d). From Figure 4-11, the breakdown voltage varies non-linearly with the product of p and d.

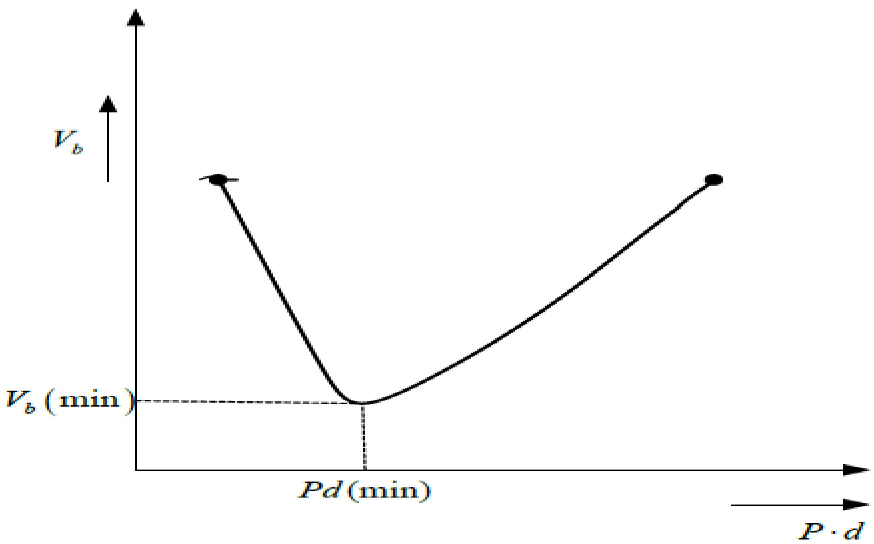


Figure 4-11: A graph varies non-linearly with the product pd [64]

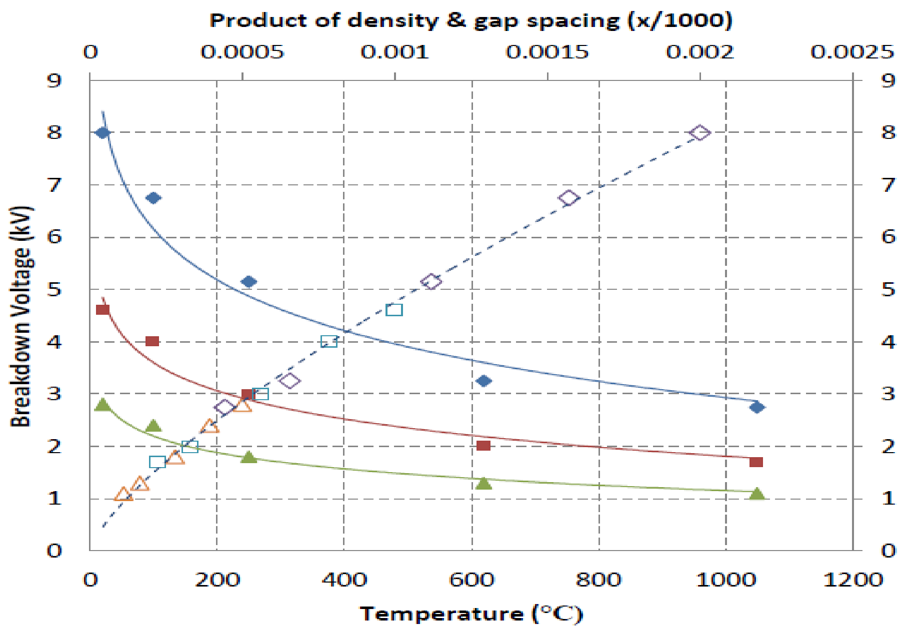


Figure 4-12: A plot of breakdown voltage against temperature [60]

Symbol		Gap, mm
(T, V)	(x, V)	
◆ 2mm	◇ 2mm	2
■ 1mm	□ 1mm	1
▲ 0.5mm	△ 0.5mm	0.5

In Figure 4-12 [60] plotted the breakdown voltage to a base temperature, T (full curves) and plotted parameters of x (dotted curve) as a function which is proportional to the product of gas density and gap spacing (mm) defined as:

$$x = \delta d \qquad (4.4)$$

It can be observed that the three voltage against temperature curves has resulted in only one V/x curve, this proves that the breakdown voltage is a function of the temperature alone. This reduction in breakdown voltage as the temperature increases as observed in Figure 4-12 is supported by other literatures [59], [60].

Peng Li et al. conducted an experiment to study the AC and DC discharge characteristics of air-gap in the presence of fire particles. The study focused on the influence of forest fire particles on the breakdown characteristics of a conductor-plane air gap aimed at obtaining measures to reduce the tripping of transmission lines due to forest fire particles [60]. From Figure 4-13 we find that the breakdown of gap always occur at the positive half wave under the action of AC voltage. The breakdown voltage of positive polarity is lower than negative polarity in the DC test. The AC breakdown voltage is slightly lower than of DC positive polarity under the same conditions.

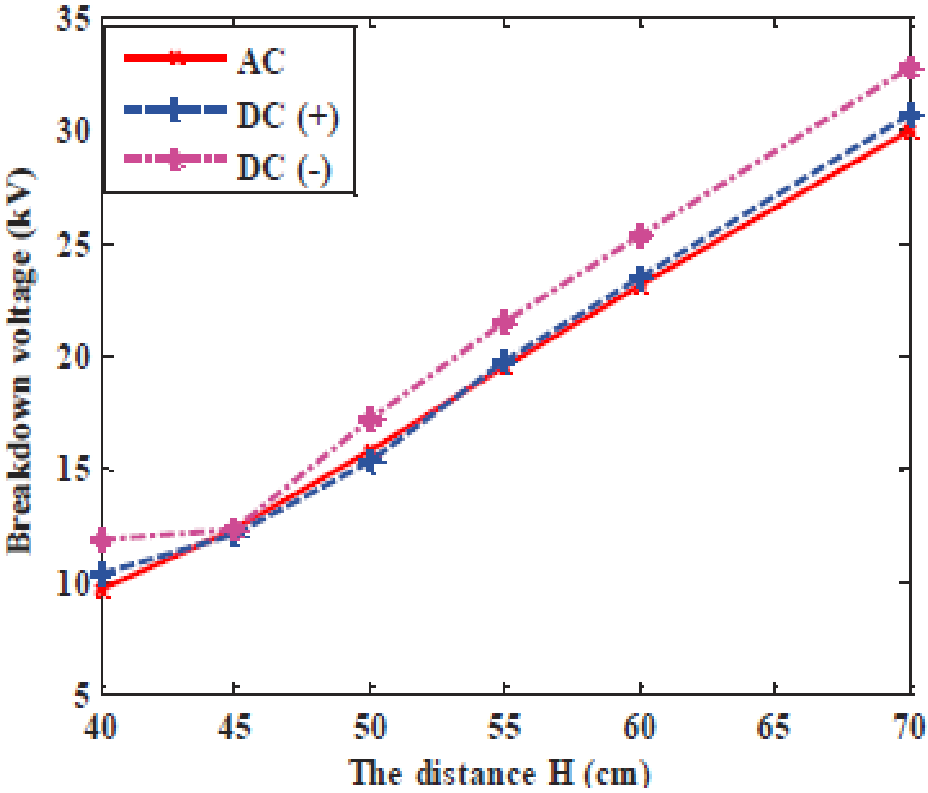


Figure 4-13: The AC and DC breakdown under fire conditions [60]

4.4.2 Field experimental tests under AC voltages

A study by [9] illustrated the practical significance of high temperatures on the breakdown voltage and investigated the dielectric properties using a model transmission line that was subjected to fire conditions. They performed experiments on a 70 kV AC model transmission line. The authors cited several factors that could be attributed to the reduction in breakdown levels of air gaps in the presence of fire which are Ionization produced by the flame, solids carried by the convection currents associated with combustion, the reduction in air density resulting from high temperatures and a combination of these factors.

Results that were obtained from burning various fuels portrayed a significant reduction in breakdown levels in comparison with the experiments that were conducted in the absence of fire with a fixed height of 1.15 m and a conductor spacing of 12 cm. The reduction levels were found to be 37% for sugarcane leaves, 49% for gas, 29% for sugarcane bagasse and 27% for wood. As the withstand voltage gradient with no fire was recorded to be approximately 4.5 kV/cm, it thus means that the mean withstand voltage gradients were reduced to 2.3 kV/cm for gas, 2.8 kV/cm for sugarcane leaves, 3.2 kV/cm for sugarcane bagasse and 3.3 kV/cm for wood.

The study concluded that the most dangerous air insulation degradation factors are temperature and ionization. It was further indicated that during the combustion process, as a result of the solid particles that are released, these would play a significant role only with shorter spans between conductors. Additionally, this significance is also subject to physical properties such as the fire concentration and the size of particles. The 49% reduction in the breakdown level reported in [9] is in good agreement with [3] where a 50% reduction in breakdown voltage was observed for a gap spanned by the flame for the 15 mm – 30 mm air gap size.

However, for larger air gaps (200 mm – 1000 mm) the reduction in breakdown voltage was of the order of 75%. The shape of the electrode was found to have played no role. The presence of floating particles in the air gap resulted in the reduction of breakdown voltage of between 20 and 30%. In [3] it was shown that the air density effect (reduction of) played a more prominent and significant role than the degree of ionization. Further, if a gap is completely engulfed in flames, due to the introduction of micrometric particles this would act to significantly reduce the level at which the air gap will breakdown. Such an observation is in agreement with the factors that were cited in [9] attributed to the reduction in voltage breakdown levels.

