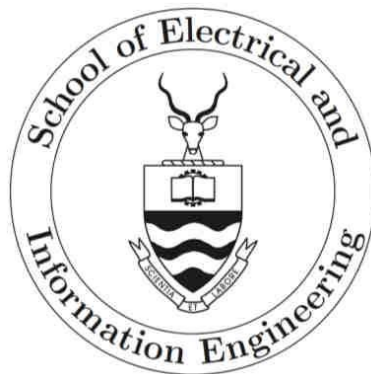


COMPARISON OF THE LIGHTNING PERFORMANCE BETWEEN THE POLES OF THE CAHORA-BASSA ± 533 kV HVDC LINES

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, May 2016

Declaration

I declare that this research report is my own unaided work, other than where specifically acknowledged. It is being submitted in part fulfilment for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Signed on 18 May 2016

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Abstract

This work contributes toward research in the field of lightning performance of High Voltage Direct Current (HVDC) transmission lines, focusing on the impact of the line polarity on the incidence of line faults. Although there has been some recent research into the influence of polarity, there appears to be no confirmed effect that might influence the design of new lines. The research presents an investigation into the lightning performance of the two poles of the Cahora-Bassa HVDC transmission line. In order to compare the performance of the two polarities, the average lightning exposure over an 8-year period was confirmed to be very similar for both lines. Lightning stroke data from the South African Lightning Detection Network was correlated with fault times from the transmission-line protection scheme. The classification of the lightning related faults was used to determine the relative performance of the two poles, particularly in relation to polarity, and to infer if there was any influence of polarity on the lightning attachment process. This investigation for the Cahora-Bassa scheme shows that twenty-three out of twenty-five lightning related faults occurred on the positive pole. The results concur with performance experience on several HVDC lines from China and Canada, which indicate that lightning related faults favour the positive pole by a ratio of between 8:1 and 10:1. This represents a valuable contribution, which substantiates that HVDC line polarity has an influence on the lightning attachment process, and indicates that there is a need to re-examine the lightning shielding design for HVDC transmission lines.

This dissertation is dedicated to my perfect Colleen, for you have inspired me to become a better person in every way.

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Nomenclature

AC	Alternating Current
CB	Cahora-Bassa
C-C	Cloud to cloud lightning stroke
C-G	Cloud to ground lightning stroke
CC	Coupling Capacitor
CS	Converter Station
CIGRÉ	International Council on Large Electric Systems (Conseil International des Grands Reseaux Electriques)
DC	Direct Current
DE	Detection Efficiency
DRC	Democratic Republic of Congo
EGM	Electrogeometric Model
EHV	Extra High Voltage
FALLS	Fault Analysis and Lightning Location System
GPS	Global Positioning System
HF	High Frequency
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IET	(The) Institution of Engineering and Technology
IMPACT	Improved Accuracy using Combined Technology
ISH	International Symposium on High Voltage Engineering
kA	Kiloampere
kV	Kilovolt
LA	Location Accuracy
LDN	Lightning Detection Network
LF	Low Frequency

LFD	Lightning Flash Density
LFL	Line fault Locator
LIWL	Lightning Impulse Withstand Level
MDF	Magnetic Direction Finding
Ms	Millisecond
MW	Megawatt
PLC	Power Line Carrier
RA	Reliability Analysis (A tool in the “FALLS” software package)
SAE	Small Area Exposure (A tool in the “FALLS” software package)
SAUPEC	South African Universities Power Engineering Conference
TFR	Transient Fault Recorder
TOA	Time of Arrival
UHV	Ultra High Voltage

1. Introduction

The Cahora-Bassa High Voltage Direct Current (HVDC) scheme was commissioned in 1979, and was the first to utilise thyristor devices for Alternating Current (AC) to Direct Current (DC) conversion. It was also the longest line length, highest HVDC voltage and highest HVDC power transfer capacity at the time. Since then, modern large capacity (HVDC) schemes have been widely applied for several decades. Despite this, there are certain areas for which international standards and guidelines have not yet been developed and accepted. One of these areas appears to be lightning shielding design. In the past, the principles for High Voltage Alternating Current (HVAC) lines have been applied to HVDC applications. International literature shows that the two poles of HVDC lines do not perform equally in respect of lightning. The lightning performance of the Cahora-Bass HVDC lines is investigated in order to determine if there is a disparity in the lightning performance of the two poles, which could arise from the polarity.

The structure of the dissertation is as follows:

Chapter 2 (Hypothesis and Research Objectives): The hypothesis to be investigated in this work is presented and the key research questions to be answered are discussed in this chapter.

Chapter 3 (Background): This chapter covers an overview of international trends in HVDC transmission lines and why the performance of these lines is important, compared to HVAC in general. The implications of lightning induced faults and the importance of lightning performance of HVDC lines are discussed. The possible influence of the HVDC polarity in the lightning attachment process is introduced. The Cahora-Bassa HVDC transmission lines are described, and compared to other international HVDC schemes, in order to illustrate the unique construction of these specific lines. The reasons for the distinctive line configuration of the Cahora-Bassa lines, and how this facilitates the investigation into the lightning performance of the two polarities are explained. The general principles for lightning protection design for transmission lines such as the impact of shield wire number and its position relative to the pole conductor(s) are discussed in the context of various examples.

In order to investigate the lightning performance of the Cahora-Bassa transmission lines, fault times from the protection system must be compared to lightning activity. Firstly, the operation and limitations of lightning detection networks in general is introduced. The details and performance of the South African Lightning Detection Network is described.

Secondly, the operation of the protection system for the Cahora-Bassa transmission lines, the origin of the fault times and their uncertainty, is discussed.

Chapter 4 (Literature Review and Gap Analysis): In this chapter, the findings of the literature review, that was conducted to ascertain if there are any internationally documented effects of polarity on the lightning performance of HVDC lines, is presented. This chapter explains the traditional lightning protection philosophy as applied to HVAC transmission lines and why these methods may be deficient for HVDC transmission lines.

Chapter 5 (Approach Taken): The approach for comparing the lightning exposure between the two Cahora-Bassa HVDC transmission lines is detailed. The approach for determining the fault rate of these lines from the fault times of the line protection system and lightning data is explained.

Chapter 6 (Proposed Methodology): The method for comparing the lightning exposure for the two transmission lines of the Cahora-Bassa HVDC Scheme is detailed. The methodology for fault correlation process is presented. A method for the classification of the likelihood that a particular stroke caused the fault in question is proposed.

Chapter 7 (Results and Discussion): The comparison between the lightning exposure of the two Cahora-Bassa HVDC transmission lines, is given for an 8 year period. Fault data was available for seven years and the results of the correlations between faults and lightning activity are provided for this 7-year period. Various significant trends in the results are described. Several specific examples of the fault correlations are discussed in detail.

Chapter 8 (Conclusions and Further Work): The outcome of the research is presented and it is discussed whether the hypothesis has been adequately addressed by this work. Further steps built on these findings are identified in the recommendations for further work.

Supporting information is included in the appendices as follows:

Appendix A: Appendix A provides a tabular summary of the analysis of all the individual faults that were conducted according to the methodology in **Chapter 6** over the 7-year period. The software tools used, as well as the results of the simulations, are provided for each case. The faults that have been correlated with lightning are highlighted and the details of the correlation result are contained in **Appendix B**.

Appendix B: The graphical analyses of the fault correlation for all probable strokes are presented in Appendix B. The details of the temporal and spatial correlation are summed up on the graphical depiction of the correlation.

Appendix C: Appendix C contains a paper that was accepted and presented for publication at the “19th International Symposium on High Voltage Engineering”, in Pilsen, Czech Republic, 23 – 28 August 2015. The paper is entitled “Comparison in the Lightning Performance between the Poles of the Cahora-Bassa ± 533 kV HVDC Lines”.

2. Hypothesis and Research Objectives

The hypothesis to be investigated in this work, namely the influence of the HVDC pole voltage on the lightning fault rate, is presented. Furthermore, the key research questions to be answered are discussed in this chapter.

2.1 Hypothesis

The hypothesis is that the HVDC line polarity has an effect on the lightning induced fault rate. This research aims to investigate the effect of the HVDC polarity on the lightning performance of the Cahora-Bassa HVDC transmission lines.

2.2 Effect of Pole Voltage on Shielding Failure

The first hypothesis is that the positive pole on HVDC transmission lines is more likely to experience shielding failure under approaching negative downward leader. This is due to the positive pole voltage having an additive effect on the positive induced potential developed on the conductor, and therefore increases the likelihood of the initiation of an induced upward leader (Maruvada 2008).

This increases the effective “attractive radius” of the positive conductor compared to the negative pole conductor or shield wire, which is shown in a simplified way in *Figure 1*. This renders the positive pole more vulnerable to shielding failure represented by the shaded area “Dc+”, which is larger than that for the negative pole shown as “Dc-”. Downward leaders approaching within the shaded areas may terminate on the conductor, thus representing “shielding failure”.

Downward leaders in “Zone 1” and “Zone 3” are likely to terminate on the ground, whilst in “Zone 2” leaders are most likely to be captured by the shield wire.

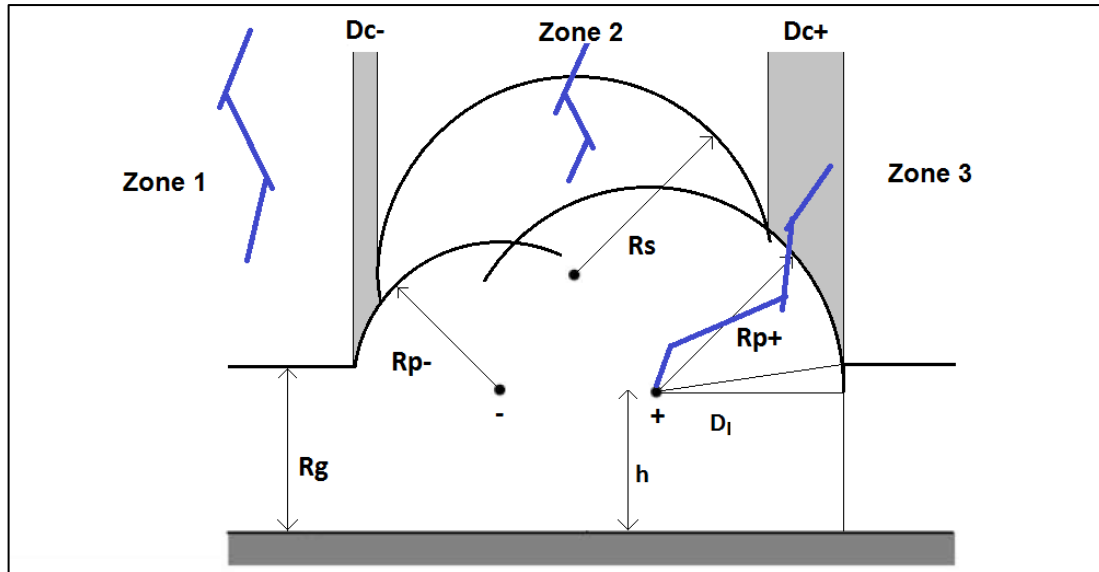


Figure 1: Attractive radii for HVDC pole conductors under approaching negative downward leader.

Actually, the attractive radius of the negative conductor is smaller than that of the shield wire, as the negative voltage is opposite to the induced voltage on the conductor and therefore has a suppressing effect on the initiation of upward leaders by decreasing the overall potential on the conductor. The situation is reversed for positive downward leaders, resulting in a larger attractive radius for the negative conductor, than that of the shield wire.

The aim of this work is primarily to investigate the lightning performance of HVDC transmission lines in relation to the HVDC polarity. The continuous voltage on HVDC lines may affect lightning attachment, unlike with Alternating Current (AC) transmission where it is generally assumed that there is no net effect of this voltage on the lightning attachment process, due to the sinusoidal variation of the line potential.

The literature indicates that the effect of polarity is ignored, and that the design for lightning protection for HVDC is based on traditional principles applied to HVAC (Rizk 2012).

2.3 Effect of Pole Voltage on Back-Flashover

The second hypothesis is that positive HVDC pole is also more vulnerable to back flashover events arising from negative strikes to the shield wire. This results from the increased stress across the line insulation, due to the difference between the negative impulse and the positive pole voltage. This propensity has been demonstrated by the modelling of a ± 450 kV DC line (Maruvada 2008), where practically all flashovers due to negative stepped leaders affect the positive pole.

For transmission lines in the conventional height range (i.e. not unusually tall structures for river crossings etc.), the majority of lightning exposure is to negative downward stepped leaders (Maruvada 2008). This generally results in a significant disparity between the lightning related performances of the two poles, and indicates that lightning protection design must be more carefully approached in HVDC cases than for traditional HVAC cases.

Although local meteorological conditions vary, affecting lightning activity, typically the majority of downward strokes, between 80% and 90% (Rakov & Uman 2003), are of negative polarity. Therefore, the lightning performance of the two poles of an HVDC scheme are predicted to show a marked inequality, with the positive pole being far more affected by lightning related faults, due to both shielding failure and back-flashover mechanisms.

In order to investigate the effect of the HVDC polarity, the lightning performance of the two poles of the Cahora-Bassa ± 533 kV HVDC lines between Mozambique and South Africa will be used as a case study.

2.4 Research Objectives

The objective is to investigate if the HVDC polarity of the conductor affects the lightning performance. The following aspects are investigated:

- Determine whether the design for lightning shielding, and for lightning performance prediction for HVDC transmission lines, is covered in the literature.
- Determine whether a disparity in the lightning performance is demonstrated in the case of the Cahora-Bassa HVDC transmission lines.

The following chapter gives the background information to lightning protection of HVDC transmission lines in general. The lightning protection design specifics of various international examples of HVDC transmission lines are compared to the Cahora-Bassa HVDC lines. The accuracy of both the lightning activity data and the protection fault times that are used in the investigation is discussed.

3. Background

This chapter covers an overview of the international trends in HVDC transmission lines and why the high performance of HVDC lines is critical. The implications of lightning induced faults and the importance of lightning performance of HVDC lines are discussed. The possible influence of the HVDC polarity in the lightning attachment process is introduced. The Cahora-Bassa HVDC transmission lines are described, and compared to other international HVDC schemes in order to illustrate the unique construction of these specific lines. The reasons for the distinctive line configuration of the Cahora-Bassa lines, and how this facilitates the investigation into the lightning performance of the two polarities are explained. The general principles for lightning protection design for transmission lines such as the impact of shield wire number and its position relative to the pole conductor(s) are discussed in the context of various examples.

3.1 Importance of Lightning Performance in Relation to HVDC Transmission Lines

HVDC schemes require very high reliability and availability and therefore all aspects affecting the line performance are important. The reasons why high performance levels are required of HVDC transmission lines are explained in the general context of HVDC transmission, as well as in the case of the Cahora-Bassa HVDC scheme.

3.1.1 International Trends in HVDC Schemes with Overhead Transmission Lines

There is an increasing worldwide need for the construction of overhead High Voltage Direct Current (HVDC) transmission systems in two main applications: Firstly, in traditional, long distance point-to-point high-energy transfer applications, where the main benefits are lower transmission line capital costs and reduced technical losses. Secondly, relatively recently there has been a rapidly increasing requirement for HVDC due to right-of-way constraints for the construction of new overhead lines to supply increasing energy demand. This is because HVDC systems use significantly less space compared to similarly insulated HVAC lines of equivalent transfer capacity. *Figure 2* depicts equivalent Extra High Voltage Alternating Current (EHVAC) and HVDC line suitable for the transfer of 7 GW.

These HVDC schemes for transferring several Gigawatts of power, utilise thyristors in the converter stations and are referred to as “Line Commutated Converter” (LCC) schemes, or colloquially as “HVDC Classic”.

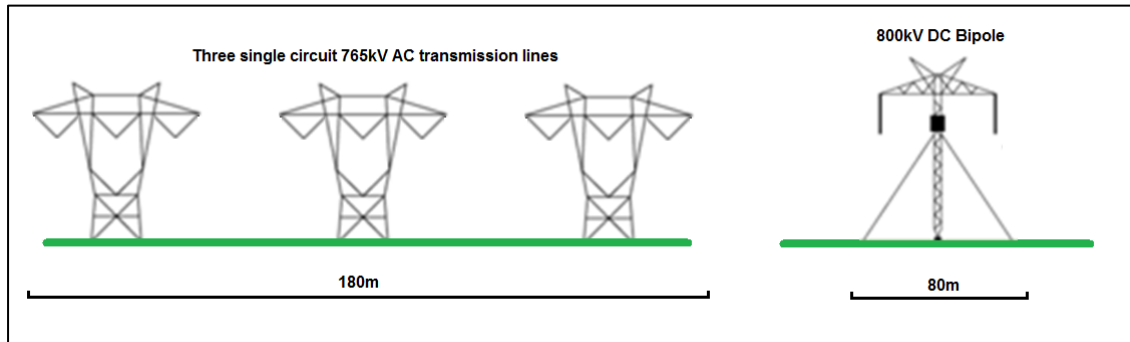


Figure 2: Equivalent EHVAC and HVDC overhead transmission lines for 6000 MW.

A similar comparison exists between the CB scheme and 400 kV EHVAC. The power rating of conventional 400 kV circuits (as opposed to high surge impedance loading lines) is around 600 MW per circuit. Therefore, three 400 kV single circuit EHVAC transmission lines are required to match the power transfer capacity of the 533 kV HVDC Cahora-Bassa scheme, which is nominally rated at 1920 MW in bipolar mode.

Consequently, for the advantages mentioned above, the application of HVDC is becoming more widespread and the need to understand aspects that affect the line performance, such as lightning, is increasing.

3.1.2 Demand for Low Fault Rate for HVDC Transmission Lines

In most cases, high performance is demanded from HVDC schemes for two primary reasons: Firstly, due to the large power transfer capacities of HVDC compared to typical HVAC lines of comparable insulation levels, outages have a proportionately larger impact.

Secondly, although the incidence of faults due to lightning may be low compared to other fault mechanisms, typically HVDC lines are relatively long compared to HVAC lines and therefore the impact of faults is emphasised, and commensurately lower fault rates are required for the same availability.

Lightning induced faults are a significant contributor to outages on transmission lines in general.

This places emphasis on understanding the impact of lightning on HVDC transmission lines, particularly in areas of high lightning activity. A global Lightning Flash Density (LFD) Map in *Figure 3* indicates that the LFD varies widely across the globe and highlights the consequent effect on transmission infrastructure. The LFD is given in flashes per km² per year and has been averaged from data over the period from 1995 to 2003. Several HVDC schemes besides Cahora-Bassa are described and compared later in this chapter: Inga-Kolwezi (Democratic Republic of Congo), Nelson River (Manitoba, Canada) and Leyte Luzon (Philippines). These four schemes have been indicated on the map. As can be seen from *Figure 3*, the lightning exposure and therefore the potential impact of lightning related outages would vary greatly across these examples. The schemes located in tropical zones such as the Inga-Kolwezi and the Leyte-Luzon schemes which experience LFD of 40 - 70 and 10 - 30 respectively, would therefore experience a larger effect due to lightning induced faults compared to the Nelson River Scheme, which experiences a LFD of 0.2 - 3. In areas of high LFD, it is clear that it would be critical to consider lightning in the design of the transmission lines.

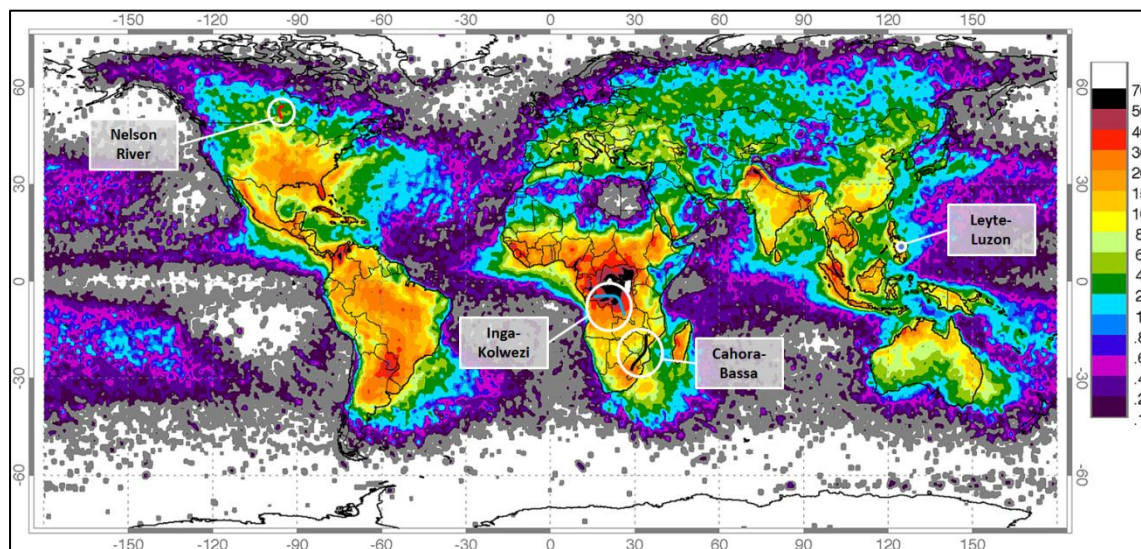


Figure 3: International HVDC schemes in relation to global lightning flash density¹.

3.1.3 Significance of Outages due to Lightning Faults on the Cahora-Bassa HVDC Lines

In the case of HVAC overhead lines, faults are interrupted by circuit breakers and after a brief time, usually 300 ms, the line is reconnected in a process called “Auto Re-Close” (ARC). This results in brief outages which can affect consumers with sensitive processes.

¹ Adapted from “Global Lightning Frequency” produced by NASA/GHRC/NSSTC Lightning Team, 10 December 2001.

Flashovers due to lightning on HVDC lines also result in momentary outages (approximately 200 ms) where the voltage falls to zero and is then restored again.

The effect of a lightning induced fault is indicated by the following example of a fault on Cahora-Bassa Line 1 that occurred on the 26th of October 2013 at a time of 20:43:26.995.

The Transient Fault Recorder (TFR) is installed at Apollo CS to record the voltage and current waveforms during transients such as faults. The TFR recording from the time of the occurrence of the fault is presented in *Figure 4*. At the time of the fault, the voltage collapsed to zero, and remained at zero for close to 250 ms. Thereafter, the voltage level ramped up for 50 ms, and beyond about 320 ms after the fault time, the voltage level on Pole 1 was restored to normal operational voltage. Although the system recovers rapidly, there may still be a significant impact in certain cases.

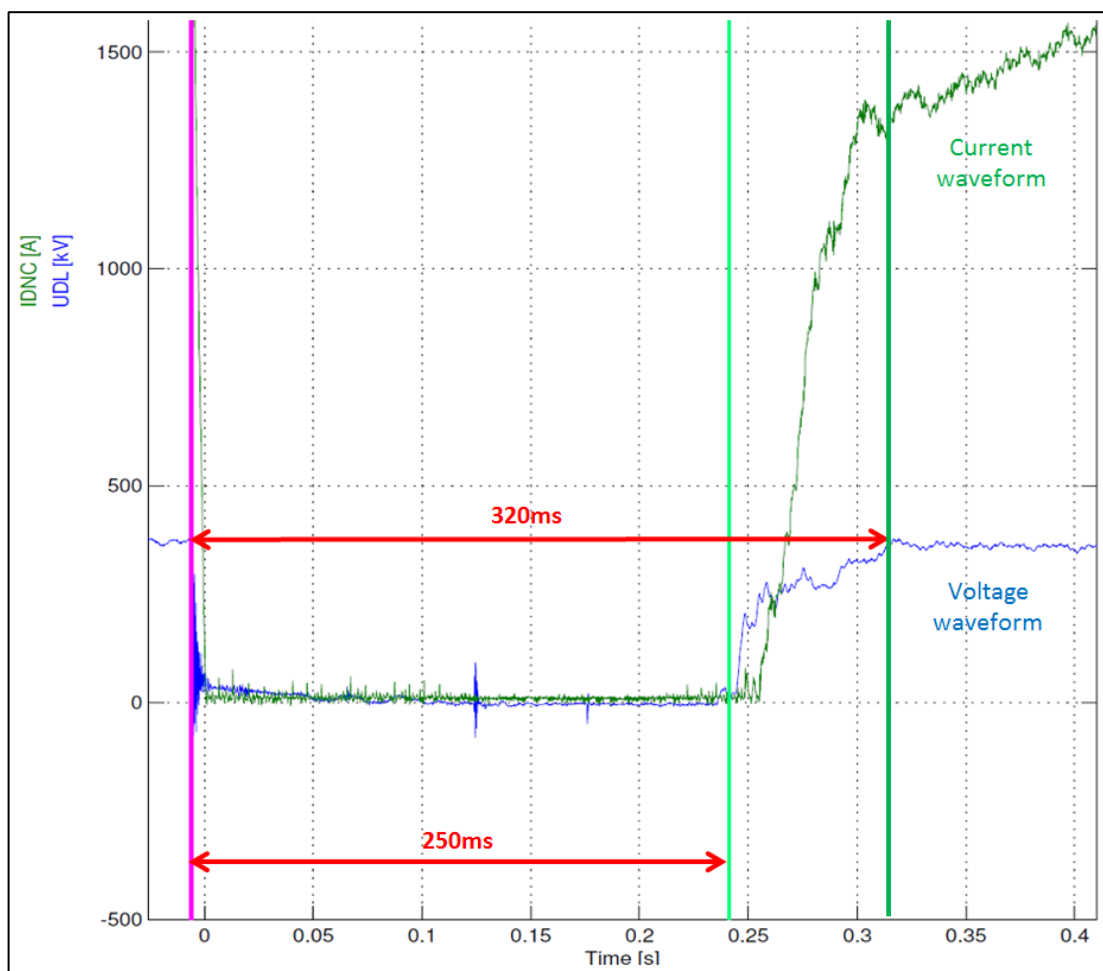


Figure 4: TFR recording for fault on Line 1 at 20:43:995².

² Adapted from Miya (2014a).

The pole voltage is restored after up to two successive faults. If there are more than two faults on one of the lines, the protection system will automatically switch the line back with one less bridge in series for that pole, and therefore at reduced voltage. Both Apollo and Songo CS's have 4 bridges of 133 kV each in series per pole giving a rated voltage of 533 kV as shown in the simplified schematic in *Figure 5*. Therefore, the post-fault voltage would be at 400 kV for the positive pole instead of normal full operational voltage of 533 kV.

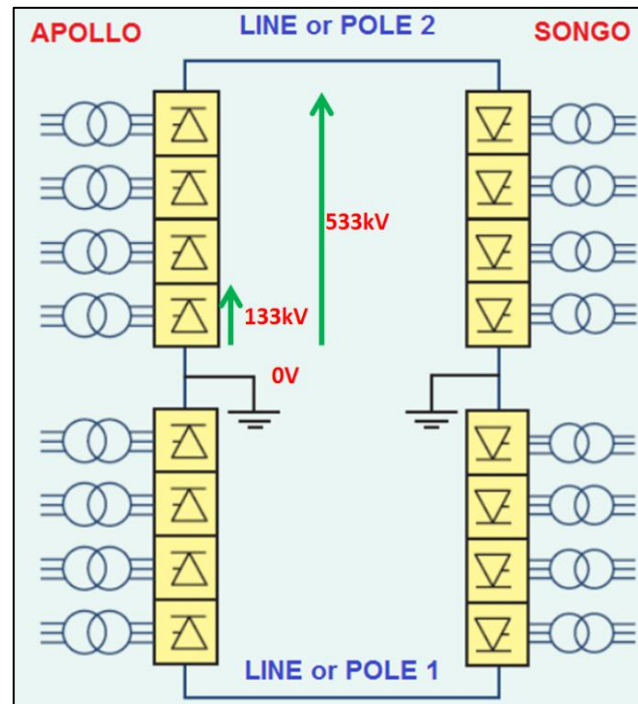


Figure 5: Cahora-Bassa bipolar HVDC scheme showing the bridge voltages³.

The rated power per pole is 960 MW. Since the power transfer is proportional to the voltage, reducing the voltage from 533 kV to 400 kV results in a substantial loss of almost 320 MW ($400^2/533^2 \times 960 = 540$ MW). The fourth bridge is only switched back manually by operators when the line is stable, and no further faults have occurred. Therefore, there can be a substantial loss in MW.hr whilst the line operates at reduced voltage for several minutes. The transient and subsequent reduction in voltage which occurs when there is a line fault places stress on the generators at Cahora Bassa, as well as the line reactors which are subjected to dynamic forces arising from the transient. In particular, the reactors at Apollo, which are oil filled, are a concern as the forces that the windings are subjected to during these events cause insulation damage.

³ Adapted from Bahrman (2007)

3.2 Lightning Performance Design for Overhead Transmission Lines

The lightning performance of overhead transmission lines is dependent on the coordination of a number of related parameters that are discussed below.

3.2.1 Failure Modes of Overhead Lines due to Lightning

There are two modes of failure due to lightning that may affect transmission lines, namely “back-flashover” and “shielding failure”. These two failure modes are described below.

The main design considerations that affect “back-flashover” performance are tower surge impedance and tower footing resistance. The primary aspects that would affect the performance in respect of “shielding failure” are the number and position of the shield wire(s) in relation to the pole conductor. The tower geometry and its effect on the lightning shielding for the various schemes indicated on the map are contrasted later in this chapter.

For EHVAC and HVDC transmission lines, faults due to shielding failure dominate in situations where the lines have been adequately designed and constructed, e.g. correct design tower footing resistances have been implemented.

Shielding failure

In the case of shielding failure, the approaching downward leader bypasses the overhead shield wire, and strikes the live phase (in the case of AC) or pole (in the DC case) conductor bundle (Eskom 2005). The current impulse travelling along the conductor bundle causes the development of a voltage proportional to the steepness of the impulse front and the conductor bundle surge impedance. If the magnitude of the lightning current is sufficiently high, a conductor potential which may exceed the line insulation level, will be developed at the insulator attachment. In this case, there is a significant probability that there will be a flashover across the line insulation, from the conductor to the earthed structure. Below a certain threshold stroke current (“critical” or “coordination” current), strikes to the conductor will not result in insulation failure as the voltage developed will be insufficient (IEEE 998 2012). For overhead lines (neglecting the conductor voltage), the permissible stroke current threshold must therefore be coordinated with the line insulation level. With the development of the EGM it has been shown that the “striking distance” (defined in 3.2.2 herein) of a downward leader is proportional to the stroke peak magnitude.

Therefore, large amplitude strokes are normally captured by the shielding system and only relatively small strokes result in shielding failure, and in some cases these strokes result in faults. The above is valid for both stroke polarities, since this is the general case where a DC offset is not considered.

Back-flashover

In the case of “back-flashover”, a lightning stroke is successfully captured by the lightning protection system and terminates on the structure, or shield wire. The lightning current impulse causes the structure potential to increase in relation to the surge impedances presented by the tower and tower footing earth connection. If the potential on the structure cross arm supporting the insulator exceeds the line insulation level, a flashover may occur across the insulation from the tower to the pole conductor (Kießling et al. 2002; Eskom 2005).

Since this flashover occurs from the structure to the live conductor, in the opposite direction to the potential gradient during normal operation, it is termed a “back-flashover”. Faults due to back-flashover typically occur due to relatively large magnitude strokes (Figure 6), which are successfully captured by the shield wire, but due to high tower footing resistance, may result in a rise in tower potential that may exceed the line insulation level.

3.2.2 Traditional Lightning Shielding Design Methods

Conventionally, various versions of the Electrogeometric Model (EGM) are applied to the lightning shielding design for transmission lines.

The traditional Electro-Geometric Model (EGM) was first applied to the shielding design of the first EHV (345 kV) AC transmission lines in North America in the 1950's. It was developed around horizontal 3-phase AC configurations with tower geometries that had large lightning shielding angles and relatively low tower heights (He, J, et al. 2009). The EGM as applied to tower designs with comparatively smaller shielding angles and higher conductor attachment heights is shown by operational experience to consistently underestimate the shield failure rate significantly (He, J, et al. 2009). This has led to the EGM being widely challenged. Tower heights increase with the larger ground clearances required for higher line voltage and due to field effects in order to meet guidelines for the electric field at ground level. Therefore, HVDC lines typically have higher tower heights and smaller shielding angles, which compensate for the increased lightning exposure.

According to the EGM the design is dependent on parameters associated with the downward leader and is not affected by potential on the line.

Therefore, for both HVAC and HVDC transmission lines, the voltage on the energised conductor is neglected in the lightning shielding design.

The EGM states that the stepped leader approaching ground will flash-over the air gap between the tip of the leader to a grounded structure that touches a radius around the leader tip that is defined as the “striking distance”. The striking distance is therefore the length of the “final jump” between the downward leader and the ground object where the electric field exceeds the electrical breakdown strength (IEEE 998 2012).

The striking distance is a function of several parameters associated with the downward leader, namely the leader potential and its associated charge, as well as the rate of change of electric field. The geometry of the gap influences the electric field and therefore the striking distance.

In this model, the “striking distance” of the stepped downward leader is related to the charge in the downward leader channel, and in turn the stroke peak current amplitude. The magnitude of the stroke defines the “striking distance” given by a formula of the following form:

$$D_s = aI^b \quad \text{Equation (1)}$$

Where

D_s is the striking distance in meters.

I is the return stroke current in kilo-ampere.

a and b are constants that depend on the ground object.

The striking distance depends on electric field enhancement associated with the ground object and therefore the coefficient “ a ” in *Equation (1)* is different for masts, horizontal wires and the ground. It can be seen from *Equation (1)* that the proficiency of a lightning protection system increases with increasing stroke magnitude. Various versions of the *Equation (1)* (with different values for a and b) produce results that vary by as much as a factor of two (IEEE 998 2012). The expression adopted by the IEEE 998 Working Group produces shorter striking distances and thus results in a more conservative design.

Equation (2) expresses these radii in terms of the stroke current (I), for the conductors (r_c) and shield wire (r_s) is as follows:

$$r_s = r_c = 8 I^{0.65} \quad \text{Equation (2)}$$

Figure 6 depicts the striking distances for the conductors (r_c), shield wire (r_s) and ground (r_g). The coefficient “ a ” for the striking distance to ground is not the same as for conductors.