Sarduski [3] conducted experiments with air gaps between live and earthed components and with flames spanning part and the total distance of the gaps. His experiment showed that with as little as 60% of the gap between the ground and the conductor of 400 kV and 275 kV lines bridged by flames with particles, was sufficient for the line to experience a flashover [9]. These results are shown in Table 4-3 [71].

Table 4-3: The effect of floating particles and flashover for various voltages [71]

Nature of the flame	Portion of gap bridge	Line Voltage (kV)								
		22	32	44	66	88	132	220	275	400
Clean	100%						N	N	N	Y
With floating particles	100%	N	N	Y	Y	Y	Y	Y	Y	Y
	80%	N	N	N	N	Y	Y	Y	Y	Y
	70%	N	N	N	N	N	Y	Y	Y	Y
	60%	N	N	N	N	N	N	N	Y	Y
	50%								N	N

In Table 4-3 the areas indicated in red (Y areas) are those that resulted in a flashover. It is of interest to note that only a 400kV line with a clean flame experienced a flashover when the entire air gap was bridged by a flame.

The results of the study in [60] show in Figure 4-14 that the dielectric strength of conductor-plate gap has declined under the condition of forest fires (different sources of fire) compared to that of pure gap. The average breakdown voltage gradient of the gap for a single conductor is 0,73 kV/cm and 2.5 kV/cm for a 3m conductor plane.

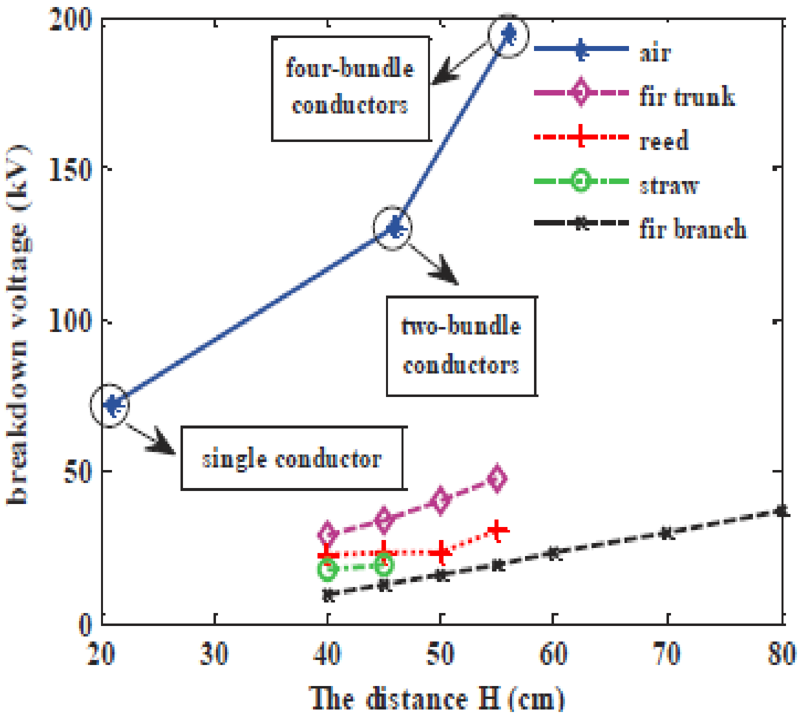


Figure 4-14: AC breakdown voltage under forest fires [60]

4.4.3 Field experimental tests under DC voltages

Lanoie *et al.* [6] in 1987 conducted a study to investigate the characteristics of a bipolar ±450 kV DC model line exposed to burning trees and vegetation in Canada. This model line had a 13.7 m clearance at mid-span, a pole-to-pole distance of 11.8m and a 70m span length. Each pole was a hollow aluminium tube, 4.4cm in diameter. This study represents the most practical experimental test setup done for a DC line. Temperatures of the flame reached 1000^{0}C, which is equivalent to a relative air density of approximately 0.2. According to IEEE standards (Std 930 ™ 2004) one would expect a 50% reduction in the efficiency of air insulation based on temperature effects alone but the test results obtained by the author yielded a figure of approximately 90%. This reduction in this study was to a certain extent attributed to the chemical characteristics of the flame, in addition to their thermal properties [6].

The study by Peng Li *et al.* in [60] shows in figure 4-15 that the breakdown voltage is increased with the gap distance under three kinds of vegetation flames, but the rate of rise is smaller. Comparing to that of pure air, the DC breakdown voltage is sharp decrease under the condition of fire. Figure 4-15 shows that the breakdown voltage has an evident effect of polarity characteristics under the fire conditions and the breakdown voltages under DC positive polarity are less than that of DC negative polarity voltage.

The study by Peng Li *et al.* in [59] concluded that the AC arc is brighter than DC arc under the same conditions. It was reported that when the arc is formed, the leakage current under AC voltage is slightly larger than that of DC voltage. The conductor-plate gap under flame is said to be equivalent to the parallel of capacitor and resistor for AC. However, for DC voltage, the leakage current is mainly conduction current. While the leakage current contains the displacement current and conduction current under AC voltage. Hence, under AC condition, the value of leakage current is a little bigger and the gap breakdown voltage is slight lower as a whole, compared to DC voltages [59].

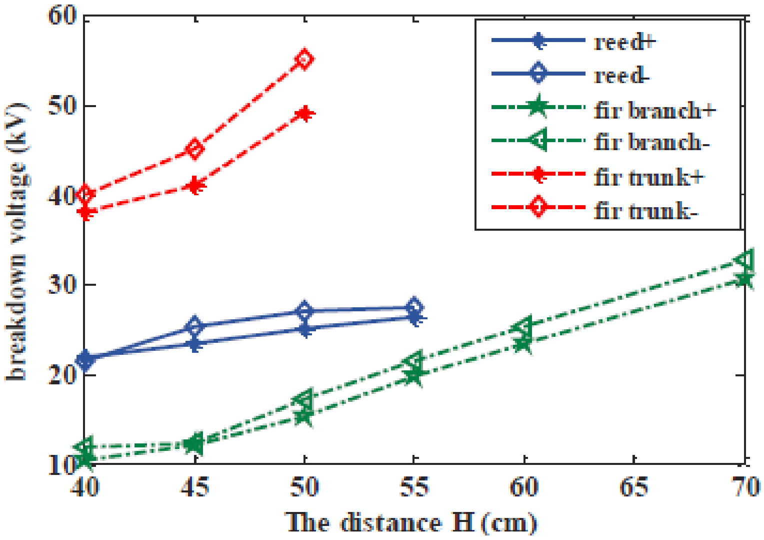


Figure 4-15: Voltage breakdown characteristics for different kinds of flames [59]

4.5 Breakdown of air insulation

The spacing between power system electrodes (between phases, phase-to-overhead-earth-wires and phase-to-ground) are designed such that the air gap between them will not become conductive under normal operating conditions. The applied voltages, electric and magnetic fields and several other parameters are taken into account to ensure that the air insulation remains intact. In addition, the power losses due to the high electric field stresses in the air gap are also considered. If the surface gradients on the conductors are too high for any typical conditions, the 50Hz power losses will be higher and reduce the overall efficiency of that particular section of the power network [7].

Breakdown of the air gap is a progressive process from partial to complete breakdown. Continuous partial breakdown of the air gap leads to system power losses without a network failure taking place [7].

4.5.1 DC breakdown voltage

Authors [66]-[70] conducted investigations on the breakdown characteristics of rod-rod air gaps up to 2m under negative and positive DC applied voltages. From the investigations, the median of the mean withstand voltage breakdown gradients was observed under DC applied voltage and approximated to be 4.3 kV/cm which is higher than the 3.5 kV/cm observed for AC applied voltage. The result obtained indicates that given an air gap of a specific length, it will portray inferior dielectric strength properties under an AC applied voltage as opposed to DC applied voltage.

From Figure 4-16, the obtained air gap voltage breakdown characteristics under positive DC voltages in the smaller 0-500 mm air gap range had to be extrapolated to allow for a comparative analysis of the literature from different authors. The results observed show a linear relationship between the breakdown voltage and air gap length for positive DC applied voltages. The authors in [69] concluded that the linearity resulted from the fact that breakdown is determined by the movement of positive streamers initiating from the anode and approaching the negative electrode. As a result, negative streamers which are determined to be shorter are formed.