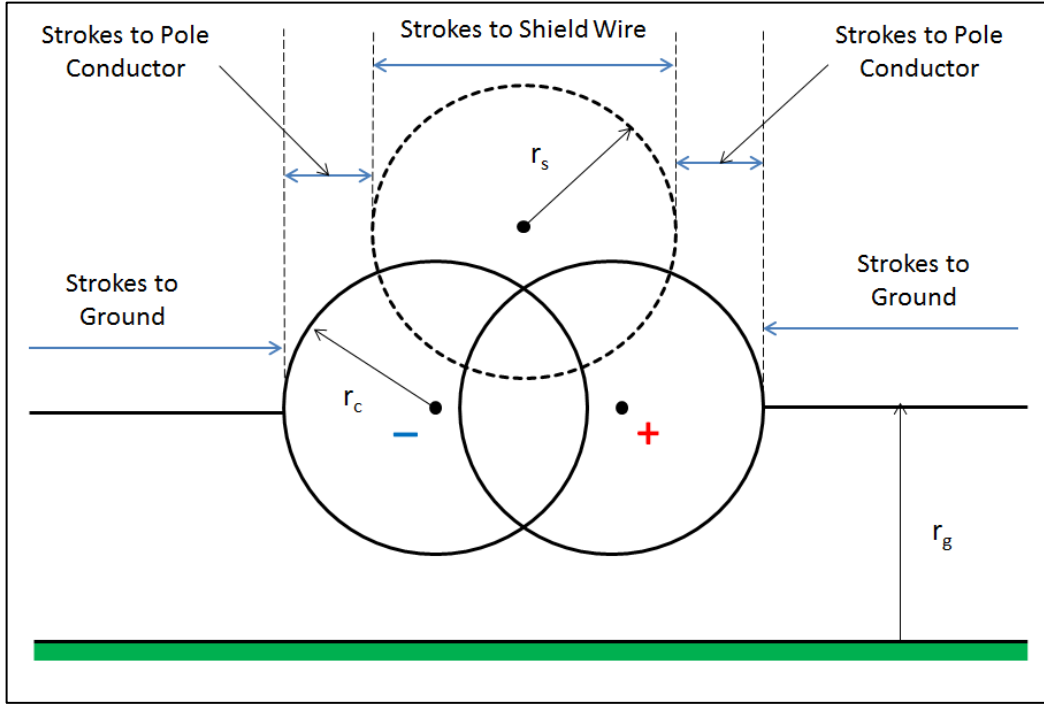


Figure 6: Traditional electrogeometric model representation for a bipolar HVDC transmission line.

More sophisticated versions of the EGM have been developed that consider other factors such as the structure height. Notably, Eriksson discovered that the attractive potential of a structure to intercept lightning was not only dependent on the striking distance, but also the connection of the downward stepped leader and the induced upward leader (IEEE 998 2012). This interception depends on the relative velocities and positions of these two leaders. The successful leader interception is defined by a parabolic locus. The leader capture distance is defined as the “attractive radius” (R_a) and was found to be related to the structure height, as shown in Equation 3:

$$R_a = 0.671 I^{0.74} H^{0.6} \quad \text{Equation (3)}$$

Where

H is the structure height in meters.

Eriksson's geometrical model is depicted in *Figure 7*.

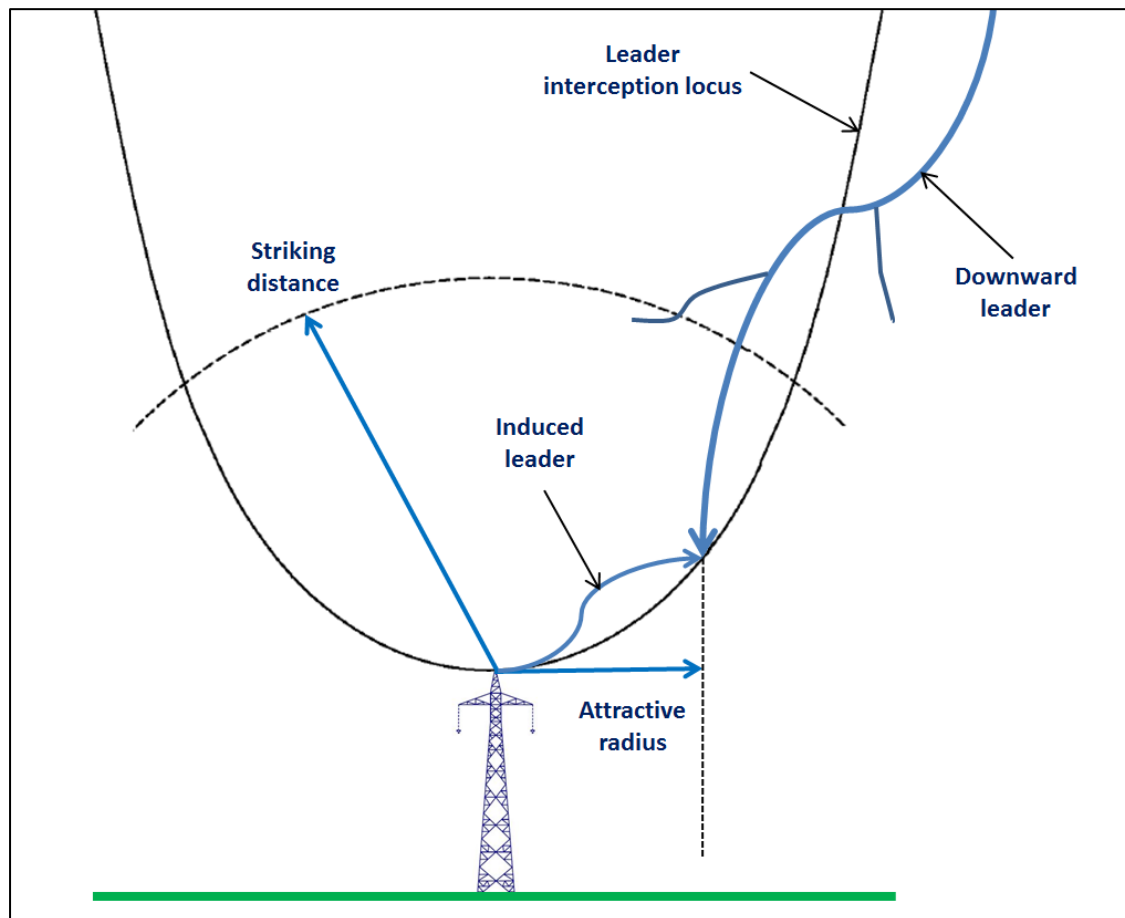


Figure 7: Eriksson's Electrogeometric Model⁴.

3.3 Review of Existing Lightning Shielding Designs for HVDC

This section presents a review of some international HVDC schemes with particular reference to lightning shielding design. The differences between these schemes and the case study Cahora-Bassa are discussed. The unique properties of the Cahora-Bassa HVDC scheme that facilitate the comparison of the lightning performance between the polarities is highlighted against the other examples

3.3.1 Introduction to the Cahora-Bassa HVDC Transmission Lines

The lightning performance of the two HVDC transmission lines of the Cahora-Bassa HVDC lines will be investigated in this research.

⁴ Adapted from IEEE Std 998 (2012)

The Cahora-Bassa HVDC scheme is comprised of two independent HVDC transmission lines. Each line consists of about 7000 towers, and runs 1414 km between the “Songo” Converter Station (CS) near to the “Cahora Bassa” hydroelectric power station in Mozambique, and “Apollo” CS north of Johannesburg, South Africa. This study will consider the 517 km South African portion from Apollo CS up to the border with Mozambique at “Pafuri” shown in *Figure 8*. Unfortunately, since lightning data is only available for the South African section, the remaining section will not be analysed. The “Songo” CS and the 897 km of HVDC line through Mozambique up to the South African border are managed by “Hidroelectrica de Cahora Bassa” (HCB). “Apollo” CS and the South African portion is owned and operated by South Africa’s only Transmission System Operator, “Eskom” (ABB 2016).

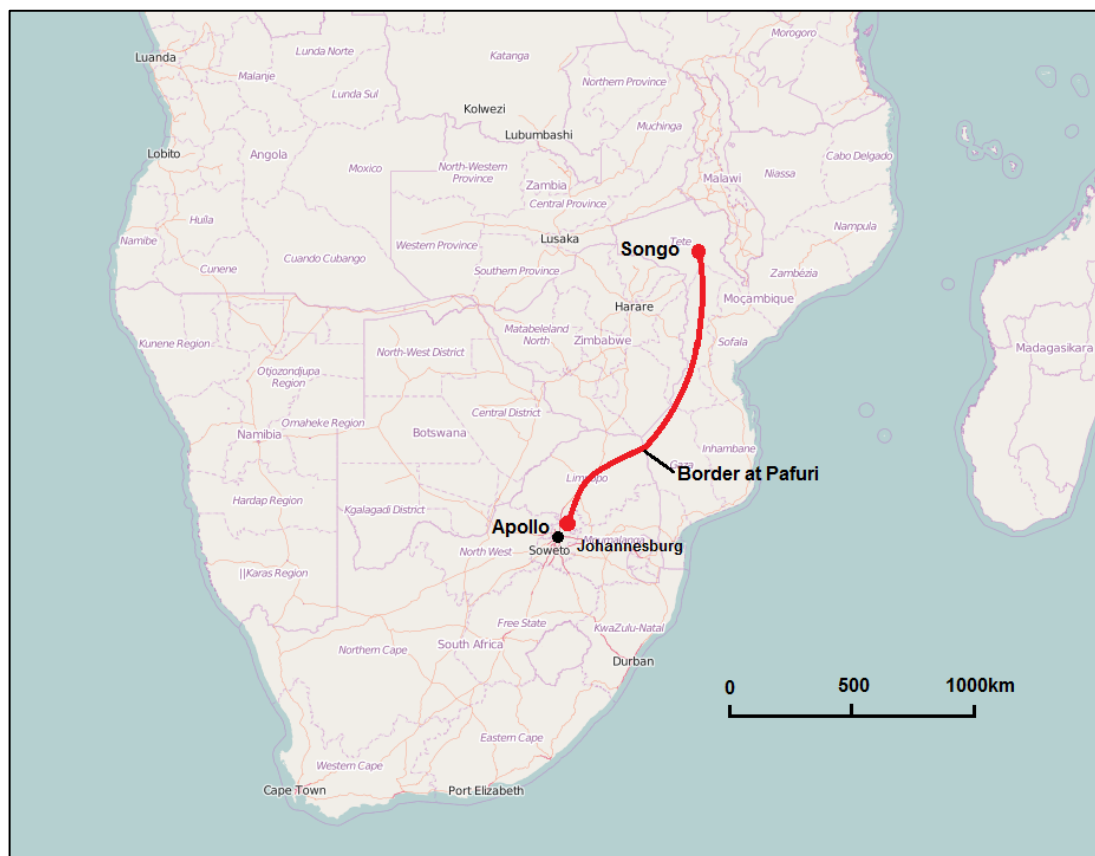


Figure 8: Route of the Cahora-Bassa HVDC scheme⁵.

3.3.2 Unique Properties of the Cahora-Bassa HVDC Lines

The Cahora-Bassa HVDC Scheme has an unusual configuration consisting of two separate transmission lines that are particularly suitable in comparing the performance between the two lines since the two lines have no mutual interaction and can be independently analysed.

⁵ Original Line drawing produced from Open Street Map

The Cahora-Bassa scheme is one of only two known HVDC schemes, where the positive and negative poles are constructed as two independent lines. This line utilises self-supporting “mono-polar” structures shown in *Figure 9*.



Figure 9: Mono-polar strain and suspension pylons of the Cahora-Bassa HVDC scheme⁶.

Cahora-Bassa is however completely unique, in that the poles follow different line routes, generally separated by several kilometers as can be seen in *Figure 10*. The separation between the lines is sufficient to distinguish between strokes to either line with high accuracy. Although the lines are well separated from a lightning shielding point of view, it must be determined if the two lines experience similar average weather conditions, and thus exposure to lightning strokes. If the lightning exposure of the two lines is very similar, a comparison between the performances of the two poles would indicate if the DC line polarity had any influence.

⁶ Photo taken by G.J. Strelec in June 2012.

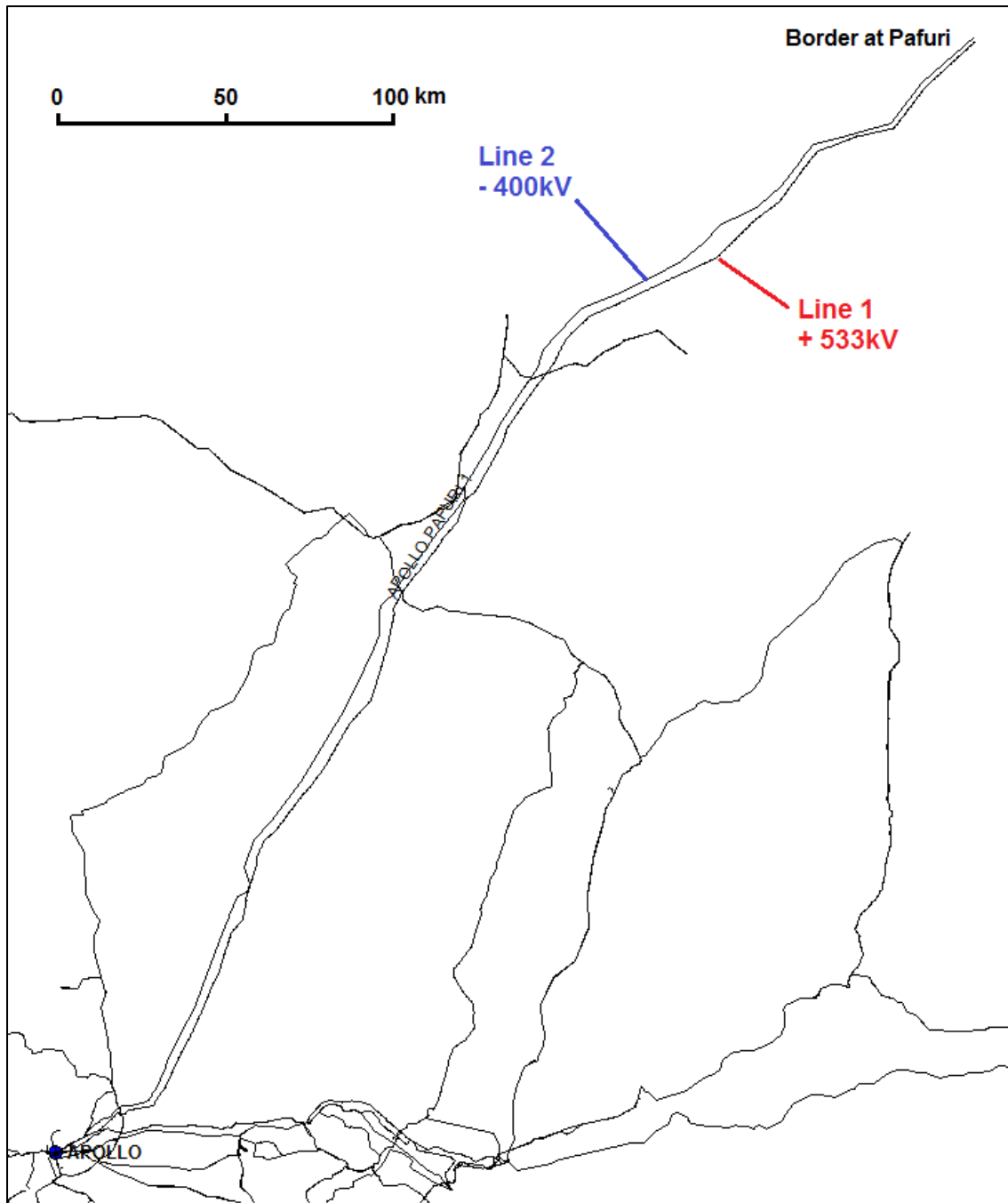


Figure 10: Mono-polar HVDC line routes between Apollo CS and Mozambique border⁷.

There are small sections, particularly close to the terminal converter substations, where the lines run relatively close together as shown in *Figure 11*. However, this is a small percentage of the line length.

⁷ Adapted from the Cahora-Bassa line asset depiction in the Vaisala FALLS® software.



Figure 11: Cahora-Bassa lines exiting Apollo CS⁸.

This scheme was constructed in this way in order to minimise the probability of common mode failure due to extreme weather conditions, or flooding. The benefit of this construction was illustrated in January 2013 when a section of *Line 1*, which is operated as the positive pole, was damaged due to flooding in Mozambique. *Line 1* was only restored in May 2013 and therefore several hundred MW was lost for about five months, while the scheme was operated at reduced capacity in mono-polar mode with only Line 2 in operation (Greyling 2014).

Another potential benefit of separate lines for the two poles is in minimising the risk due to sabotage during times of political unrest. Nevertheless, both lines were severely damaged by terrorist activity during the 1980's and were only restored in late 1997 (Siemens 2016).

3.3.3 Lightning Shielding Design Comparison Based on Shielding Angles

The main aspect that affects the shielding failure rate is the geometry of the pole conductor relative to the shield wire(s). This geometry is defined by a “shielding angle”, indicated in *Figure 12*. The shielding angle is defined as the included angle between the line intercepting the shield wire and pole conductor bundle and the vertical plane.

⁸ Photo taken by G.J. Strelec in December 2015.

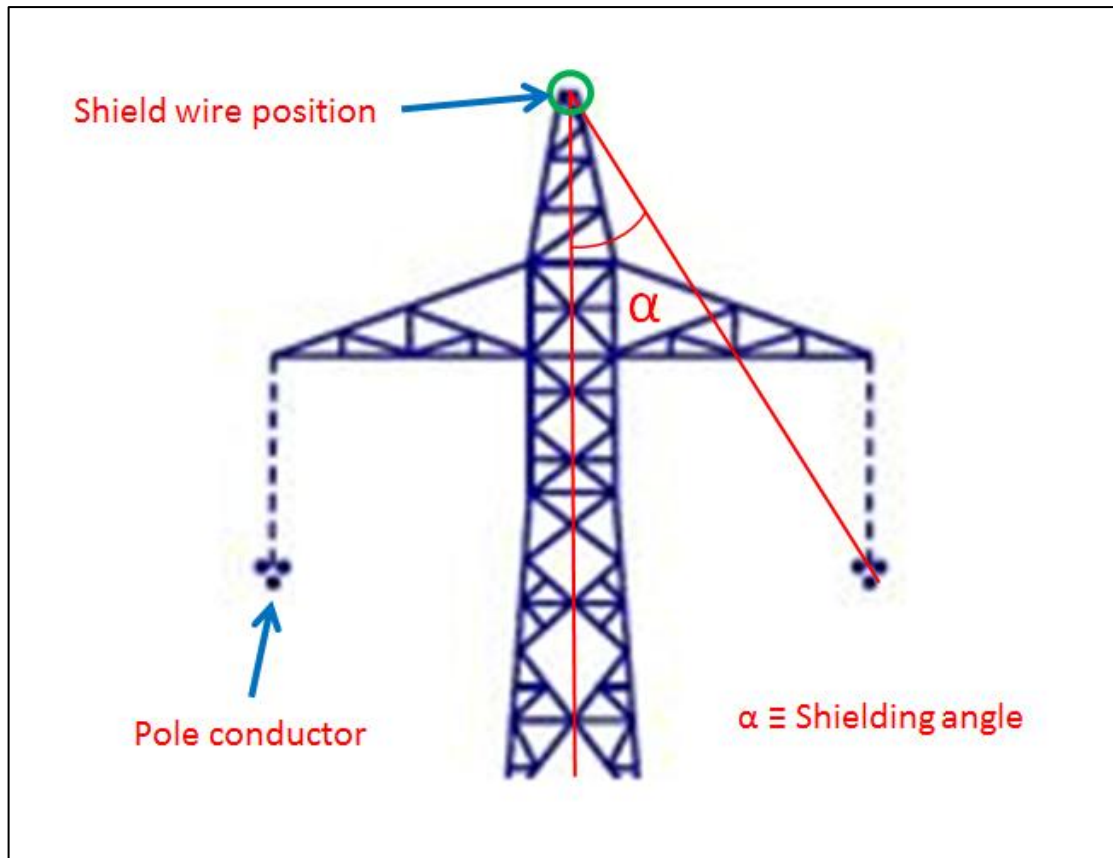


Figure 12: Bipolar HVDC tower geometry depicting the lightning shielding angle.

Traditionally, the majority of High Voltage AC lines were designed with a 30° shielding angle, based on an empirical method of lightning protection design called the “shielding angle method”. According to this method, reduced shielding angles engender superior lightning shielding protection. This “shielding angle method” was commonly applied to HVAC lines prior to the development of the Electro-Geometric Model (EGM). The EGM was developed as an improved model for lightning shielding design, after the shielding angle method was applied to the first EHV transmission line in North America, and resulted in shielding failure rates that were substantially higher than predicted. The EGM is described in more detail earlier in this chapter.

Although the EGM does not directly provide shielding angles but rather defines the geometry in terms of the lightning “striking distance”, the shielding angle can nevertheless be used to describe the basic tower-top geometry. The EGM prescribes geometry that is related to several parameters including the tower height, and electrical clearances, as well as insulation levels. The EGM will effectively result in reduced shielding angles being necessitated in order to achieve the required lightning performance targets for EHVAC and HVDC transmission lines.

3.3.4 Cahora-Bassa Lightning Shielding Design

The Cahora-Bassa structures are not laterally symmetrical, with the position of the shield wire offset from the center of the structure, to reduce the shielding angle. The shielding angle is 15° for downward leaders approaching from the left as viewed in *Figure 13*. Leaders approaching from the right hand side, however, encounter a *negative* shielding angle, i.e. -15° .

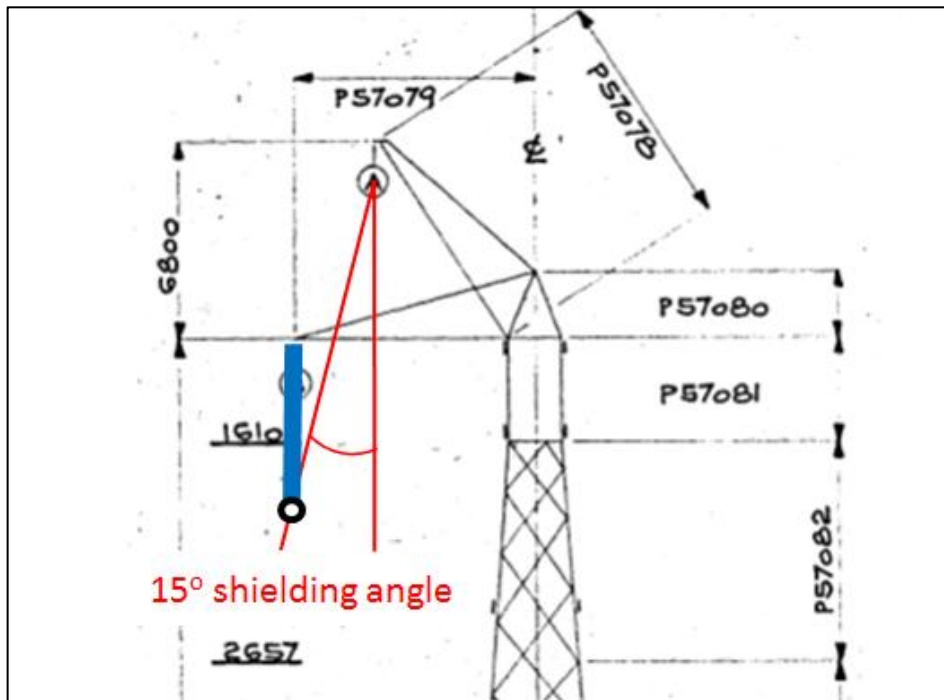


Figure 13: Cahora-Bassa mono-polar suspension tower-top geometry⁹.

This means that the lightning shielding is more stringent for leaders approaching from the side of the negative angle and the probability of a shielding failure is thus much lower.

⁹ Extract from Cahora-Bassa suspension tower outline - Eskom drawing no. 051/601A.

3.3.5 Inga-Kolwezi Lightning Shielding Design

Besides Cahora-Bassa, the only other known HVDC scheme to be constructed on mono-polar structures is the 1700 km ± 500 kV HVDC Inga-Kolwezi scheme in the Democratic Republic of the Congo (Figure 3).

Separate structures reduce the risk due to common mode failure in certain cases, such as construction defects, but since the lines follow the same route, the risk of failure due to extreme weather or flooding is not appreciably reduced.



Figure 14: Route of the Inga-Kolwezi HVDC scheme in the DRC¹⁰.

In this scheme, there are two main aspects that affect the shielding failure rate. Firstly, the shielding angle, and secondly, the relative position of the shield wires and pole conductors of the two independent HVDC lines.

A shielding of 20° is indicated in the *Figure 15*. As is the case with the Cahora-Bassa HVDC line, the Inga-Kolwezi structures are not laterally symmetrical and the position of the shield wire has been offset from the centre of the structure to improve the shielding of the pole conductor.

¹⁰ Original line drawing produced from Open Street Map.



Figure 15: Mono-polar structures of the Inga-Kolwezi HVDC scheme¹¹.

In this scheme, the pole conductors are separated by a modest 60 m. The close separation of the two poles significantly influences the mutual lightning shielding effects between the two lines. This has the effect of reducing the shielding failure rate in the zone of interaction between the two shield wires, where the shielding effects of the two overlap. Leaders approaching from the outside of the two mono-polar lines encounter a negative shielding angle of -20° , and shielding failure is improbable.

Smaller shielding angles improve the lightning shielding. The shielding angles here are not as small as some other cases e.g. Cahora-Bassa HVDC transmission lines. However, the relative arrangement of the two lines and mutual shielding interaction optimises the efficacy of this design. The design challenge would be to balance the shielding failure rate from both sides.

Since the Lightning Flash Density (LFD) is exceptionally high along the route of this line (between 40 and 70), the reduction in reliability associated with the close proximity of the two lines may have been outweighed by the improvement in shielding accompanying the arrangement.

Unfortunately, this mutual influence makes it complex to evaluate the lightning exposure of each line independently, and the effect of polarity on the lightning failure rate cannot be readily investigated.

Photo taken by G.J. Strelec in March 2013.

Although both the Cahora-Bassa and the Inga-Kolwezi HVDC schemes utilise independent mono-polar structures for each pole, the Cahora-Bassa lines are singular in that due to their substantial separation between the two poles, the lightning performance of each line can be independently evaluated.

3.3.6 Nelson River Bipoles Lightning Shielding Design

The Nelson River bipoles of Hydro Manitoba are significant as the lines are located in Canada where the lightning flash density is significantly lower than for the rest of the examples discussed in this section.

Overview of Nelson River Bipoles

All other HVDC schemes besides Cahora-Bassa and the Inga-Kolwezi are constructed on bipolar structures for reasons of economy, and in order to minimise land usage. Bipole 1 is rated at ± 463.5 kV and runs nearly 900 km from the inverter station “Radisson” to a rectifier station “Dorsey”, near Winnipeg, Manitoba, whilst Bipole 2 is rated at ± 500 kV and is about 40 km longer, running between the inverter station “Henday” and “Dorsey” (Figure 16).



Figure 16: Route of the Nelson River HVDC scheme in Manitoba, Canada¹².

¹² Original line drawing produced from Open Street Map.

A further economic saving is that the Nelson River bipoles are constructed of predominantly guyed-mast bipolar structures, which utilise significantly less steel than self-supporting structures (Eskom 2015). The use of guyed towers introduces the advantage of reduced tower surge impedance due to the parallel combination of the mast and four guywires, contributing toward a reduced fault rate resulting from the back-flashover mechanism (Eskom 2015).

Lightning shielding design of Nelson River Bipoles

Operationally, the two inside pole conductors are of positive polarity. The pole conductors are separated by only 60 m (Rizk 2012), therefore the inside pole conductors experience enhanced lightning shielding compared to the outside negative pole conductors in an analogous way, as described for the Inga-Kolwezi scheme. Similar to Inga-Kolwezi, this configuration is not conducive for comparing the performance between the positive and negative polarities since the lightning shielding of the two poles is not equal.



Figure 17: Structures for the Nelson River number 1 and 2 bipoles at Dorsey CS¹³.

Single lightning shielding wires per bipole are evident in the structure geometry of the Nelson River towers, which results in shallow shielding angles of 30°. A single shield wire reduces costs in terms of the cost of the conductor and also as the resultant reduced loading on the structure saves tower steel mass.

¹³ Photo taken by J. Lindsay, August 2005, under license of the Creative Commons.

It is likely that the lightning shielding design for the Nelson River bipoles were based on the traditional shielding angle method and 30° was selected. This is due to relatively low risk of lightning induced faults arising from the low keraunic level associated with these northern latitudes, as can be seen in *Figure 3* of a global lightning flash density map where the LFD is less than 3.

Nelson River Bipole Lightning Performance

The lightning performance of the Nelson River HVDC lines between 1998 and 2000 show that several lightning related faults occurred relating to both “back-flashover” and shielding failure (Shelemy & Swatek 2001).

Faults attributed to shielding failure were due to relatively low lightning stroke amplitudes as shown in *Figure 18*. The lightning shielding design coordination is such that shielding failure will occur for small amplitude strokes below a threshold level (“critical” or “coordination” current) that is unlikely to cause potentials large enough to cause insulation failure and thus line faults. In this case, the strokes leading to faults due to shielding failure are below the threshold level, indicating that the lightning shielding design may be inadequate. It is unexpected that a stroke with an amplitude of 15 kA (*Figure 18*) resulted in a fault.

Conversely, large amplitude strokes result in failures that are assumed to be due to the back-flashover mechanism.

Therefore, the lightning induced faults exhibit a “bimodal” distribution for the two fault modes. There will be a range between the distributions of current amplitudes for the two modes of failure, where the lightning protection system and insulation coordination design will successfully prevent lightning induced faults (Shelemy & Swatek 2001).

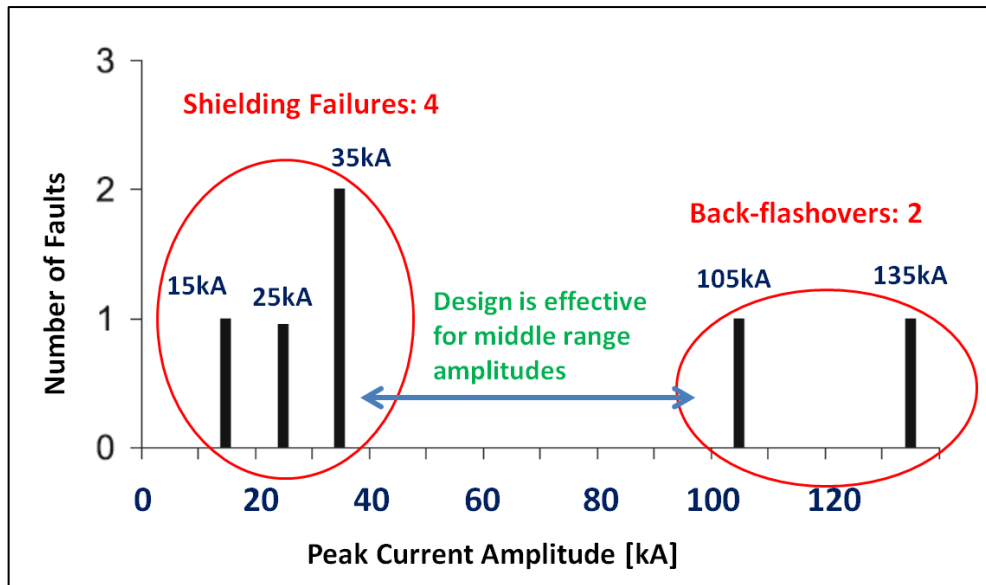


Figure 18: Lightning related faults on the Nelson River HVDC lines¹⁴.

3.3.7 Leyte-Luzon Lightning Shielding Design

Most other HVDC schemes are constructed of bipolar structures that support both positive and negative pole conductors, and are generally isolated from other HVDC lines as shown in *Figure 19* of the Leyte-Luzon ± 350 kV HVDC scheme in the Philippines.



Figure 19: Structures of the Leyte - Luzon HVDC scheme in the Philippines¹⁵.

¹⁴ Adapted from Shelemy & Swatek (2001).

¹⁵ Photo from <http://www.mapelveiculos.com.br/home/hvdc-transmission-ppt> accessed on 10 January 2016

In such cases, lightning performance studies comparing the performance of the positive and negative poles are valid, as the structure is laterally symmetrical and the pole conductors are equally exposed to downward leaders.

This particular HVDC line is constructed with two shield wires positioned for a relatively steep shielding angle (15°) improving the shielding of the pole conductor. In addition, the shield wire is relatively close to the pole conductor compared to single shield wire designs. This improves the inductive coupling between the shield wire and pole conductor, and therefore results in a proportionately lower voltage difference between the shield wire (and tower), and the pole conductor, during a strike to the shield wire. This reduces the probability of a back-flashover.

3.3.8 International Lightning Protection Design Best Practice for HVDC Lines

As can be seen in the previous examples, the lightning shielding design varies significantly, but does seem to be loosely related to the prevailing lightning flash density in the area. A concern over the lightning performance prediction of HVDC lines is that in many cases there does not appear to be consistency in the lightning shielding design for HVDC. This is apparent in the previous examples where various configurations and shielding angles have been employed. A compelling example is shown in *Figure 20* which depicts the only HVDC line-crossing in the western hemisphere, near Wing in North Dakota. Such line crossings pose a large risk to the power system as a structural failure on one line could result in the loss of two bipoles.

This case is curious because the two bipoles have significantly different lightning shielding designs despite being exposed to a similar average level of keraunic activity along their routes. The Square Butte (SB) bipole (commissioned in 1977) uses guyed-mast structures, similar to the Nelson River scheme with a single shield wire (30°) whilst the Coal Creek–Underwood (CU) bipole (commissioned in 1979) uses self-supporting towers with two shield wires and therefore steeper shielding angles (15°) offering better protection (Chan-Ki et al. 2009). The self-supporting towers and dual shield wire configuration come at a substantial cost premium but it seems that the shielding benefit over the single shield wire design has not been quantified. The CU bipole that is comprised of self-supporting towers operates at ± 400 kV, and SB bipole operates at ± 250 kV (Chan-Ki et al. 2009) and it appears that the design has been optimised to save costs.

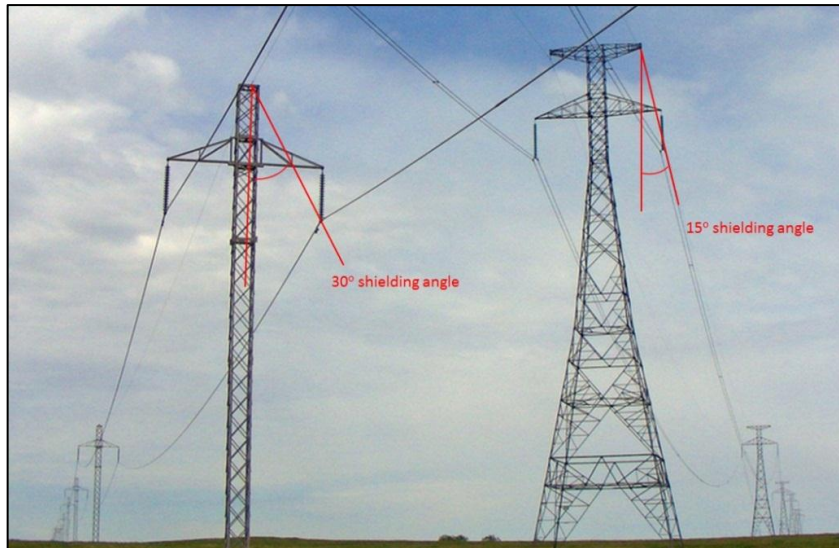


Figure 20: HVDC line crossing in North Dakota, USA¹⁶.