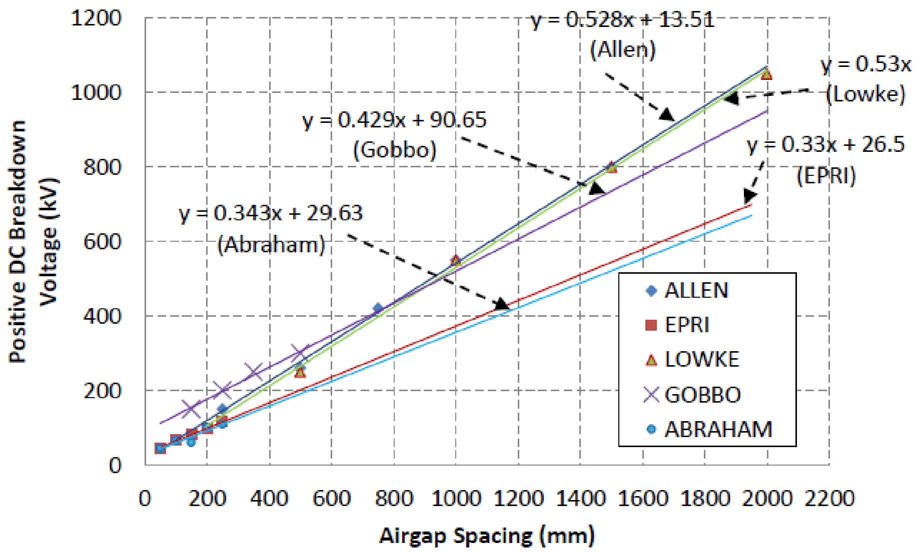


Figure 4-16: Positive DC breakdown characteristics of rod-rod air gaps based on [66]-[70]

Figure 4-17 shows an air gap voltage breakdown characteristics under negative DC voltages investigated by different authors as observed under AC and positive DC voltage applications, the linear relationship between the breakdown voltage and the air gap length is observed under negative DC applied voltages. For this investigation, the maximum mean withstand voltage gradient was found to be 5.7 kV/cm by Gobbo [68] and Lowke [70]. The least obtained withstand voltage gradient is 3.4 kV/cm by Abraham *et al* [67], in which flashover characteristics of several type gaps including rod-rod gap (12.5 mm x 12.5 mm) square cut brass rods.

The median of the withstand voltage gradients observed in Figure 4-17 is approximated at 4.7 kV/cm. This is higher than the mean gradient observed under positive DC and AC voltages respectively. This indicates that the performance of air as a dielectric is superior when subjected to negative DC voltages than AC and positive DC voltages.

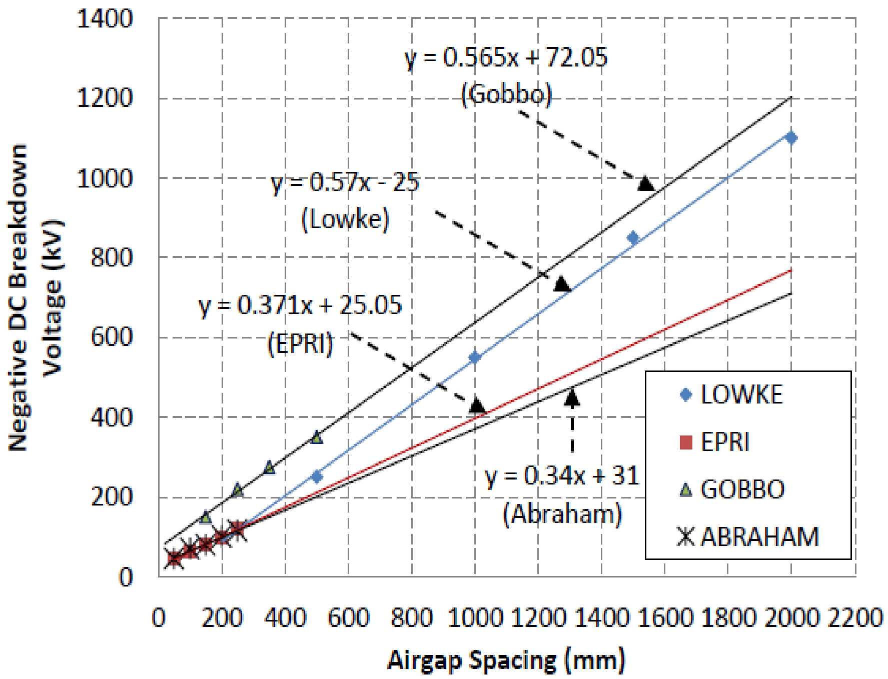


Figure 4-17: Negative DC breakdown characteristics of rod-rod air gaps based on [66]-[70]

4.5.2 AC breakdown voltage

EPRI in [66] published a report on the spark over performance and gap factors for gaps less than 1m for both AC and DC. The study in [66] for ease of reference and comparison of experimental results obtained in this study and the published literature, the spark over performance of the horizontal rod-rod electrode gap configuration under both AC and DC applied voltages are of particular interest.

Figure 4-18, AC voltage breakdown characteristics (r.m.s.) of a horizontal rod-rod air gap configuration are illustrated for the 0.02 m – 1.6 m range as observed by different authors. The rods used were flat cut squares with a varying edge width of between 12.5 mm and 25 mm and were made of brass. Results obtained by Fonseca et al. [5] and Robledo-Martinez et al. [9] were estimated for larger air gaps as these were obtained only for the 0 – 200mm air gap range. It is evident that a linear behaviour exists (or can be estimated) between the breakdown voltage and the air gap length.

It is of interest to note that results obtained by Razevig [72] and those obtained by EPRI [66] are in direct agreement with each other. The observed mean withstand voltage gradient from both these authors is approximately 3.5 kV/cm which also represents the median.

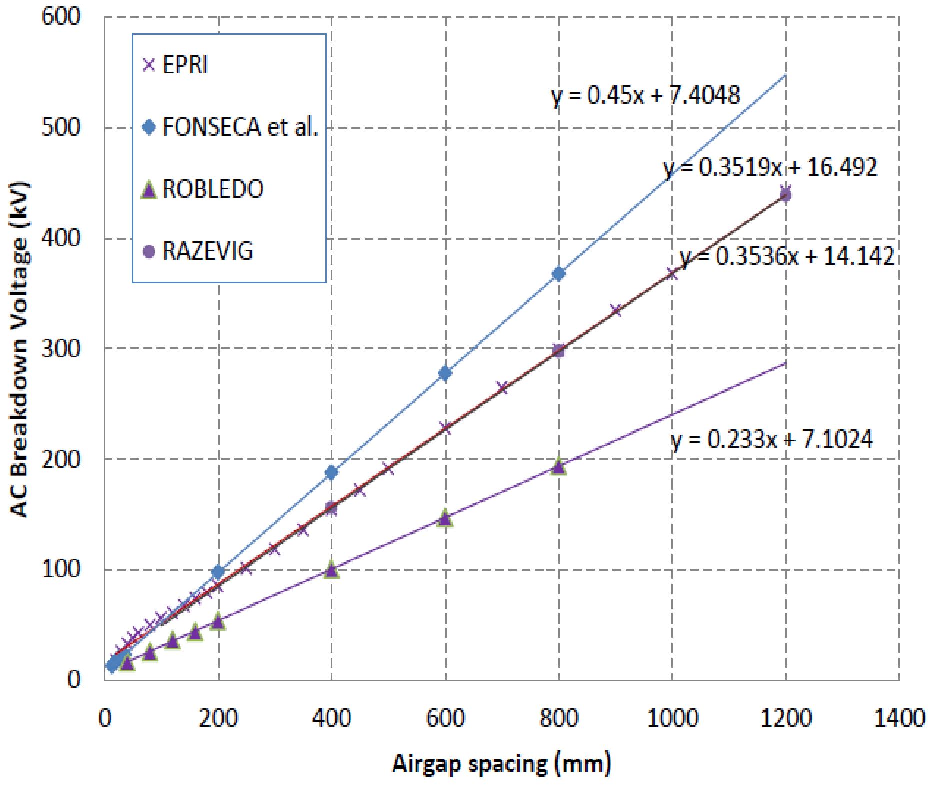


Figure 4-18: AC breakdown characteristics of rod-rod air gaps based on [5], [9], [73], [72]

4.6 Effect of increased temperatures and solid particles

A Sukhnandan [65] conducted a theoretical and experimental investigations to find out if fire does induce flashover on high voltage transmission lines, and presented the flame conductivity theory and the effect of fire on the air gap space charge. The study shows that fire induced flashover is dynamic and complex. Three parameters have been identified as the main causes that are responsible for reducing the breakdown strength of air in the presence of fire, namely:

- The thermal ionization caused by the flame,
- The reduced air density caused by the high temperature and,
- The particles generated as a result of combustion.

4.6.1 Thermal ionization

If a gas is heated to sufficiently high temperatures, many of the gas molecules or atoms acquire sufficiently high velocity to cause ionization on collision with other atoms or molecules. The conductivity of the gas is described as follows:

$$\sigma = \mu\rho \qquad (4.5)$$

Where: μ is the mobility of ions in m^2/Vs

ρ is the charge density in C/m^3

σ is the conductivity in mho/m

From equation (4.5), it is shown that the conductivity increases as the concentration of ion increases. The flame is plasma where the air molecules are thermally and chemically ionized. The main source of ions and electrons in the flame are the molecules with a low ionization potential such as carbon. An increase in temperature increases the rate of ionization. Thermal ionization is the main source of ionization in flames. Saha derived an expression for the ionization in terms of absolute temperature and gas pressure as follows [74]:

$$\frac{\beta^2}{1-\beta^2} = \frac{1(2\pi m_e)^{1/2}}{ph}(kT)^{1/2}e^{-W_i/kT}$$

$$\frac{\beta^2}{1-\beta^2} = \frac{2.4\times10^{-4}}{p}T^{5/2}e^{-W_i/kT} \quad (4.6)$$

Where: ρ is the gas pressure in mm

T is the absolute temperature in Kelvin

h is the Plank's constant

W_i is the ionization energy of the gas

k is Boltzman constant= $1.3806488 \times 10^{-23} m^2 kg{:}\, s^{-2} k^{-1}$

m is the mass of the electron

β depends on temperature, for thermal ionization of gas it becomes significant only if the temperature exceeds 1000ºC

4.6.2 Combustion particles

Particles such as ashes, smoke and soot are generated within the gap in the presence of fire. The amount of particles generated depends on the source of the fire. In most cases the amount of particles is greater in a forest fire or a sugar cane fire than for a refuse burning or a gasoline fire and these particles in the flame reduces the air breakdown voltage. The effect of the particles on the dielectric strength is strongly affected by the size and concentration of the particles and can be more significant in smaller gaps. Also the thermionic emission phenomena can be considered at high temperatures. However, the phenomena are only more significant under laboratory conditions where the gap space is short [75].