Besides the variation in lightning shielding design, another aspect that is apparent in all these examples is the need to optimise the costs of the HVDC transmission line. The cost optimisation of HVDC lines is perhaps even more critical than with HVAC, due to the generally significantly longer line lengths. Yet the performance is also more important than HVAC due to the much higher power transfer of HVDC and therefore impact of outages. These two 56+ factors, which affect the cost-to-performance ratio (discussed further in 3.1.2), logically emphasise that the understanding of the lightning performance and the shielding design implications of HVDC lines, is of utmost importance.

3.4 Lightning Detection Networks

In this section, the general operation of the South African Lightning Detection Network (SALDN) is described. The operation of the Lightning Detection Network (LDN) explains the performance potential, which is dependent on the circumstances such as the stroke magnitude and the position of the lightning detection sensors of the LDN.

3.4.1 Background of the South African Lightning Detection Network

The South African Weather Service (SAWS) manages the South African Lightning Detection Network (SALDN). The initial network, comprised of nineteen “Vaisala LS7000” Thunderstorm CG Enhanced Lightning sensors, was installed in 2005. The sensors are located across South Africa in order to provide lightning data coverage of South Africa, Lesotho and Swaziland.

¹⁶ Photo taken by “Wtshymanski”, June 2010, under license of the Creative Commons.

“Vaisala” is one of the foremost international LDN system suppliers and also owns and operates the U.S. National Lightning Detection Network (Bardo 2005). The sensors (*Figure 21*) were an international performance standard at the time. The LS7000 sensors are designed to detect cloud-to-ground (CG) lightning strokes. Later models such as the LS7002 can also detect Inter-Cloud and Intra-Cloud (collectively IC) lightning discharges; however, these are of lesser practical interest compared to CG strokes that affect ground objects.



Figure 21: Vaisala LS700 Cloud-Ground Lightning Sensor (Bardo 2005).

In 2010, 4 additional sensors were added to the network for a total of twenty-three sensors. Figure depicts the complete SALDN at present (Jan 2016).

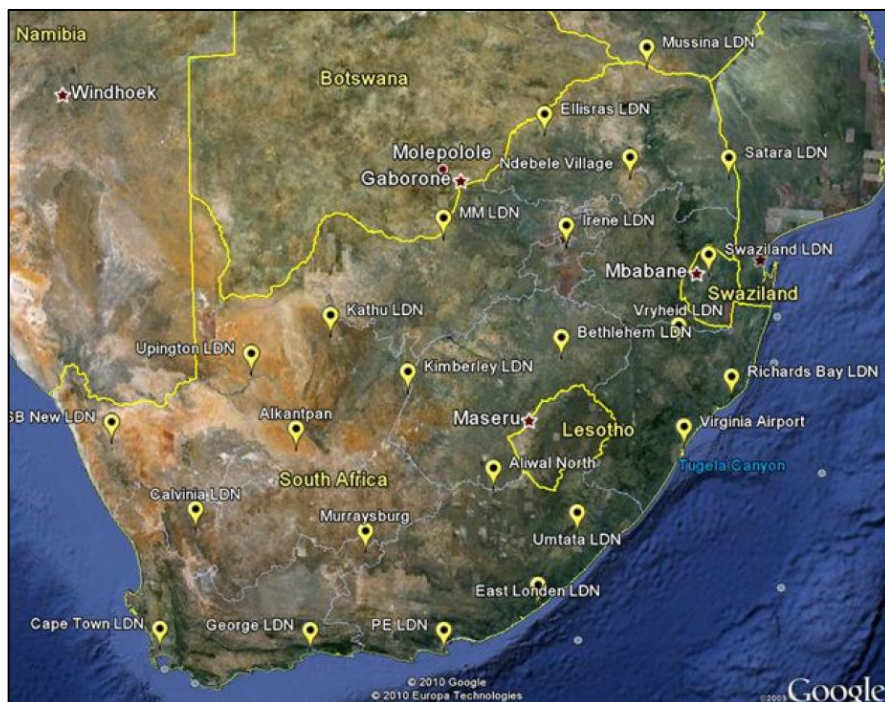


Figure 22: The South African Lightning Detection Network sensor positions (Gibjen 2012).

3.4.2 Lightning Detection Techniques used by the SALDN

The Vaisala LS7000 sensors that make up the SALDN use a combination of two techniques called Low Frequency (LF) Magnetic Direction Finding (MDF) and Time of Arrival (TOA) to provide lightning stroke location (Smidt 2004). The combination of the MDF and TOA technologies in a single detection sensor is referred to as “Improved Accuracy using Combined Technology” (IMPACT).

The operation principles and limitations of the two techniques that are used by the SALDN sensors are described in more detail in the following two sections.

Magnetic Direction Finding Technique

The Magnetic Direction Finding (MDF) sensors detect the direction of the magnetic pulse emanating from a lightning stroke. The direction of two or more sensors can be used to determine the stroke location as shown in *Figure 23*. Triangulation must be used to determine the stroke location when only two MDF sensors detect the field. There is an azimuth error in the direction detection, which produces a quadrilateral locus, within which the stroke occurred. The most likely and therefore reported location is determined by minimising the sum of the square of the azimuth errors (Hunt 2012).

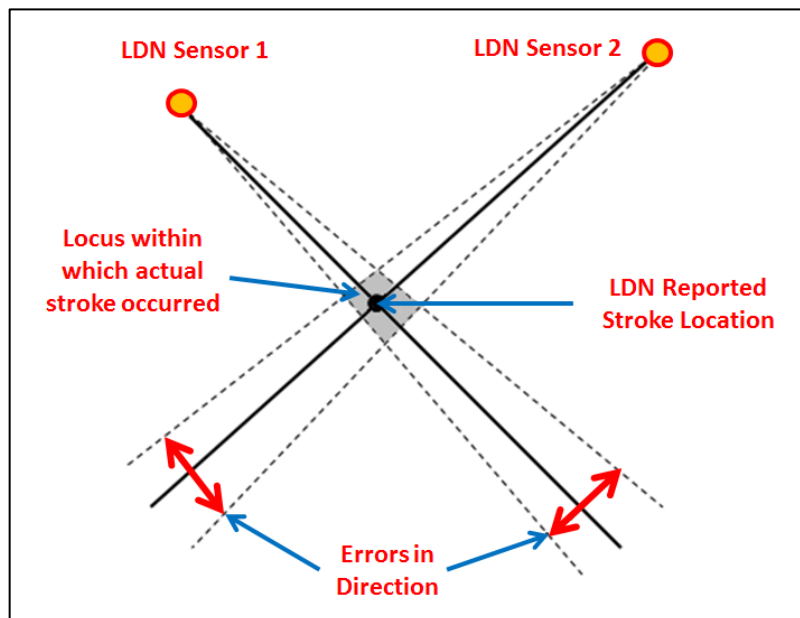


Figure 23: Reported stroke position as determined by the MDF technique¹⁷.

¹⁷ Adapted from Hunt (2012).

When three or more sensors report a lightning discharge, an optimisation algorithm can be used to minimise the “angle disagreement” between the sensors. *Figure 24* shows the “triangle of error” that is produced by the azimuth errors between the three sensors. The “optimal” or “most probable” location is computed by minimising the errors between the reported directions of the three sensors. The most probable location is not necessarily the actual stroke location but should be in close proximity.

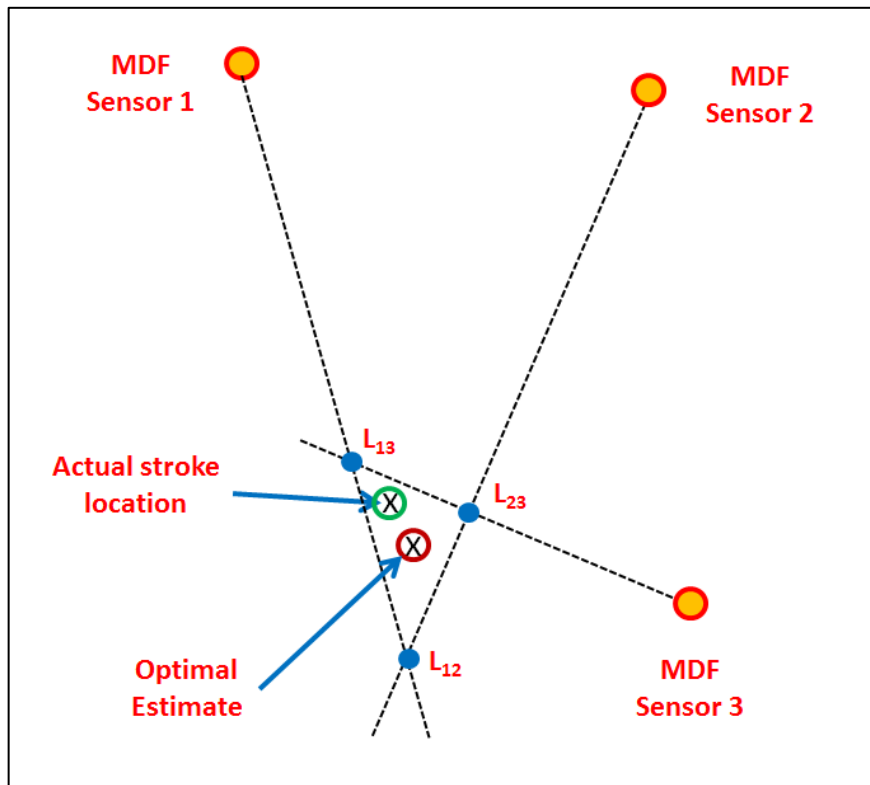


Figure 24: Optimal location for stroke location by MDF technique with three detecting sensors.

There are certain geometrical arrangements of the relative positions of the detecting sensors and lightning stroke, where the MDF technique can produce poor results. When the lightning strike occurs close to the line between the only two reporting sensors, even small errors in azimuth can produce large errors in location. Therefore, for useful results in all cases, there should be at least three detecting sensors (Cummins et al. 2000).

Time of Arrival Technique

The Time of Arrival (TOA) technique determines the position of the lightning based on the (Global Positioning System) GPS coordinates of the sensors, and the difference in the time of detection of the electromagnetic pulse that emanates from the lightning stroke.

As the sensors are located at different distances from the position of a stroke and the detection times are known, the location of the stroke can be calculated.

From the arrival times of the electromagnetic pulse, the possible location of the stroke as detected by each sensor is described by a hyperbolic locus. For the determination of the stroke position, a minimum of three sensors must detect the pulse. Errors in time detection of the pulse by each sensor result in an offset in the position of the stroke as defined by the hyperbolas. Due to these errors, the hyperbolas will not intersect at a single point and instead multiple intersections of the hyperbolas define an area within which the position of the stroke is located as shown in *Figure 25*. The reported location is obtained by minimising the sum of the squares of the errors between the detecting sensors (Hunt 2012).

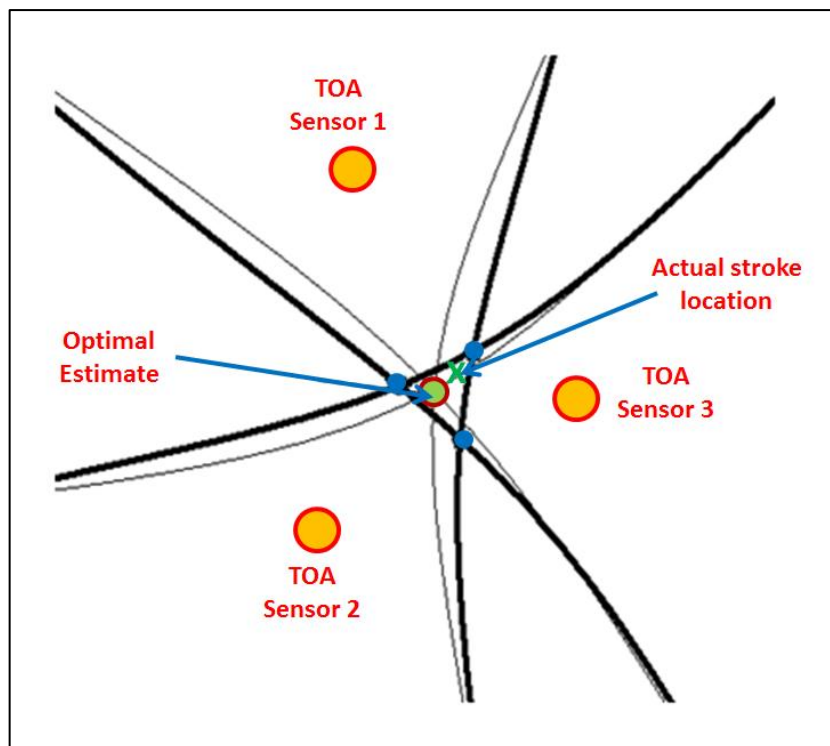


Figure 25: Optimal estimate of stroke position as defined by the TOA technique¹⁸.

Combination Method

By using a combination of the MDF and TOA techniques which is commonly referred to as the Improved Accuracy using Combined Technology (IMPACT), the stroke location can be reported even when only two sensors detect the electromagnetic pulse (Hunt 2012).

¹⁸ Adapted from Hunt (2012).

This method depicts the reported location of the stroke by means of a “location error ellipse” which is an area within which the true position of the stroke exists with a finite probability. These ellipses are alternatively referred to as “confidence ellipses” and are associated with a particular confidence (usually 50%, 90% or 99%) that the true stroke position is within that ellipse. The center of the ellipse is the optimal position, and not necessarily the true position, as shown in *Figure 26*. A 50% ellipse means that there is a probability of 0.5 that the stroke occurred within that ellipse. The 50% ellipse is substantially smaller than the corresponding 99% ellipse, as the larger 99% confidence ellipses encompass a larger area related to the higher probability that the stroke occurred within the ellipse. The scaling factor between the 50% and 99% ellipse major and minor axes is a fixed 2.578 (Cummins et al. 1998b).

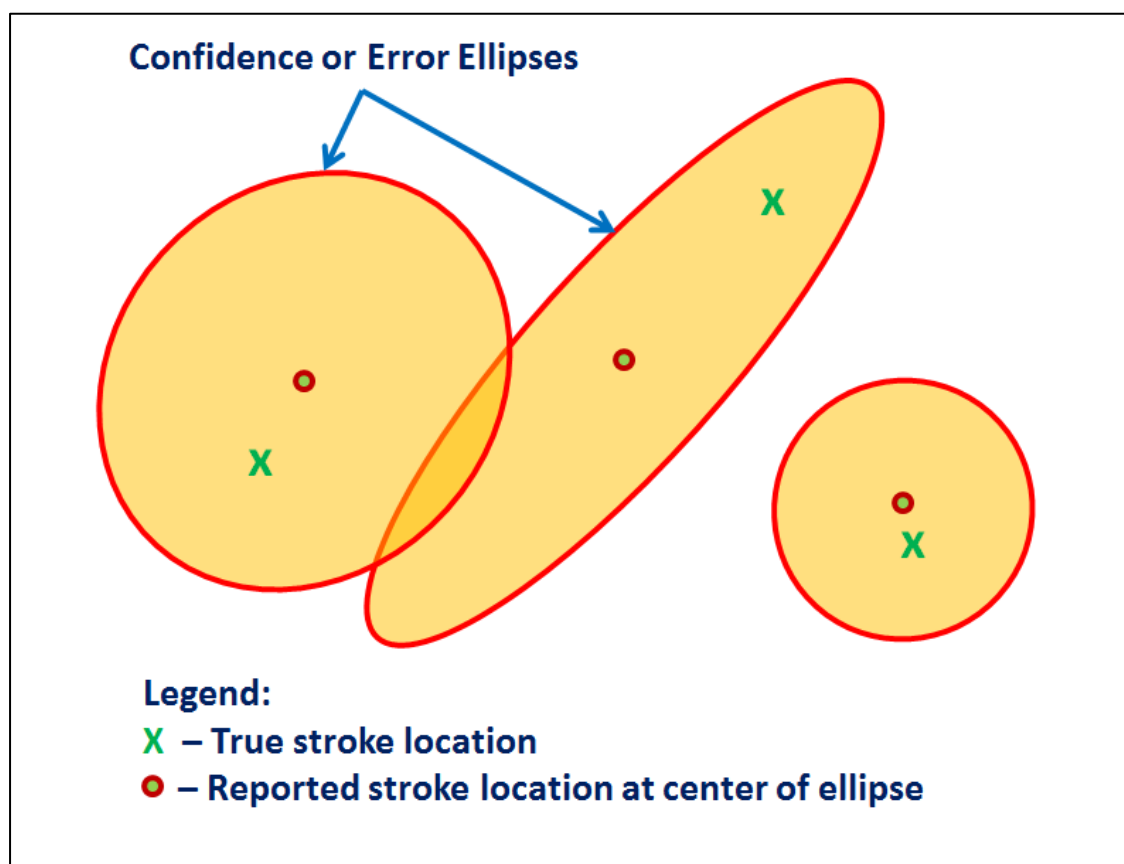


Figure 26: Confidence ellipse with the reported location and true stroke location.

3.4.3 LDN Operation and Performance

LDNs utilise sensors that detect the magnetic field associated with the lightning return stroke current. The stroke peak current amplitude is inferred from the measured peak magnetic field while the electric field is sampled in order to determine the stroke polarity.

The accuracy with which the LDN reports a lightning stroke location depends on the number of sensors that detect the magnetic field associated with the stroke. Two factors determine the number of sensors that detect a stroke.

- a. Stroke peak current amplitude: The magnetic field is proportional to the return stroke current, and the sensors have a minimum detection threshold, therefore the number of detecting sensors will be dependent on the return stroke peak current amplitude.
- b. Distance between the sensors and the stroke: The magnetic field is inversely proportional to the distance between the sensor and the stroke location. Therefore, the number of detecting sensors will also depend on the relative position of the sensors to the stroke location.