4.6.3 The flame conductivity theory

Sugar cane and veld fire flames can be classified as diffusion flames. The flame may be conductive because of the thermal ionization of the air and also the presence of hydrocarbon ions from fuel oxidation reactions. The fuel oxidation is a complex process with the creation of H_3O^+ ion from the chemical ionization reactions between oxygen, water and the hydrocarbon flame [16].

$$CH + O \rightarrow CHO^+ + e \qquad (4.7)$$

Followed immediately by the charge exchange reaction;

$$CHO^+ + H_2O \leftrightarrow H_3O^+ + CO \qquad (4.8)$$

H_3O^+ is the dominant ion in both fuel lean and slightly rich hydrocarbon flames.

$CH3^+$ is the dominant ion in a very rich and near-soothing flames formed by:

$$CH + C_2H_2 \rightarrow C_3H_3{}^+ \qquad (4.9)$$

The principal reactants CH and O are produced by decomposition and other reactants of the fuel and oxidant. They will continue to react and eventually be incorporated into final products such as CO_2 and H_2O. The concentration of ions increases as the temperature increases and the conductivity increases as the ions concentration increases. In [16] it is described that thermal ionization becomes significant at 1000K.

Flame conductivity is the general reflection of electron and ion characteristics in flame. This shows the ionic concentration and mobility ratio in the flame. As discussed earlier on in the chapter that the charges in the flame are mainly ions and electrons, their corresponding flame conductivity can be expressed as follows:

$$\delta = e(u_e n_e + u_i n_i) \qquad (4.10)$$

Where: δ is the flame conductivity

u_e is the electronic concentration

n_e is the electronic mobility ratio

u_i is the electronic concentration

n_i is the ionic mobility ratio?

Under the effect of electric field E, the movement of ion and electrons in the flame generates current, the relationship between electric field intensity and current density is expressed as follows [75]:

$$J = \delta E = eE(u_e n_e + u_i n_i) \qquad (4.11)$$

As the temperature increases, the electronic mobility ratio also increases in the flame. According to electric diffusion coefficient D_e and mobility ratio u_e

$$\frac{D_e}{u_e} = \frac{kT_e}{e} \tag{4.12}$$

The electronic mobility ratio is approximately constant when the flame temperature is under certain conditions. Current density in the flame is affected by the electric field intensity and electronic field direction shall produce some effect on leakage current in the flame [75].

4.7 Measures to reduce power interruptions due to burning

4.7.1 Risk Assessment

The vast majority of wildfires in all over the world are caused by human sources. Examples of human-caused ignition sources are campfires, hot ash from cigarettes, sparks from chainsaws and other equipment, short-circuits from faulty equipment on power lines, infrequent collisions of aircraft, and arson. The three components of fire risk are ignition points, fuel buildup, and weather conditions. Although weather conditions cannot be controlled, risk reduction measures can be taken to reduce the number of ignition points, and fuel buildup near transmission lines. This can be controlled to reduce the risk of an ignition source resulting in fire. Non-human ignition sources include lightning and interference by large birds and other wildlife. Fuel sources include living and dead vegetation beneath and adjacent to transmission line right of way (ROW) [76].

The Red Flag Warning System is a joint effort between state, federal, and local fire agencies of the United of Sates intended to pass along critical fire weather information to users and occupants of wildland areas to bring about more prudent actions in their wildland-related activities. When a Red Flag Warning is issued, SDG&E takes action in the following ways [76]:

- Notifications take place
- Tripped lines are not tested manually or remotely until the line has been patrolled or the cause of the interruption has been identified and repaired
- A Fire Patrol guard is assigned to any operation that has the potential to cause a fire
- No open burning is permitted
- All fires are extinguished
- All tree pruning and removal activities cease
- All blasting is discontinued
- All grinding and welding discontinues
- Vehicular travel is restricted to cleared roads except in case of an emergency

- Smoking is not permitted.

Utility Fire Prevention and Suppression

In addition to the above, the utility could mitigate fire risk by implementing the following measures [76]:

- Initiate or increase powerline fire patrol frequency during 25th percentile or greater fire weather periods
- Improve and maintain strategic emergency ingress/egress roads capable of safely transporting fire equipment and personnel
- Collaborate with local fire and community organizations on fire prevention education and outreach programs
- Continue to fund utility/local fire suppression departments and organizations.

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.

South Africa’s state owned utility, Eskom has implemented a detailed Environmental Management Program (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 [77]. As part of the EMP, Eskom would include an Integrated Vegetation Management (IVM) program aimed on controlling and maintaining all vegetation related aspects that may influence the servitude [77].

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 [77]:

- 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 [77]. 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:

- 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.
- Intentional burning – The controlled burning of the area below the servitudes [77].

4.7.2 Detection of fire induced corona

The numbers of flashovers caused by sugar cane fires amounted to several hundred per year in South Africa [3]. One of the strategies being used to avoid or mitigate this problem is the development of a means for detecting the presence of a fire under a line prior to possible flashover. The extreme temperatures and floating particles introduced by the fire under or near an energized line initiate enhanced corona discharges, and as a result, significant levels of radio frequency noise [77]. There is a need of discrimination between radio noise generated by fires, conductor corona and noise from polluted insulators during dry and wet weather conditions. In the most favorable dry weather conditions, the high noise levels generated by fire are distinguishable from those produced by conductor corona and polluted insulators. In heavy rain conditions, fire noise generated more than 30 to 40 km away will not be detectable at the termination.

4.7.3 Strategies to reduce outages due to agricultural burning in South Africa

South Africa has implemented a cane fire management strategy so that farmers inform Eskom (power utility) before burning, so that the affected line can be switched out. In some cases cane was removed from the servitude after compensating the farmers. To track the fires occurring in South Africa a system known as Advance Fire Information System (AFIS) is used. This is coupled with notifications from the farmers whenever possible. A study was performed to check the cane height, in other countries cane heights up to 6m is experienced and in South Africa, the heights are around 4m to 6m depending on the type of cane [50].

Eskom initiated a farmer awareness coordination program known as “Operation Firebreak” in 2009 to encourage cooperation between farmers and the utility. In the agreement, the farmer is expected to contact Eskom at a toll-free number to inform Eskom of any sugar cane plantation burning the farmer has planned. Eskom then sends out an Eskom official to establish visual contact at the point of risk. The official then maintains radio contact with the regional Eskom control center. When the fire is to commence, the affected line is de-energized until the burning process is complete. This program does however, not take care of unplanned and unforeseen fires started due to weather patterns, sabotage, vandalism or carelessness. Eskom has spearheaded several research and investigation projects to identify parameters which could minimize the effects of fires on the transmission network [77], [17].

An additional strategy implemented by Eskom was the purchase of servitudes of high priority transmission lines. The cost was millions of rand and could not be implemented along all affected lines due to budget constraints. A constraint in this approach was the "guaranteed servitude width" which would eliminate the risk of a fire fault [77].

4.7.3.1 Green harvesting

Most farmers within the sugar cane belt in Southern Africa still use the conventional way of burning and then harvesting. For South African sugar cane farmers the method of green harvesting has not met widespread acceptance, and is in its early stages of application as costs and other logistical issues have not been sorted out. On the Southern African sugar cane belt most the fields are on hilly terrain, making mechanical green harvesting inefficient and costly. Harvesters also damage the crops and replanting of the crop is done sooner than normal burning and manual green harvesting. But for ESKOM to achieve less faults and disruption on their power lines, green harvesting is an attractive option. The trash can be used to generate electricity or even used for manure and other by products of the bagasse from sugarcane. The move toward green harvesting is occurring all over the world, yet in South Africa it is posing a problem. Locals are causing run-away fires for employment opportunities. This has led to green harvesting being taken out as one of the deciding options at this stage [50].

4.7.3.2 Cane free servitudes

Cane free servitudes are becoming more difficult to obtain due to the increased amount of transmission lines running down to the KZN area. The amount of cane farms which transmission lines pass over has increased and therefore depending on the size of the farmer’s land it has to be decide whether the farmer will take the option for cane free servitude. The issue being that farmer’s with smaller plots lose significantly when they have cane free servitudes as the amount of land the transmission lines clear is a large percentage of their entire property. In total a significant percentage of cane will have to be removed to allow for all future Eskom transmission lines, this is threatening the stability of the South African sugar cane industry. The cost of acquiring cane free servitudes varies greatly depending on the farmer and miller and the location. Additional costs of maintaining a clean servitude must also be considered if the farmers aren’t going to use the servitude for fire breaks or other purposes [50].

4.7.4 Technical solution

Problems associated with sugar-cane fires beneath and in the close proximity of high voltage power lines have been experienced in many countries and have been described in many documents both locally and internationally including [3], [6], [9], [15], [17]. Phase to ground and phase-to-phase flashovers have been experienced by electricity utilities around the world under conditions of sugar cane fires. In order to determine the insulation requirements of overhead lines crossing sugar cane fields, both the dielectric strength of air gaps spanned by flames as well as the distribution of flame heights have to be established [50].

4.7.5 Strategies employed in other countries

The issue of sugar cane or agricultural burning near or under electrical transmission line which results in faults occurring in various parts of the world. Utilities in other countries reported that they implemented the following aimed at reducing power interruptions.