Depending on the combination of the stroke amplitude and the relative positions of the sensors, the number of detecting sensors will vary for each stroke. In evaluations conducted on the U.S. National Lightning Detection Network (NLDN), it was found that strokes detected by a minimum of three sensors had location errors between 0.1 and 2 km whereas strokes detected by only two sensors showed location errors of 2 km or more (Hunt 2012). As the number of detecting sensors is related to the peak current amplitude, the location error decreases with increasing stroke amplitude.

The relationship between the location error and the number of detecting sensors is consistent with the MDF and TOA techniques, whereby the process of the minimisation of the errors of individual sensors means that increasing numbers of reporting sensors will result in a decreasing location error in the reported location of a stroke.

In order for the LDN to report the stroke location using the combined MDF/TOA technique, a minimum of two sensors must detect the stroke. If there are only two detecting sensors, the ellipse has a “flattened” appearance where there is a significantly larger uncertainty along the major axis as shown in *Figure 27*. As stated above, the location error is about 2 km or more.

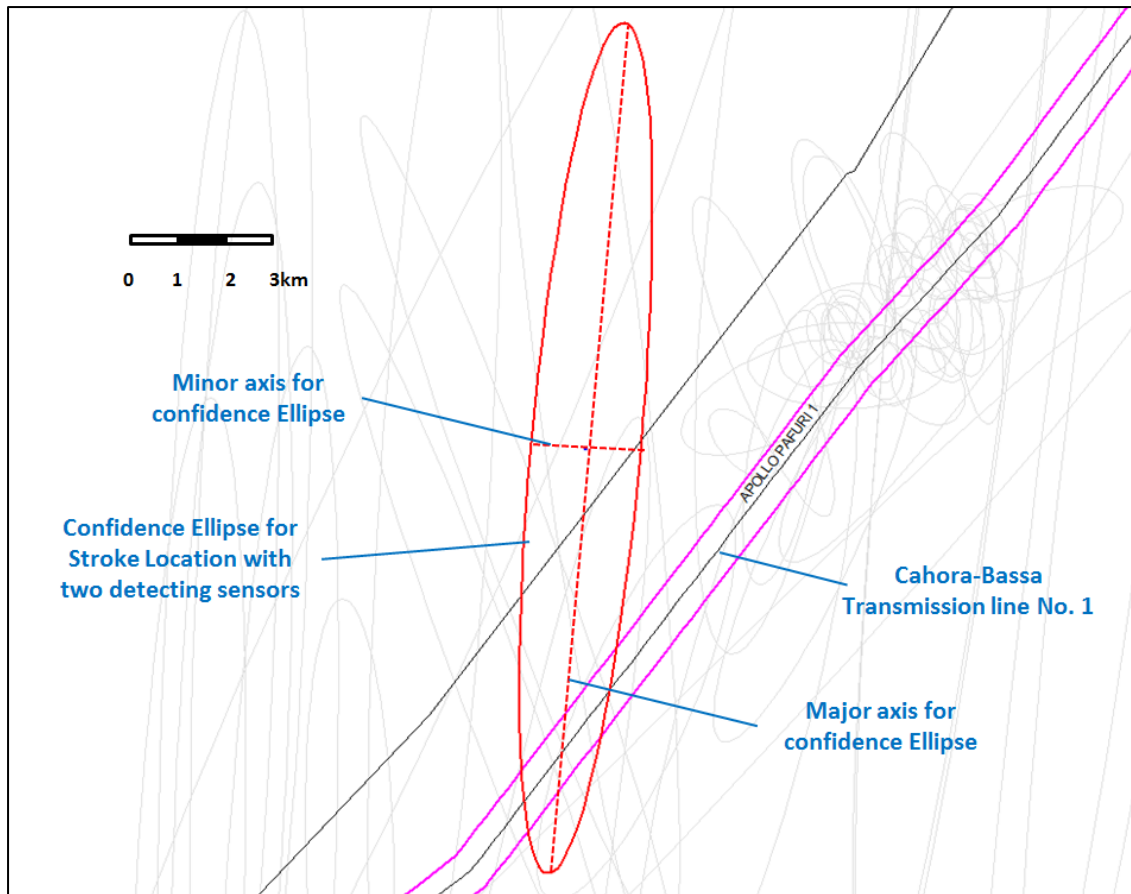


Figure 27: Confidence ellipse for the reported stroke location with two detecting sensors¹⁹.

If the combination of stroke amplitude and relative position of LDN sensors is such that more than two sensors detect the magnetic field, the accuracy in the location of the stroke improves. Confidence ellipses for three and four detecting sensors are shown in *Figure 28*.

¹⁹ Adapted from an extract from Vaisala FALLS ®.

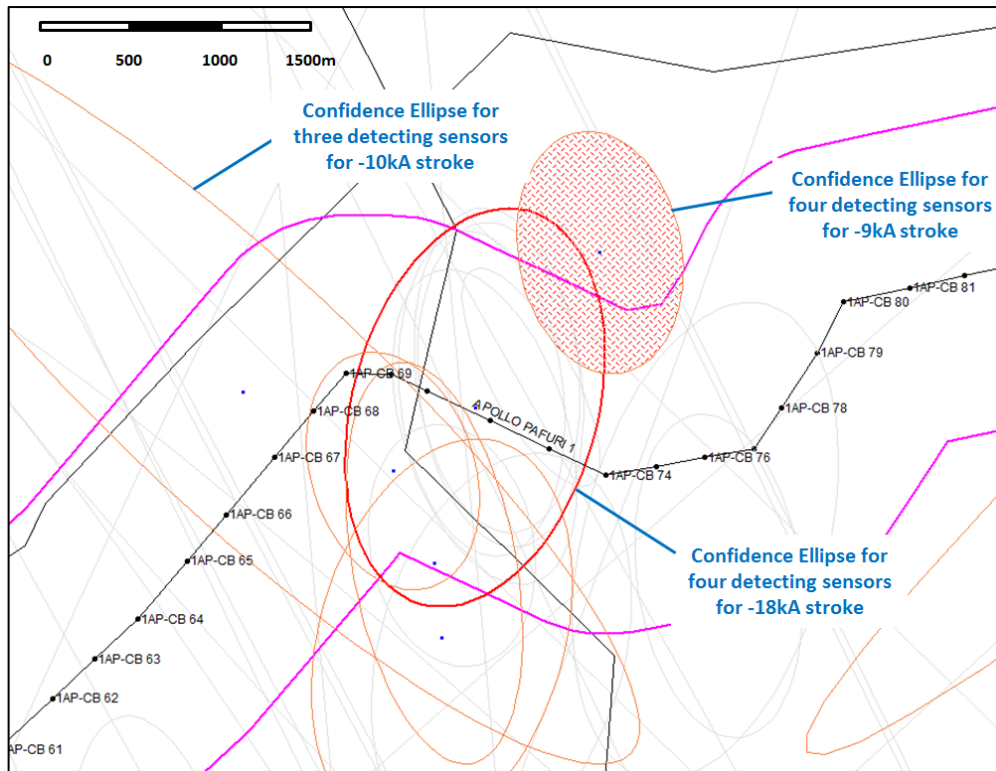


Figure 28: Confidence ellipses for stroke locations with three and four detecting sensors²⁰.

In *Figure 28*, the ellipse for the 18 kA stroke detected by 4 sensors has a scaling factor of about 2 along the major and minor axes compared to the ellipse for 9 kA detected by the same number of sensors. The relationship between the ellipse size and stroke current is not direct one. Whilst higher current strokes will generally be detected by more sensors and therefore the position will be computed more accurately, this is not true of every detection. The size of ellipse is primarily dependent on which specific sensors detected a stroke, as well as the internal settings of the LDN system and the sensors (Cummins et al. 1998b).

For the U.S. NLDN, which uses similar technology to the SALDN, strokes with an estimated peak current of 5 kA are typically detected by between two and four sensors, whilst strokes of 25 kA are detected by between 6 and 8 sensors (Cummins et al. 1998a). This is also typical for the SALDN as shown in the investigation.

If the number of sensors that detect the stroke increases further, the confidence ellipse tends toward a circle. The red circle in *Figure 29* depicts the position of a stroke that was detected by twelve Sensors. The orange ellipses are strokes, which have only been detected by three or four sensors.

²⁰ Adapted from an extract from Vaisala FALLS ®.



Figure 29: Confidence ellipses for individual strokes detected by twelve, four and three sensors²¹.

3.4.4 Accuracy of the Lightning Data

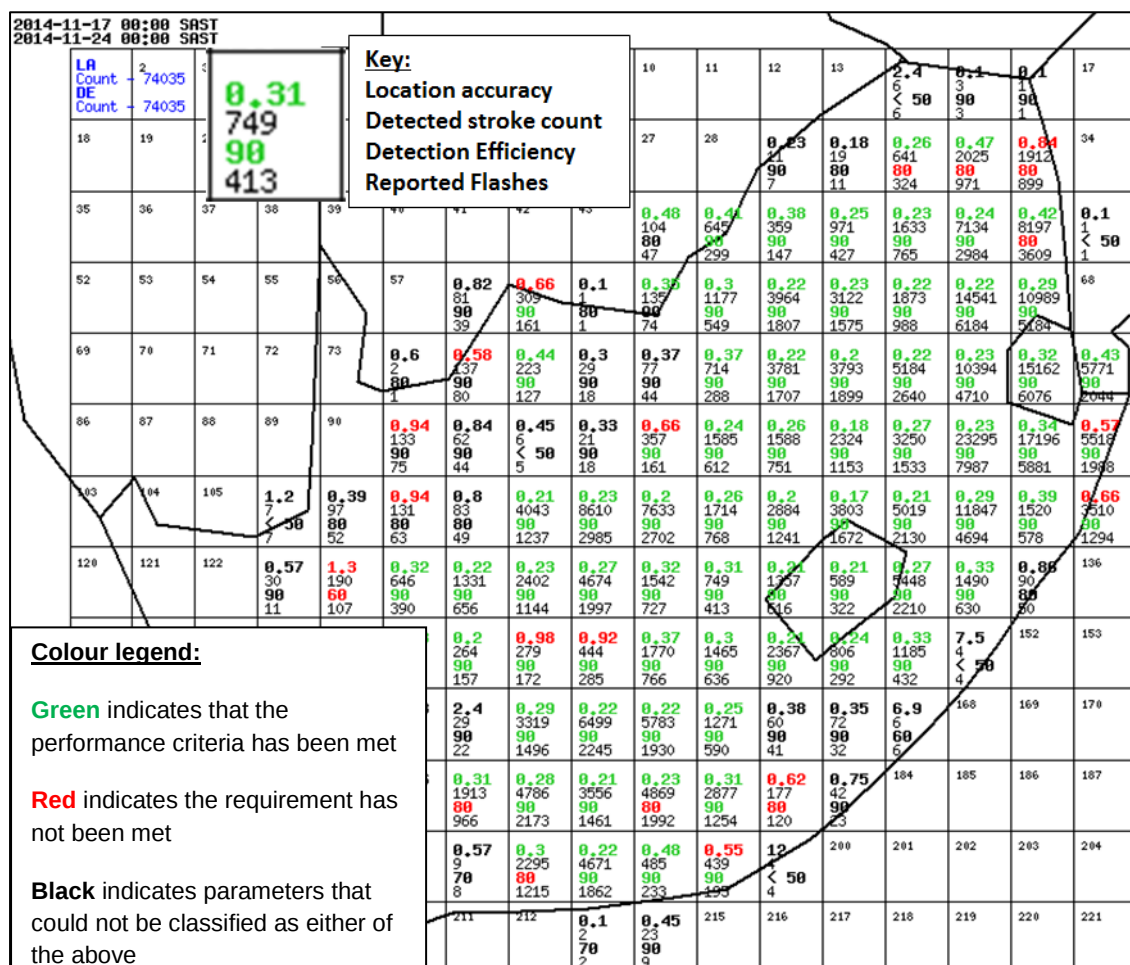
The two main performance parameters for a LDN are detection efficiency (DE) and location accuracy (LA). The flash DE is the ratio of the number of reported flashes to the number of actual flashes. If the DE is low, only relatively higher-amplitude flashes will be detected. The location accuracy is simply the resolution with which the stroke location is known.

The performance specification for the Vaisala LS7000 sensors used for the SALDN provide 90% detection efficiency (DE) of cloud-to-ground lightning and a median location accuracy of 500 m (Smidt, 2004).

Figure 30 shows a sample of the performance of the SALDN for the week between the 17th and 24th of November 2014. Each block on the map is 100 km by 100 km square. Within each block, four values are reported. The top number is the median stroke location accuracy in kilometres. The required location accuracy is 500 m, which is a typical international performance target. This median location accuracy is associated with the second value, which is the number of strokes that were detected. The third number is the flash DE, for which the target is 90%.

²¹ Adapted from an extract from Vaisala FALLS ®.

During periods with high lightning activity, the detection efficiency of the LDN is reduced, and therefore some of the strokes may not be reported by the LDN. During periods of low lightning activity, the detection efficiency is comparatively high. In cases where the correlation is close but not precise, the faults are assumed lightning related as the spatial correlation is good, and the fault is likely to be associated with a subsequent stroke. Subsequent strokes in a flash are separated by the order of between 65 and 87 ms (Cooray 2010).



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3.5 Cahora-Bassa Protection Scheme Operation and Accuracy

In this section, the basic operation of the Cahora-Bassa line protection system is explained. The accuracy of the fault time stamps used for the lightning correlation is discussed.

3.5.1 Operation of the Protection Scheme

The DC line protection system functional type is referred to as “Line Derivative Protection System”. The main system components of the system are shown in *Figure 31*. The basic operation is as follows: A surge detector is installed in the Power Line Carrier (PLC) coupling capacitors (CC) at the terminals of the line being monitored. During a fault, this detector rectifies the resulting high derivative voltage drop, which is compared to a pre-set trigger level. The detector thus triggers for signals with both positive and negative slopes (Vestergaard 2006).

The protection scheme operates with the Line Fault Locator (LFL), which is used to detect faults and to determine their location on the DC lines of Pole 1 and Pole 2 by using the Time of Arrival (TOA) technique of the travelling wave that results from a fault transient. GPS satellites synchronised at each end of the line being monitored are used to time stamp the arrival time of the incoming front of the first travelling wave (Vestergaard 2006).

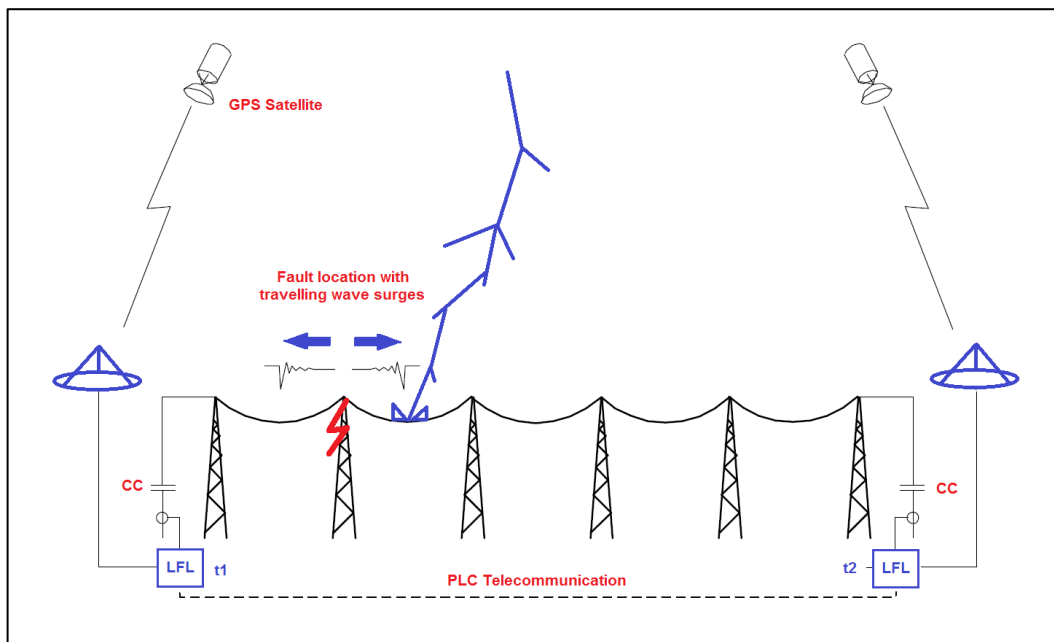


Figure 31: Main components of the LFL system²².

²² Adapted from Vestergaard (2006)

The LFL system reports the GPS clock times for the protection system pick up. For the purposes of fault correlation, the LFL system provides the fault times from the protection scheme. The times reported by the LFL are reported to nanosecond resolution and have been rounded to milliseconds for the purposes of entering the fault times into the lightning fault correlation software, which only accepts the fault times to that level of resolution.

The LFL system is comprised of two redundant systems: “Primary LFL” and “Secondary LFL” which is a backup to the primary system. The secondary system has not been operating reliably and therefore has been disregarded in this investigation. The fault times reported from the LFL system are assumed accurate as they are derived from GPS times. The LFL system was commissioned in September 2008. Protection scheme reports therefore commence on the 17th September 2008.

3.5.2 Fault Reporting from the Line Fault Locator

For the purposes of this investigation, a line fault constitutes a breakdown of the line insulation and a short circuit to earth. This short circuit results in the normal operational voltage collapsing to a very low value. The operation of the protection system is based on the rate of voltage collapse, i.e. dv/dt . There is a defined threshold of dv/dt that is used as a trigger for the protection system. Rates above the threshold will result in either “Pole 1” or “Pole 2” being recorded, indicating a fault on either one of the two lines. If the dv/dt is above the protection threshold, the current is reduced to zero by altering the bridge thyristor firing angle to 0° . After 250 ms has elapsed allowing the fault arc to be extinguished, the voltage is ramped up to 10% below full operational voltage for testing period of five minutes, to see if the line resists further flashovers. If there is a second fault within five minutes, the affected pole is “locked out” and the voltage is kept at zero.

Rates that are below the threshold may result in “Pole 0” being recorded by the LFL scheme. These events are due to indeterminate transients, which are currently under investigation, and not line faults. One of the possible events that may result in “Pole 0” being recorded is suspected to be flashover of the insulated shielded wire spark gap. Therefore, “Pole 0” does not indicate a fault on either Line 1 (“Pole 1”) or Line 2 (“Pole 2”) and has been disregarded.

There is one LFL report per day while the system is in operation. Most of the reports are blank, indicating that no fault events have been recorded. A small portion of the reports detail faults on either Pole 1 or Pole 2, or in some cases both.

The primary LFL system is not operational at all times and therefore there may be some line faults that are not reported by the LFL. For this reason, the faults from the LFL system have been crosschecked with a database of faults maintained by the Apollo CS operational staff (Greyling 2015). During the crosschecking process, some faults were identified on the database that were not reported on the LFL. These additional faults have been considered for the correlation with lightning activity. However, the database fault times are accurate only to a second resolution, and in a few cases a minute resolution, which increases the uncertainty in the lightning correlation process.

Generally, the LFL time stamps should be precise. However, there may be cases where the LFL may not always be accurate, as the threshold for protection pickup may not be calibrated. In order to calibrate the system, it is necessary to stage several faults on the line, as these faults stress the line reactors and generator machines at the Songo hydroelectric plant, the calibration has not been completed. There is no definite information available regarding the potential inaccuracy of the LFL.

In order to have fully redundant systems, it is planned to commission a new and more sophisticated LFL system in February 2016, and to calibrate both systems simultaneously.

3.6 Scope of the Dissertation

The scope is to investigate the lightning performance of the 517 km South African portion of the two Cahora-Bassa HVDC lines. Firstly, the overall average lightning exposure of the two lines will be determined, allowing the exposure of the two lines to be compared. Secondly, all line faults from the line protection system will be correlated with lightning data, in order to determine if the fault was caused by lightning.

The faults that are determined to be lightning related are not differentiated between the shielding failure and back-flashover modes of failure, but probable causes for failure are discussed. The classification of the modes of failure based on modelling will be investigated in future work.

The aim of the investigation is primarily to compare the influence of the DC polarity on the incidence of lightning faults, and to determine if the results agree with other published findings.

The research does not address the underlying lightning physics that may explain a disparity in the performance of the two poles. The dissertation proposes further work that may be necessary to model the HVDC case, and determine the lightning shielding design impact.

In the following chapter, the literature review into the lightning performance of HVDC transmission lines in relation to polarity, is given. The gaps in the understanding of the lightning protection of HVDC lines, is discussed.

4. Literature Review and Gap Analysis

In this chapter, the findings of the literature review, that was conducted to ascertain if there are any internationally documented effects of polarity on the lightning performance of HVDC lines, are presented. This chapter explains the traditional lightning protection philosophy as applied to HVAC transmission lines, and why these methods may be deficient for HVDC transmission lines.

The research commenced with a literature review in order to develop an impression of the state of the art lightning protection design and lightning performance of HVDC transmission lines.

There is substantial literature on the lightning protection design of transmission lines. Comprehensive textbooks on lightning protection (Cooray 2010) and on overhead lines (Kiessling et al. 2002; Eskom 2005), do not consider particular lightning protection requirements for DC lines. There is only one known published reference book (Maruvada 2008) that considers the requirements for lightning protection design for HVDC (Rizk 2012). Although this philosophy is based on the contribution of a single researcher, it remains the best approach for HVDC design to date.

Traditional lightning protection design methods such as the Electro-Geometric Model (EGM), and published international standards (IEEE 998 2012) as applied to HVAC applications may not be suitable for HVDC, and revised models are required. Notably, these traditional design principles do not cater for ground objects energised at an HVDC voltage and may therefore be inadequate for design optimisation and performance prediction. Traditional methods have been extended, or new models developed, for HVDC lightning protection analysis as proposed by several researchers (Maruvada 2008; You 2010; Nayel 2010). These models include the effect of the HVDC pole voltages, but there appears to be no consensus on the approach at present.

In February 2012, the Cigré working group WG C4.26 was established to assess the existing methods (EGM) for lightning shielding analysis for Extra High Voltage (EHV) and Ultra High Voltage (UHV) for both AC and DC transmission lines (Cigré 2016).

There have been several papers published around the performance of HVDC lines in respect of lightning related faults with the focus on shielding failure.

The general operational experience with bipolar ± 500 kV HVDC lines in China indicates that the positive pole experiences significantly more direct stroke penetration events that lead to outages. In particular, for the ± 500 kV Jiang-Cheng line, which is a part of the Three-Gorges project commissioned in 2004, 11 out of 13 lightning shielding failure related outages occurred on the positive pole (He, H, et al. 2009). This trend is consistent with performance records on the ± 500 kV Tian-Guang and Gui-Guang lines (He, H, et al. 2009).

The operational experience data for the ± 500 kV HVDC lines in China Southern Power Grid, indicates that the ratio between the number of shielding failure faults for positive and negative poles of lines is roughly between 8:1 to 10:1 (He, J, et al. 2009). In agreement with the operational data, fractal simulation results showed that the probability of shielding failures to positive pole conductors is significantly higher than that of negative conductors (He, J, et al. 2009). This is also consistent with the lightning physics (explained further in 8.2.1) where under conditions of negative downward leaders, the positive pole conductor more readily experiences induced upward leaders and is consequently, more vulnerable to shielding failures (He, J, et al. 2009).

During the period of 1994 and 1995, the Hydro Quebec ± 450 kV line from Radisson to Nicolet (1200 km), experienced 12 lightning related faults, i.e. 0.5 Faults/100 km/year, where 9 of these faults occurred on positive pole (Rizk 2012).

Another compelling example demonstrating the apparent vulnerability of the positive pole is the two bipolar Nelson River (Bipole 1: ± 463 kV and Bipole 2: ± 500 kV) HVDC lines of Hydro Manitoba, where 4 out of 5 faults that occurred due to lightning, affected the positive pole (Maruvada 2008). Furthermore, despite being better shielded, the positive poles are more affected by lightning, than the negative poles. Operationally, the positive polarity is run on the inside conductors of the two bipolar lines, which are separated by a mere distance of 60 m (*Figure 32*). This results in significantly better shielding for the positive poles than for the negative poles, which are operated on the outside conductors. This case also suggests that the positive pole is more susceptible to lightning-induced outages.

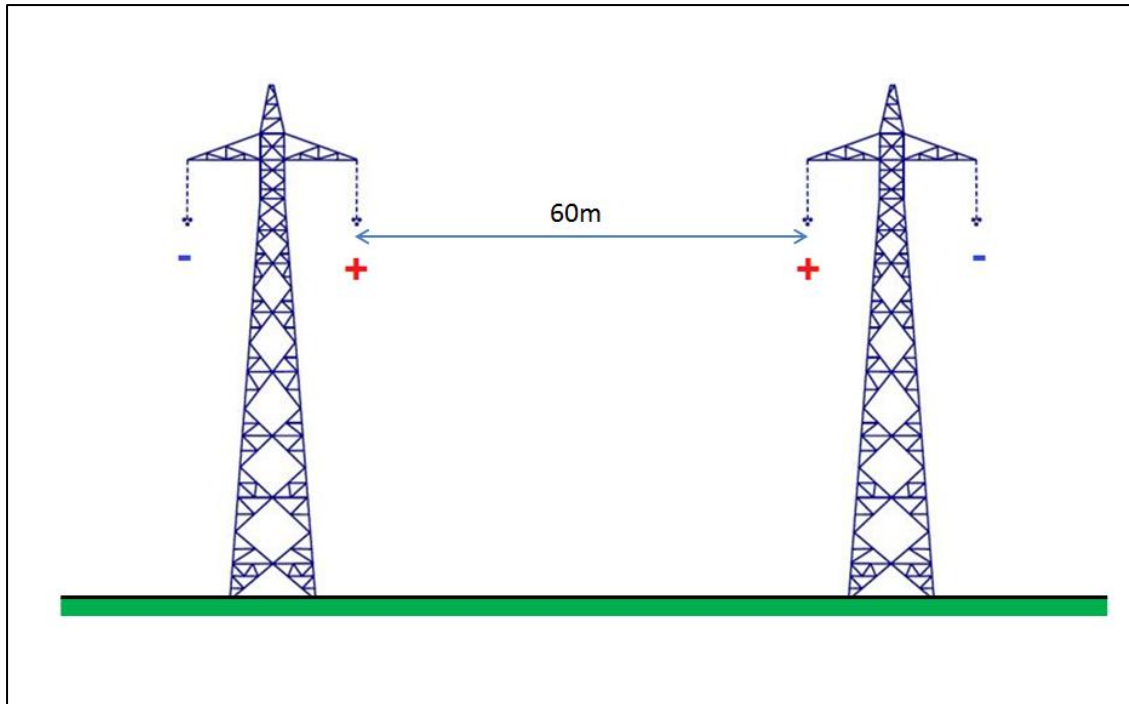


Figure 32: Hydro Manitoba's Nelson River two bipolar HVDC transmission lines configuration.

Although the above three examples are not statistically significant, there is a consistent indication that there appears to be an influence of the pole voltage on the lightning attachment process.

Over several decades, worldwide operational data for 500 kV EHVAC transmission lines has shown that the majority of lightning related faults are due to shielding failure (He, H, et al. 2009). This is consistent with performance data from China, which indicates that for EHVAC transmission lines, more than 90% of lightning related outages are due to shielding failure, and further that the rate of failure for HVDC lines exceeds that of EHVAC lines (He, H, et al. 2009). Therefore, lightning shielding failure is emphasised over back-flash incidents in the performance of HVDC lines.

From the literature review, it seems that the HVDC polarity does affect the lightning performance of HVDC transmission lines. It is also apparent that the understanding of lightning protection applied to HVDC transmission lines is inadequate.

The next chapter explains the approach for investigating the lightning performance of the Cahora-Bassa HVDC Transmission lines.

5. Approach Taken

The approach for comparing the lightning exposure between the two Cahora-Bassa HVDC transmission lines is detailed. The approach for determining the fault rate of these lines from the fault times of the line protection system and lightning data is explained.

5.1 Overall Approach

The two transmission lines of the Cahora-Bassa (CB) HVDC scheme will be used as a case study to investigate trends in lightning induced faults on these lines, in order to compare the two poles in terms of lightning performance.

Reliable performance data is accepted to be scarce internationally (Rizk 2012). This is despite lightning faults having characteristic signatures with steep wave fronts that are readily distinguishable from other faults e.g. flashover due to ground fires under the line. Furthermore, the sensitivity of historical performance information makes it difficult for utilities to publish. It is therefore fortunate that about 7 years of fault and lightning data is available for the Eskom portion of the Cahora-Bassa HVDC Lines.

The first part will be to compare the overall lightning exposure of the two poles of the CB scheme over an 8-year period.

The second part will be to correlate all line faults over a 7-year period with lightning activity in order to determine which line faults were caused by lightning.

If the lightning exposure for the two lines is very similar, a comparison can be made in order to determine if the HVDC line polarity has any influence on the fault rate.

5.2 Approach for Comparing the Lightning Exposure

The aim of the research is to compare the influence of the pole voltage, of the two polarities, on the incidence of lightning related faults. For the comparison to be valid, all other influences must be excluded.

5.2.1 Factors Affecting the Lightning Exposure of Ground Objects

Several factors may influence the formation and discharge of lightning to the ground. The lightning exposure of the two lines could be different due to various factors including the following:

Altitude – As the lines may be separated by several kilometres, the altitude of the two lines may differ by several hundred meters. The reduced distance between cumulonimbus clouds and ground may affect the lightning exposure of the two lines. There is also a decrease in the return stroke current with increasing altitude, which may affect the probability of lightning induced faults.

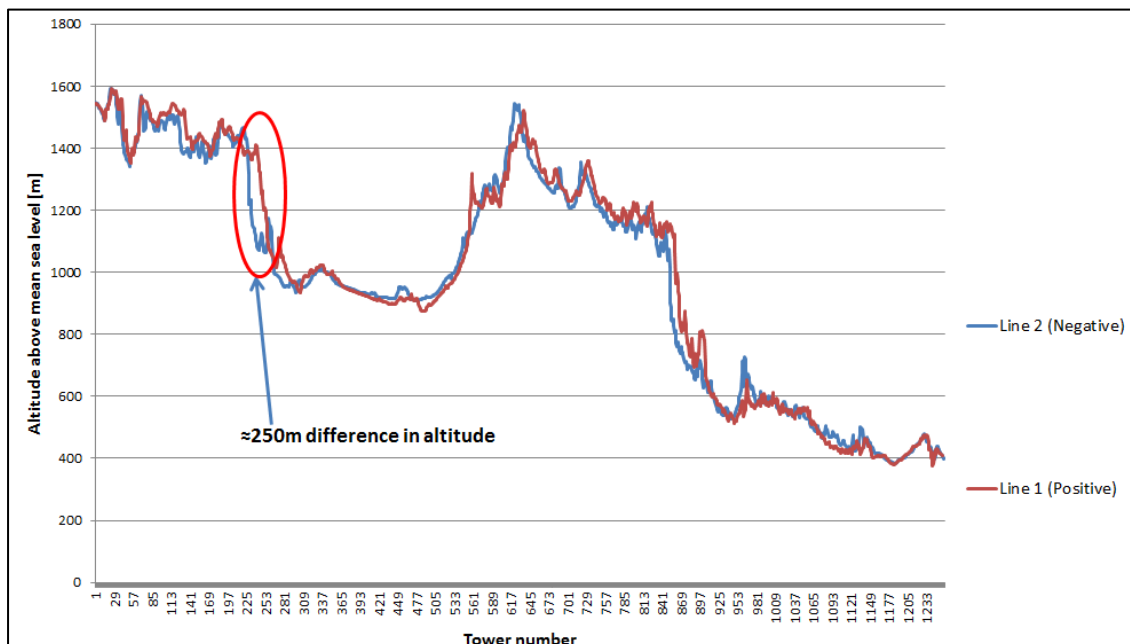


Figure 33: Altitude above Sea Level along the South African Portion of the CB Transmission Lines.

Topography – The ground topography associated with the line route may result in parts of the line being elevated, compared to the surrounding area, which may affect the line's exposure to lightning activity.

Vegetation – Where the lines are partially shielded by tall trees, a lower strike incidence can be expected. In open areas, the line will experience a shorter strike period

Local meteorological effects – Altitude and ground topography may affect local weather conditions, thereby influencing lightning exposure.

Besides the above-mentioned factors, there may be other unknown aspects that influence the lightning exposure of the two lines.

5.2.2 Approach for Comparing the Lightning Exposure

There are two main reasons why the factors that influence the lightning exposure listed above will not be investigated:

- a) The first is that since the situation is complicated with several influencing factors, a detailed analysis along the line route is not considered a practical approach and the significant effort of such an analysis will not produce corresponding value in the outcome.
- b) The second is that the data set of lightning strokes that resulted in faults is insufficient to be of statistical significance. The aim is to determine if there are any trends that concur with international reporting on the performance of other HVDC lines.

For these reasons, the approach is rather to compare the overall lightning exposure of the two lines for the 500 km line length, and if the exposure is very similar, then any factors that may result in a disparity are effectively negated, only the effect of the polarity will determine the incidence of lightning induced faults. That is, if the overall lightning exposure is very similar, the factors that affect this exposure can be ignored.

Therefore, the overall exposure of the two lines will be compared, in order to determine if a comparison between the two polarities would be valid, without detailed investigation into all the factors affecting the lightning exposure of each individual line.

5.3 Approach for Determining Fault Rate

Fault times from the line protection system will be correlated with lightning data. Since faults cannot practically be correlated with absolute certainty, a means of classifying the likelihood that a particular stroke caused the fault in question will be defined in the methodology.

In the next chapter, the methodology that will be followed in order to implement the approach described in this chapter will be proposed.

6. Proposed Methodology

The method for comparing the lightning exposure for the two transmission lines of the Cahora-Bassa HVDC Scheme is detailed. The methodology for fault correlation process is presented. A method for the classification of the likelihood that a particular stroke caused the fault in question is proposed.