Brazil: Employed increased mid-span clearance to ground until a law prohibiting burning of sugar cane up to 15m away from transmission line was passed [50].

Australia: Green harvesting employed in most areas and increased heights of conductor mid-span in areas where green harvesting was no possible [50].

Costa Rica: Prohibit the growing of sugar can within the servitude and compensate the farmer [50].

4.8 Conclusion

From the literatures reviewed and critically evaluated, it is clearly evident that there are a number of factors such as smoke, ash particles, transmission line phase spacing and temperature that contributes to the flashover due to the effect of fires. There is in fact very little or no comprehensive research work if there is very old that has covered the effect of fires on the performance of the transmission line. The effect of fire on the performance of transmission line is of utmost importance which cannot be ignored at any level since many industries are affected with the disruptions caused by the fires, which ends up affecting the production of the industries. However it is also very important to understand how a system fault along a line causes a disruptive voltage sag which further result in a voltage depression across all loads connected from these line including all the associated step-down transformers and also characteristics or features related to smoke to cause a flashover on an insulator. Hence, current work focuses on the effect of fire on the flashover voltage of overhead transmission line.

Chapter 5: Methodology

5.1 Introduction

This chapter discusses the methodology followed when conducting the study for the dissertation. In order to determine the specific outcomes of this research study a suitable research and analysis is needed. Having identified that there are several parameters that influences the flashover voltage, it is of the outmost importance to understand all the possible conditions involved. Through in-depth literature review it was identified that most authors are focusing on the reduction of the air insulation strength [7], the effect of fire on the reduction of the performance of the transmission lines [3], [5]. This study focuses on giving an understanding as to when is it likely for fire or burning cause power outages

5.2 Existing fire theories

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. 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 ionization model.

5.2.1 Reduced Barometric Model

Developed by [65], this theory postulates that the flashover voltage depends on the temperature and humidity. The theory is explained in detailed on section 4.4.

5.2.2 Particle Initiated Flashover Model

This theory is based on the idea that fire induced flashovers occur because of the presence of particles between the conductors and earth brought about by the presence of the flame. Initially studied by Sadurski [81], the research was first brought into light due to the concerns Eskom had over the severe problems experienced with veld and sugar cane fires [71]. 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 [81].

5.2.3 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 [4]. 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 conditions that lead to flashover mechanism.

5.2 Data Comparison

Since data has been taken from different sources [71], [78], [79] it is important to understand where the possible 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, in case of a fire reported in the vicinity 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.
- For the DC line, 62% of the faults were classified as unknown until the data was filtered using the time of day and season analysis and also the relative humidity measurements [78]. 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 6 different authors supplied the relevant source data) thus further inconsistencies may exist within these different sources.

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 since the focus of the dissertation is to give an understanding on the conditions that lead to flashover.

5.3 Methods to determine fire faults

5.3.1 Time of the day analysis

These types of faults occur mainly during the day and are correlated via observations of burning underneath the power lines at the time of fault occurrence.

5.3.2 Time of the year analysis

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

5.3.3 Season of the year analysis

During seasonal changes, the fire patterns changes. This may influence fires since farmers are harvesting seasonally. During the lightning season, there are a lot of fires as a result of lightning. This analysis will help understand the weather condition in correlation with a fault occurrence.

Chapter 6: Statistical analysis of the outages caused by burning

The chapter focuses on categorizing the faults on the transmission line as a result of burning. The main focus is on the 132 kV, 220 kV, 275 kV, 400 kV and 765 kV voltage levels. The performance of the entire network is subjected to statistical analysis for a period. Faults recorded were then analyzed in terms of time of the day, month of a year, season of the year and climatic conditions when the fault was reported. Table 6-1 categorizes different line faults in terms of percentages and it can be seen that the topic in study contributes 26% for 400 kV AC applied voltages, 19% for 765 kV AC applied voltage and 49% for DC applied voltage, of the total number of line faults that are occurring on a transmission line for a period of one year [78], [71].

By looking at the number of faults for each fault type on the AC and DC systems, one will be able to understand the relative influence that the fault type causes on the line and also understand which voltage level is affected the most. 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 for those that occur on the 400 kV, 765 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 show trends in line performance. Table 6-1 below shows a breakdown of the percentage of total faults for each system. [78], [71].

Table 6-1: Breakdown of faults for different voltage applications [78],[71]

Fault type	400 kV AC	765 kV AC	±533 kV DC
Fires	26%	19%	49%
Contamination	3%	2%	31%
Lightning	17%	43%	8%
Birds	38%	0%	0%
Other/ Uknown	16%	32%	12%

6.1 Fault caused by fires

According to the study by [78] and [71], fires have been identified as the cause of 26% of 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. Based on this information, it is questionable as to whether any vegetation clearance was being performed on the Mozambique side that was causing the substantially high number of fire faults.

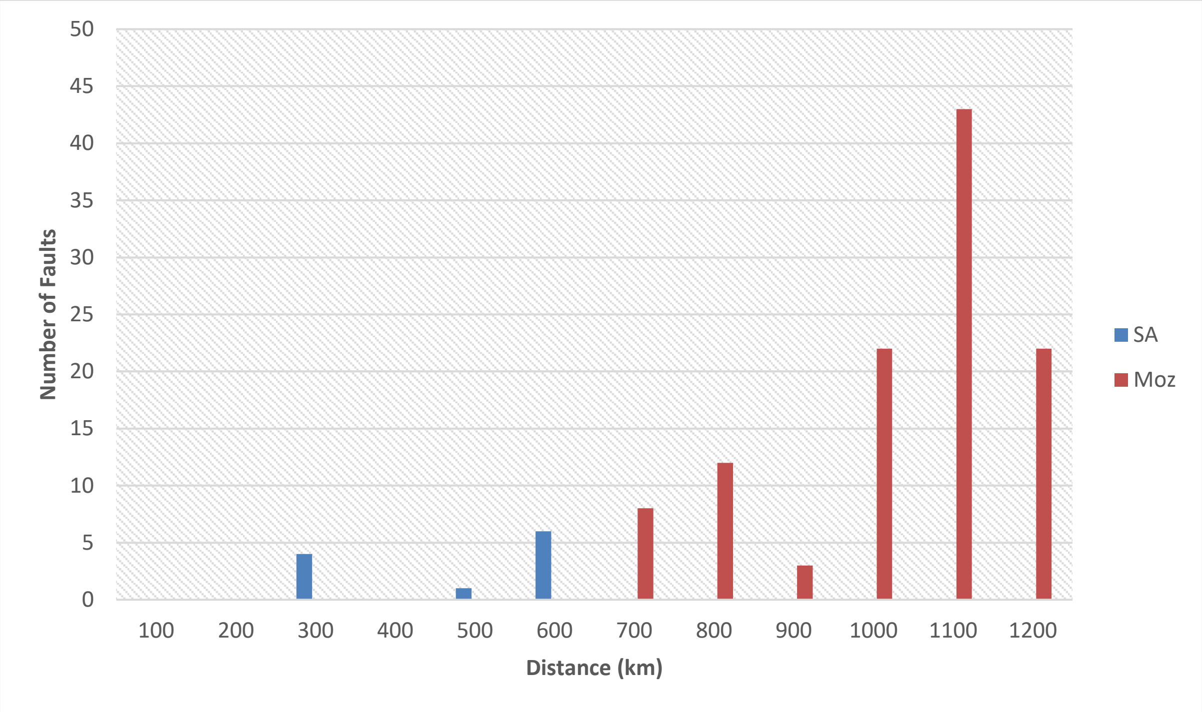


Figure 6-1: Fire faults location on a DC applied voltage line [78], [71]

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 an adequate result compared to result obtained by author [60]. Based on recommendations made by Eskom for transmission line vegetation clearance distances, a Fire Critical Zone distance of 23m 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 [78].

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, this is because 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 Eskom records a total of 3006-5000 faults/outages per year that had actually resulted from fires. At the mid-span clearance, the field gradient is 30.6 kV/m, which exceeds the assumed fire flashover withstand gradient of between 20 and 25 kV/m [79].

From the above results, it cannot be concluded that the most exposed line to fire faults is the 765 kV lines. Hypothetically stating, the 765 kV lines within South African network have performed adequately against the risk of fire faults with only a 0.0635 faults / 100km per year value recorded, see Figure 6-2.

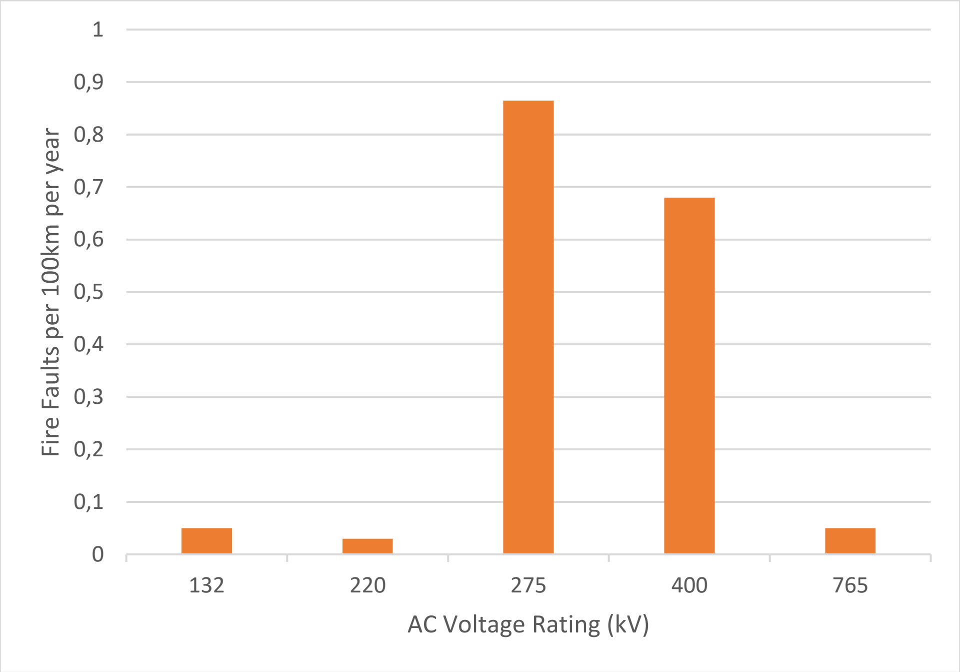


Figure 6-2: AC applied voltage fault rate per 100km for varying voltages [79]

6.2 Fault caused by contamination

As explained in the earlier chapters that during forest fires or burning, there are fire particles generated that are deposited on the surface of the insulator. The particles especially coal ash has carbon, which is conductive, making it easy for the insulator to fail, or flashes over. This may happen immediately or over time depending on the environmental and the weather conditions.

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. It is of great importance to note that burning does contribute to contamination due to particles generated that gets deposited on the surface of the insulation; hence we must consider outages due to contamination. Even though the particles generated do not actually cause failures or outages same time, it depends on the weather condition and relative humidity. Hence the importance of analyzing the faults due to contamination under this topic of study [78], [71].

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 6-3.

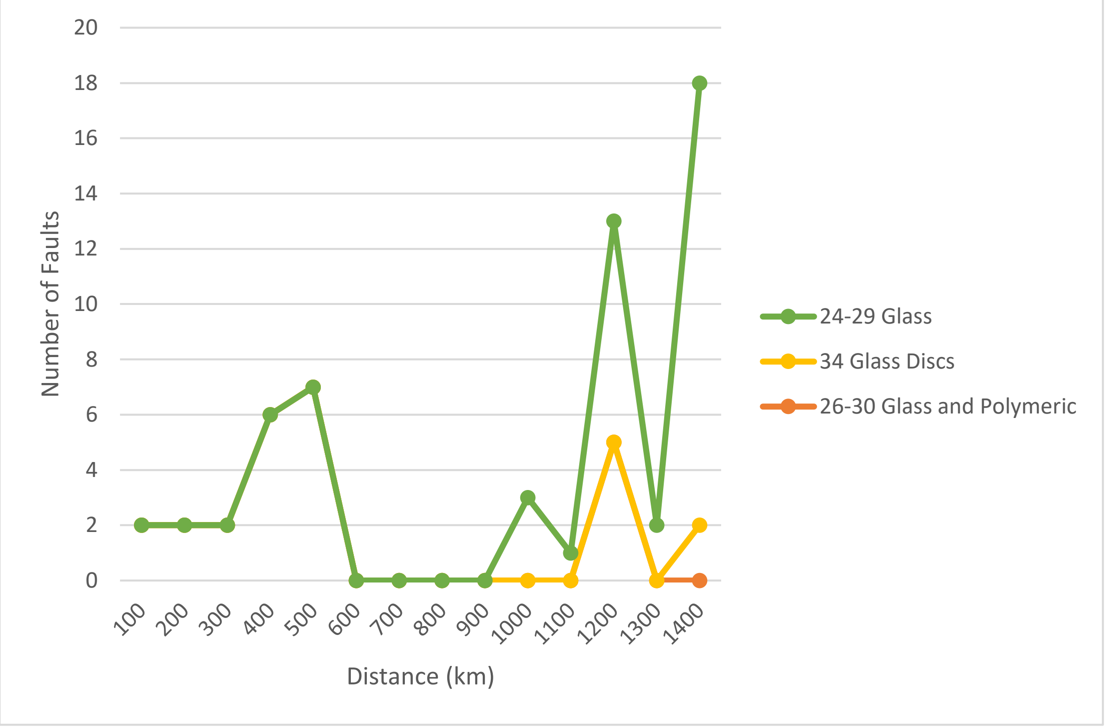


Figure 6-3: Fault distribution on a DC applied voltage with various insulation [78]

Through a refinement of data by checking faults that are related to insulator flashing over because of contamination especially in areas where fire was reported before, then link the failure to contamination. Sometimes an insulator can fail in the vicinity of fire, making it easy to correctly record the failure to the correct cause. Using the data, we can then obtain the fault/100km per year values for each of the three sections as shown in Figure 6-4.

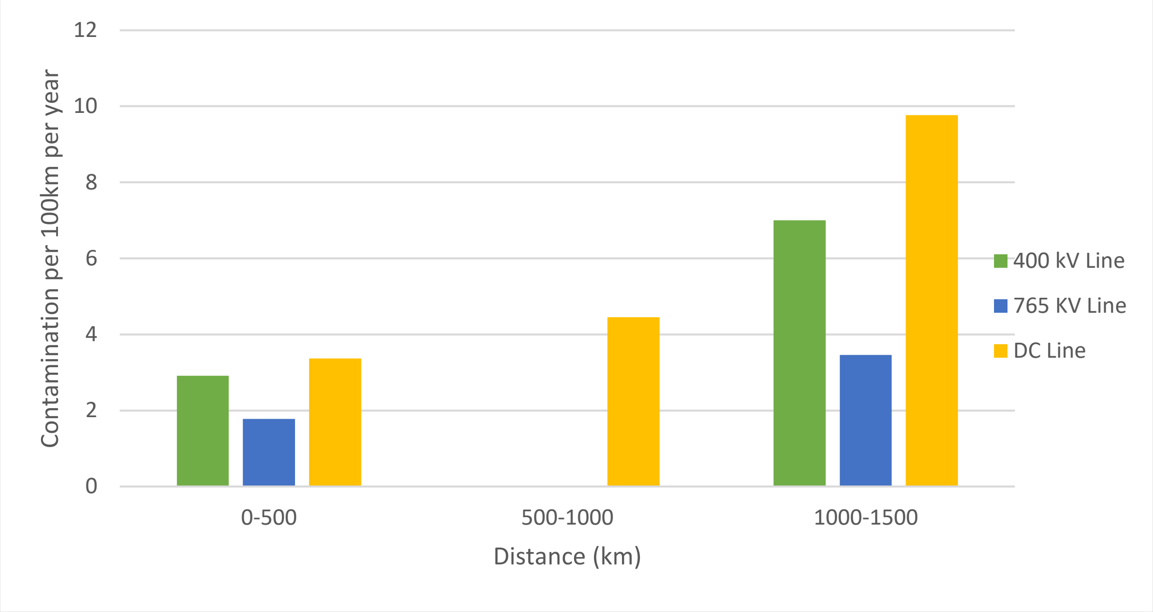


Figure 6-4: Contamination fault per 100km per year for different section with different insulation [78]

Figure 6-4 shows the difference in number of faults for different distances by varying the number of insulator discs on the string which ends up changing 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 (but only for AC applied voltage) 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 which turns out to be 3.041 faults /100km per year [78].

From Table 6-1, 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 [78].

Figure 6-5 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 [78],[71].

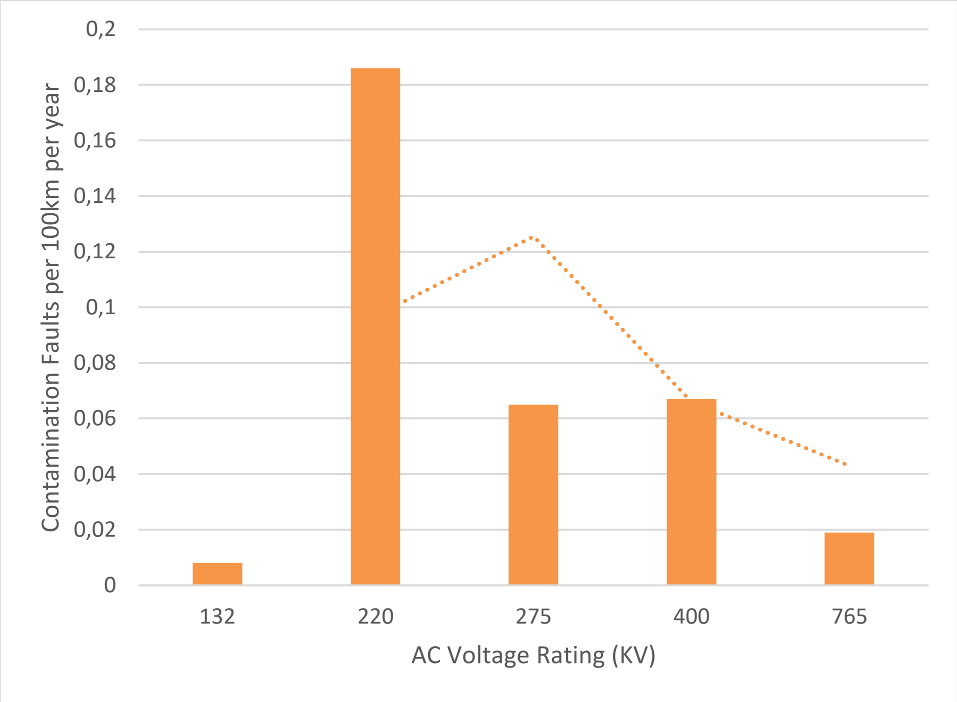


Figure 6-5: Contamination faults per 100km per year for varying AC applied voltage levels [78], [79]

6.3 Conditions that influences the flashover voltage

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

1. Time of the line fault?
2. In which month did the line fault occur?
3. Which season is likely to have flashover as a result of burning?
4. In what climatic area/vegetation is the line running through?

6.3 1 Time of day analysis

Outages due to forest fires are relatively very easy to identify. These types of faults occur mainly during the day and are correlated via observations of burning underneath the power lines at the time of fault occurrence. Forest fires can normally be identified by visually inspecting the servitude underneath the line. As said in earlier chapters that smoke can cause an outage as a result of a phase-to-phase or phase-to-ground fault because the ionized air in the smoke become a conductor of electricity resulting in arcing between lines on a circuit or between a line and the ground. For a forest fire to be able to cause a flashover to ground, the environmental factors and weather condition play a huge role. Normally, hot fires occur during the middle of the day, this is defined as the hottest period [16].

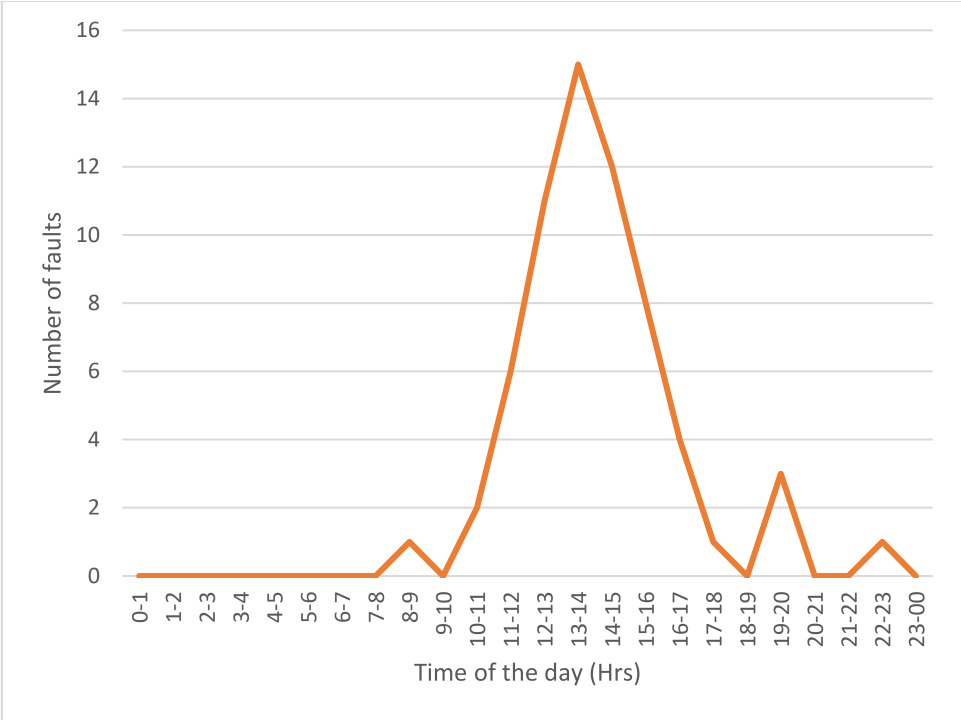


Figure 6-6: Number of faults caused by fires in August over a period of 24 hours [16]

An analysis of time of day of the unexplained faults for the whole Transmission Network is given in Figure 6-6. The total number of faults subjected to this analysis was 1433. The figure indicates that across the whole network the number of forest fire faults for the whole network is a strong function of time of day.

The time of day occurrence of forest fire faults normally exhibits a peak from 12:00 noon to 16:00. This is because the temperatures are at the highest, are likely to reach maximum during the day, which now warms up the surface, and cause fires to burn more intensely when the temperature is the highest resulting in higher fuel temperatures. Further, a slight increase can be seen on Figure 6-6 around 18:00 to 19:00. A possible reason for this is that line sagging may occur at that time of day due to high system load demand and high winds since that’s when wind start to cool of the atmosphere, the wind then cause the head of a fire to move rapidly, cause the wind to crown into the top of trees and jump barriers. This then makes it easier for the fire to reach overhead conductor and insulators damaging them [16].

Wind also influences prescribed fire smoke dispersal which will the contaminate insulators and cause them to flashover. Due to this, 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 [16].

6.3.2 Time of year analysis

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.

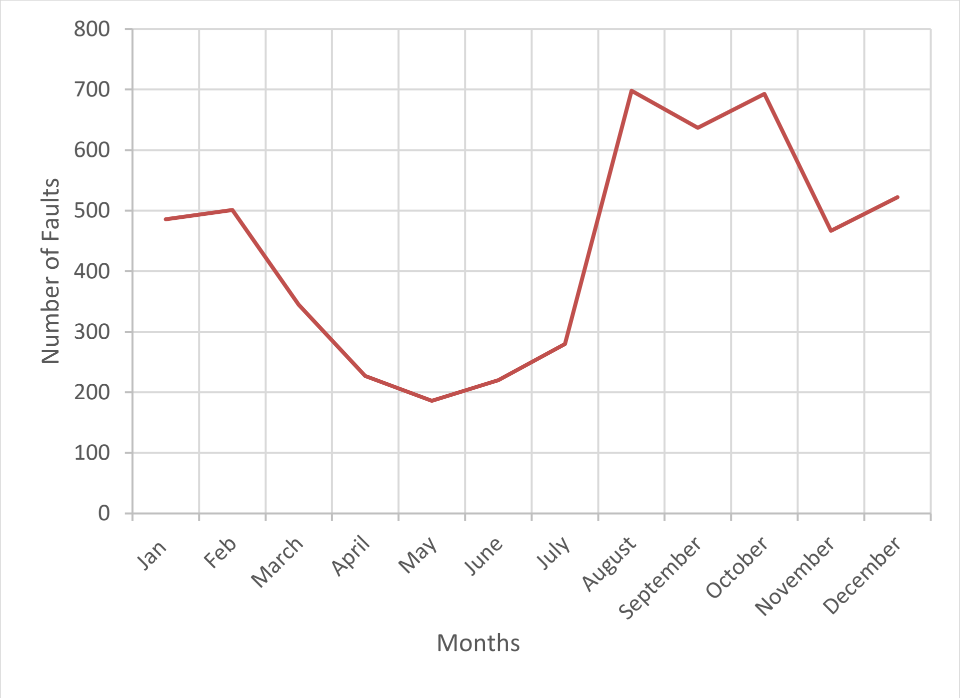


Figure 6-7: Number of faults per month for a year [4]

During June to December it is clearly visible, in Figure 6-7, that the faults start increasing. The reason for this phenomenon is that vegetation is dry since we are coming from winter dry season; therefore, chances of forest fires are very high. In addition, mist and fog normally occur during these months of a year as a result of fairly high humidity and large daily temperature variations. Therefore, due to the mist and fog, insulators get wetted which then makes them more likely to flashover.

For the month of October to November, we see a decrease in those months due to the rain season. This means that even if it is likely for fires to occur, chances of rain are very high which will now stop fires if there are any. Rain washes the insulators which decrease the chance of a flashover.

December: The trend increases during this month, this is because of the high temperature and less chances of rain. In addition, the chances of lightning are very high; this mean chance of unexplained fires are very high that can end up causing flashovers.

6.3.3 Season of the year

During seasonal changes, July to September it is clearly visible, in Figure 6-8, that is an increase in fire flashovers. The reason for this phenomenon is that the winter season is finished, vegetation is dry which then makes it easy for forest fires because of dry season and fairly high humidity and large daily temperature variations.

Sunset in the October to December months normally occurs approximately 2 hours later than in the winter season. In summer, sunrise occurs at around 05:00 and in winter around 07:00. Figure 6-8 indicates that the fault frequency corresponds to this shift in time of sunrise. Most of the forest fire faults between 12:00 and 16:00 in October and between 09:00 and 11:00 in January. It tends to show then that the early morning line faults may be due to pollution and wetting of the glass of insulator discs. During the winter months, the dry weather results in dry veld grass [16]. Fire caused faults then become likely.

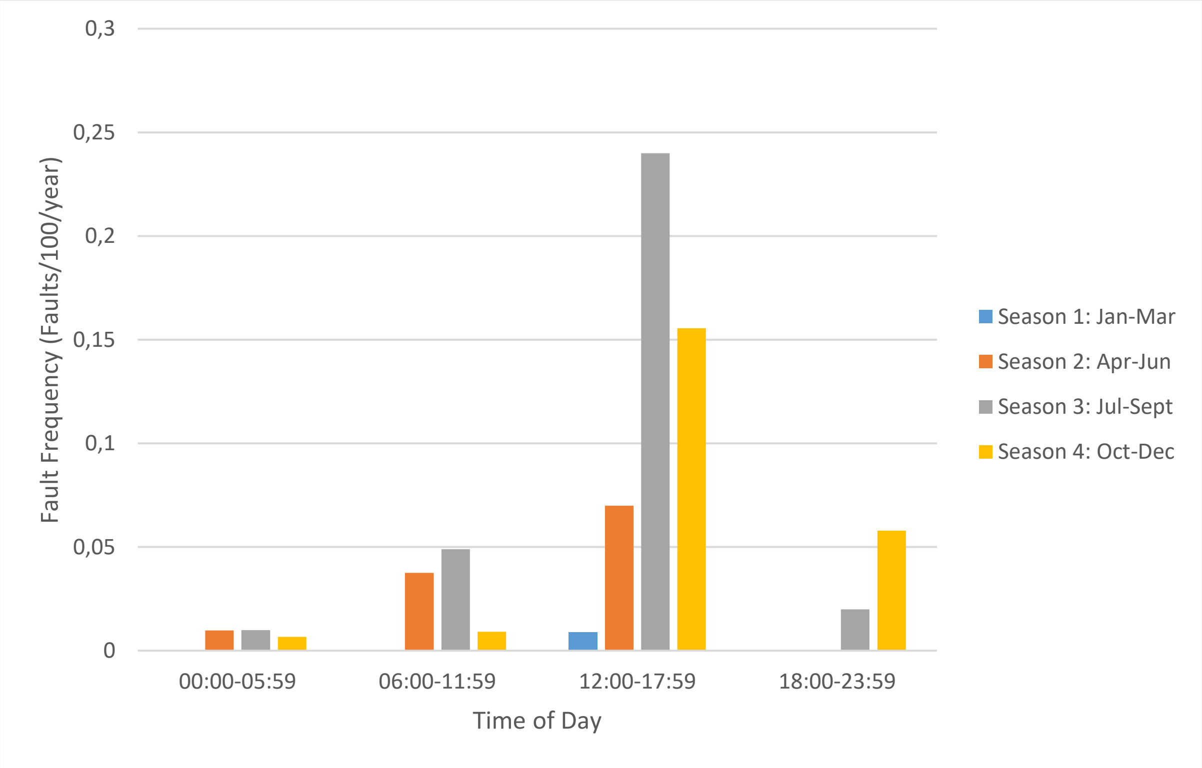


Figure 6-8: Season and time dependent frequency of fire caused faults on a 400kV network [16]

6.3.5 Fires caused by lightning

The National Fire Protection Association Fire Analysis (NFPA) and Research Divisions conducted a study for a period of 5 years to investigate fires caused by lightning [80]. During the period 2007 to 2011, United States fire department responded to an average of 22 600 fires per year that were started by lightning. It is highly possible that these fires also occur under or near high voltage transmission line and therefore affects the performance of the transmission line. The study concluded that lightning related fires are more common in June through august and in the afternoon and evening see Figure 6-9. and Figure 6-10. More than half of all fires started by lightning occurred between hours of 15:00 and 21:00 [80].

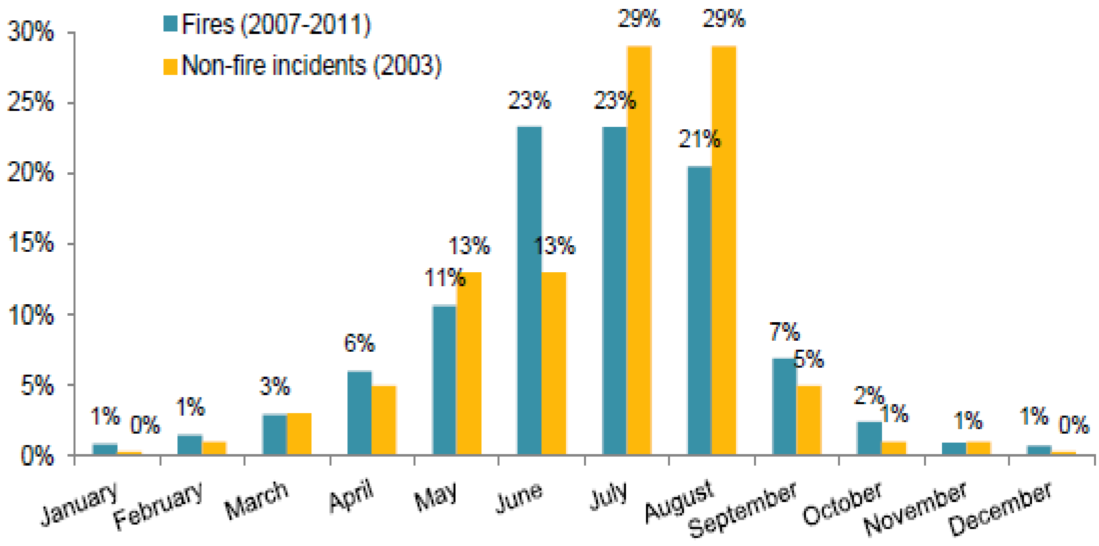


Figure 6-9: Lightning incidence by month [80]

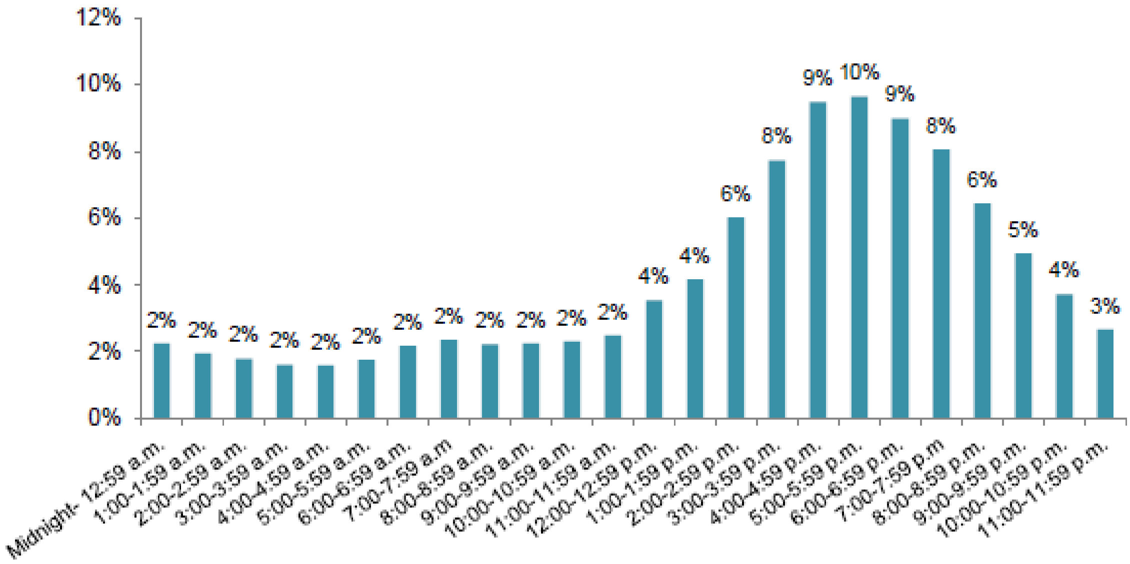


Figure 6-10: Lightning fires by hour of day [80]

6.4 Conclusion

The above analysis indicates that it may be possible to categorize the faults due to burning occurring on the system into categories of probable time of occurrence through a combination of time of day analysis, time of year analysis and the region through which an individual line runs. The overall analysis of all the lines in the transmission network indicates a strong correlation between season, time of fault occurrence and environmental conditions.

Chapter 7: Conclusion and Recommendations

This chapter summarizes the conclusion based on the study conducted. Recommendations for future work are also given.

7.1 Conclusion

Based on the study conducted, the following conclusions are made:

1. The mechanism to breakdown for both the positive and negative DC applied voltage was found to be linear. A similar result had been obtained by various authors under AC applied voltages presented in the literature review.

2. Although at high temperatures breakdown occurs at a value lower than it normally would under ambient temperature conditions, the mechanism leading to breakdown remained linear. This was observed under both positive and negative polarities.

3. For smaller air gaps, the dielectric withstand gradient observed under negative DC applied voltages at ambient temperature conditions was 5.1 kV/cm which is approximately 13% higher than that observed under positive polarity which was reported as 4.5 kV/cm. This confirmed a higher negative polarity dielectric strength compared to the positive polarity.

4. For larger air gaps it was further observed that air gaps have a higher dielectric strength under the negative polarity.

5. For a forest fire to be able to cause a flashover to ground, the fire must be hot.

The study managed to give an idea of how should the weather and environmental conditions be for a flashover to occur. From the study it can be concluded that forest fires do influences insulator failures due to the carbon deposition from the ash which is conductive that gets deposited on the surface of the insulator then flashes over. The time of the day that is most likely for fires to cause a fault on a transmission line is between 12:00 to 16:00. This is because of the temperature is at the highest causing fires to burn more intensely. Most outages or faults due to fires occur from June to December, this is because the vegetation is dry, and chances of forest fires are high. The faults are also high during the harvesting season between January and March.

7.2 Future Work

The work performed and presented in this dissertation confirms the theories from various literatures. It is however also important to know that the work conducted based on excitation systems is not only limited to the scope presented in this thesis. Therefore it is of great importance to recommend certain studies which could be conducted using the same system network. These include but not limited to the following:

1. Determine the effect of the size of the particles on the breakdown voltage levels experimentally.
2. Determine the effect of the various types of fuels experimentally.
3. The effect of a flame bridging the air gap on the breakdown characteristics for both the positive and negative polarities under DC voltages. This would provide insight into the role of high temperature plasmas on the voltage breakdown of bridged air gaps.
4. Determine the corona current signature for negative corona current under no fire and fire condition.
5. Design and conduct experiments under laboratory conditions on HVDC and HVAC lines subjected to different types of fires; gaseous partial discharge.
6. Design models to detect fires and protect the transmission system.

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Appendix A: Fire Index Table

Table A1: Fire index table [77]

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 B: ESDD Table

Table B1: ESDD values for different pollution level [32]

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

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