6.1 Overview of the Methodology

The overall methodology is illustrated in the following flow chart (read from bottom upwards):

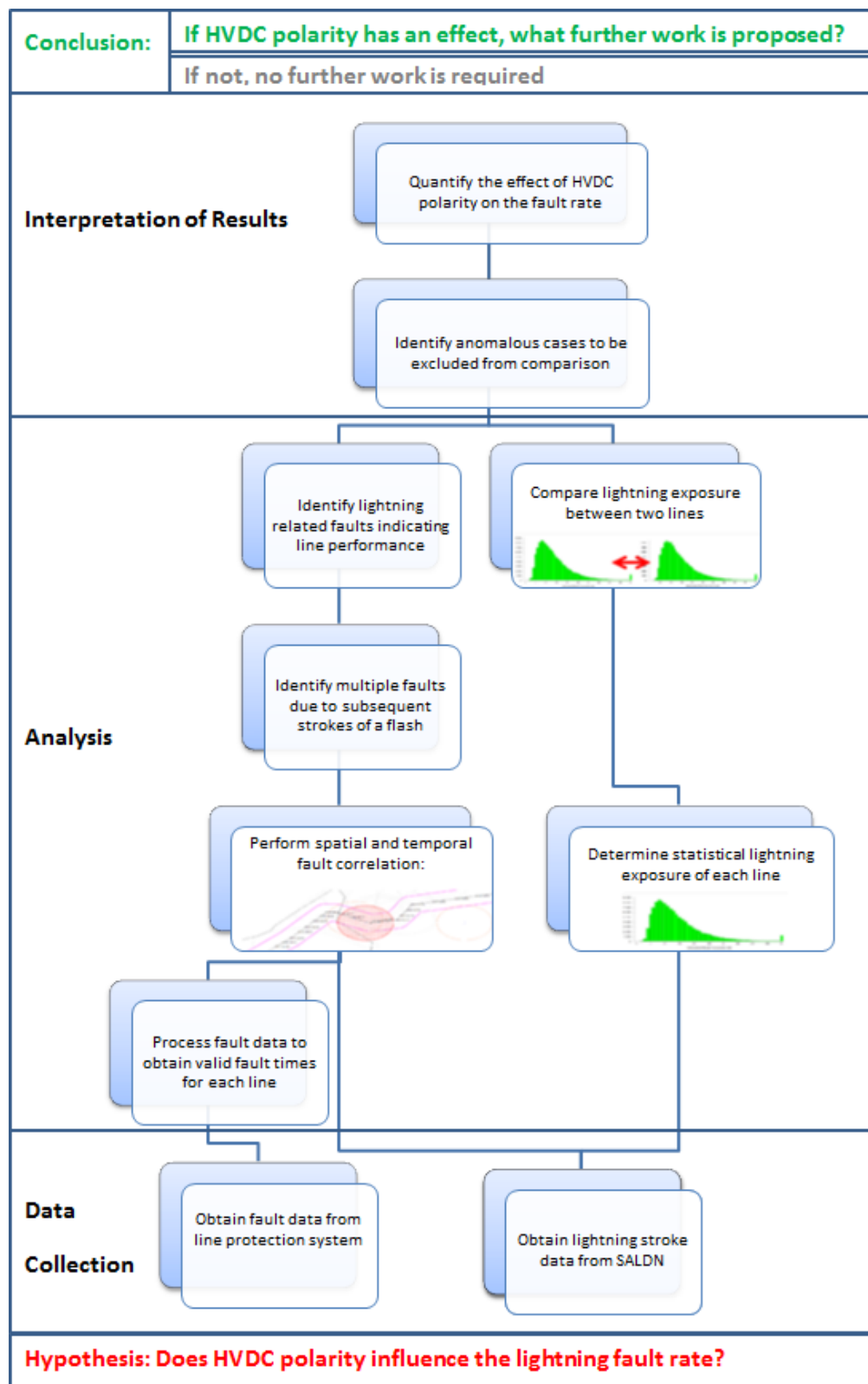


Figure 34: Overview of the proposed methodology.

There are two main processes: The first is to compare the lightning exposure of the two lines. The second is to correlate line faults with lightning activity.

Both processes require lightning data, which is provided by the South African Lightning Detection Network (SALDN) that is managed by the South African Weather Service (SAWS). The protection time stamps for the fault correlations originate from the HVDC line protection scheme.

Once both processes have been completed, the results can be interpreted to determine if the hypothesis has been proven.

Both of these processes are performed using a lightning analysis software package described in the next section.

6.2 Evaluation of the Methodology

In order to evaluate the proposed methodology, the performance results of the CB lines will be compared to other international operational experiences.

6.3 Software Package Used for Lightning Analysis

The lightning data is analysed with the Vaisala-GAI Fault Analysis and Lightning Location System ("FALLS") Version 3.2.4., developed by Global Atmospheric Inc. of Tucson, Arizona in the USA (Vaisala acquired Global Atmospheric in 2002).

FALLS is a spatial and temporal lightning analysis program, which performs lightning exposure analyses in terms of regional statistical analyses, asset exposure and asset reliability analyses (Smidt 2003). There are several tools in the "FALLS" software that can be used for lightning related analysis; however, the following two tools have been used in this work:

- a) *Small Area Exposure Analysis* – Used to determine the lightning exposure of an asset for a certain period.
- b) *Reliability Analysis* – This tool has been used to correlate lightning events with line fault times.

The SAE and RA tools produce both graphical and tabular outputs of the analysis. The SAE and RA functionality and outputs are described in the relevant sections.

The FALLS software is loaded with lightning data from the SALDN. Fault times for correlation investigations are entered manually into the software.

6.4 Methodology for Comparing the Lightning Exposure of the Cahora-Bassa Lines

A methodology for comparing the overall lightning exposure for the two lines is proposed below. This process is performed using the *Small Area Exposure Analysis* tool in the FALLS software introduced above.

6.4.1 Determining the Effect of HVDC Polarity on the Lightning Fault Rate

In order to investigate the hypothesis that the HVDC polarity affects the lightning induced fault rate, the two polarities must be compared under the same conditions. The significant factor influencing the relative lightning performance between the positive and negative poles is the overall lightning exposure of each line. If the lightning exposure of the two lines were different, a comparison would only be possible if all factors that could affect the lightning performance were compensated for.

Therefore, in order to compare the lightning related performance of the two poles, it is necessary to verify that the lightning exposure of the two mono-polar lines is very similar, despite the lines following different routes.

6.4.2 HVDC Line Polarity Reversal

Since this investigation concerns the possible influence of the DC line polarity on the lightning performance, it is critical to associate any lightning induced fault with the line polarity at the time that a particular fault occurred.

As HVDC schemes are comprised of two identical pole conductors, it is possible to assign either positive or negative polarity to a particular pole conductor, by altering the configuration of the thyristor bridges at the terminal converter stations.

Historically, Pole 1 has been operated almost exclusively in the positive polarity. This is best suited to the configuration of the thyristor bridges at the converter station.

The Scheme was constructed in the mid-1970s and spares are no longer available for most of the original bridge equipment. Apollo was refurbished several years ago, whilst the Mozambique operator does not have the capital to refurbish Songo. Presently there are only seven functional bridges at Songo (as shown in *Figure 35*), subsequently, both poles cannot be operated at full voltage simultaneously.

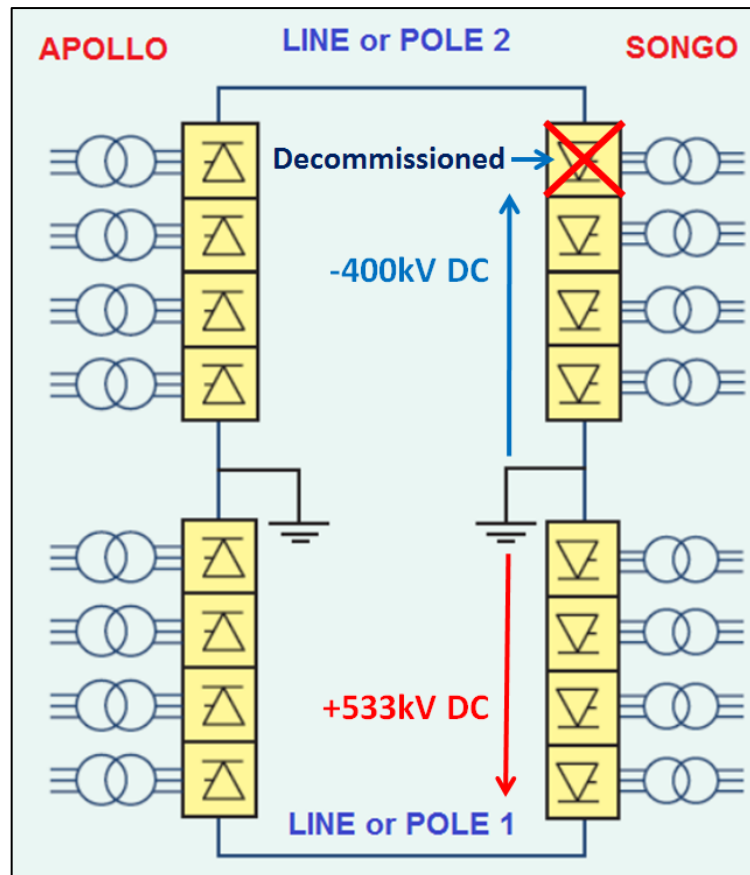


Figure 35: Cahora-Bassa Bipolar HVDC scheme with 7 bridges at Songo²³.

Pole 1 is usually operated at positive full voltage of +533 kV DC, with four bridges of 133 kV in series. Pole 2 is operated at -400 kV DC since there are only three bridges in series available for the negative pole. *Figure 36* shows the relative positions of the line routes for Pole 1 and Pole 2.

The preference is to operate the positive pole at full voltage rather than the negative, for two reasons. Firstly, the positive pole experiences a better signal-to-noise ratio (S/N) for power line carrier (PLC) telecommunications in relation to the operational line voltage (Hubbard 2016).

²³ Adapted from Bahrman (2007)

Secondly, the negative pole results in a greater influence of induced currents at ground level, due to higher negative charge carrier mobility, and therefore it is desirable to operate at a reduced voltage (Hubbard 2016).

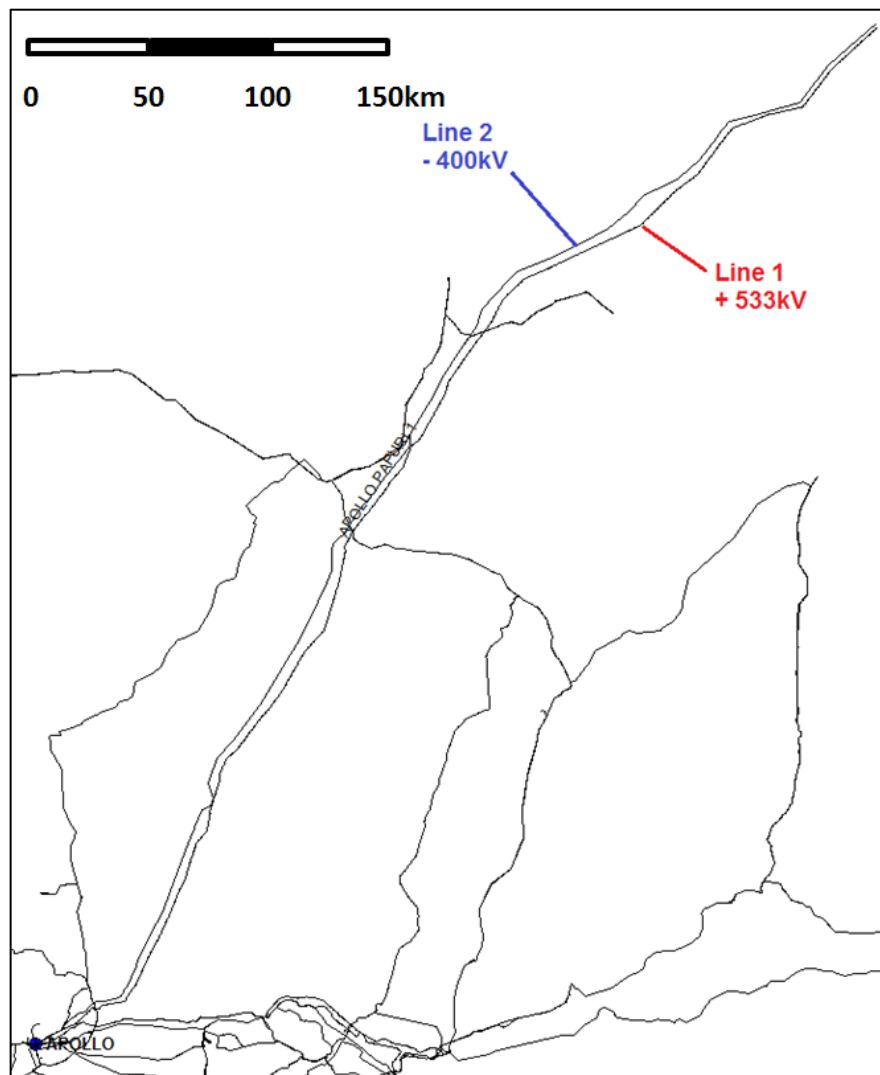


Figure 36: Cahora-Bassa Mono-polar HVDC lines showing normal polarity arrangement²⁴.

During the winter of 2014, the poles were reversed and Line 1 was operated as negative. This reversal was necessitated by a technical problem at Songo converter station. It was however, verified that there was no lightning activity close to the line during this period and therefore no influence on the performance statistics.

²⁴ Adapted from the Cahora-Bassa line asset depiction in the Vaisala FALLS® software.

6.4.3 Regional Statistical Analysis and Lightning Flash Density along the Cahora-Bassa Lines

This “FALLS” technique is used to determine the historical average lightning exposure over large geographical areas (Smidt 2003).

The lightning ground flash density map for 2006 to 2011 (*Figure 37*), shows that the flash density is higher near Apollo CS, between 10 – 15 lightning flashes per square kilometre, and reduces to between 1 – 2 flashes per km² close to the Mozambique border. Therefore, the 500 km South African portion predominantly affects the overall lightning performance of the scheme.

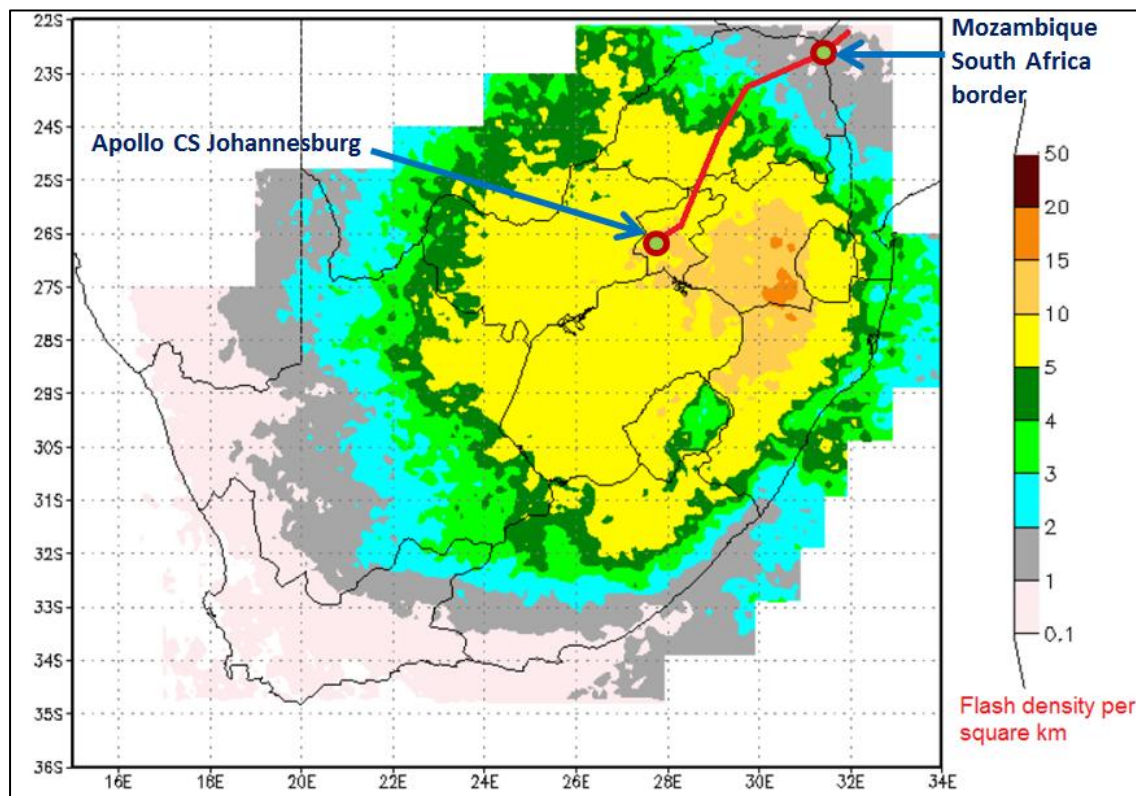


Figure 37: Cahora-Bassa line route overlaid onto the lightning ground flash density map from 2006 – 2011²⁵.

This technique is not of particular significance for the investigation of the lightning exposure of the Cahora-Bassa lines specifically, but provides a picture of the lightning activity in the general area. The Asset Exposure Analysis technique described next, is important for the analysis of the lightning exposure of the Cahora-Bassa lines.

²⁵ Adapted from Gibjen (2012)

6.4.4 Introduction to Asset Exposure Analysis

Exposure Analysis (EA) can be used to determine the level of lightning exposure within user-defined areas around asset infrastructure, such as power lines. A lightning exposure factor provides an objective relative comparison of lightning activity in relation to proximity along the exposure area of the asset (Smidt 2003).

The EA technique provides trends of lightning exposure over assets, and displays this exposure in terms of the amount and intensity of lightning, discriminated by polarity and amplitude within user-defined asset buffers (Vaisala 2012).

In general, EA allows the asset owner to prioritise mitigation measures and justify expenditure based on the risk of lightning faults.

The “Small Area Exposure” Analysis (SAE) tool in the “FALLS” software offers two variations, either a “point-by-point” or a “gridded exposure” analysis. The “point-by-point” analysis depicts individual lightning events as points signifying their reported locations, whereas the “gridded exposure” shows the density of lightning activity within defined grid squares over the analysis area.

The SAE analysis function was used to determine the lightning exposure statistics for the two Cahora-Bassa lines, over a period of eight years, from the 1st March 2006 to 1st March 2014, for which SALDN data was available at the time (December 2014).

The SAE “point-by-point” function was used to display the analysis on a “point” basis for each stroke. The density of the dots gives a subjective indication of the lightning stroke density.

The lightning exposure for the Cahora-Bassa lines is demonstrated by the cumulative lightning strokes for both positive and negative polarities, within a 1 km buffer region around each of the two lines. An example for the SAE for Cahora-Bassa Line 1 between Apollo CS and the Mozambique border for the period between the 1st October 2014 and the 31st March 2015 is shown in *Figure 38*. Individual strokes are depicted as “dots”, however, due to the scale; these dots are not individually discernible on the graphical representation of the South Africa portion of the line.

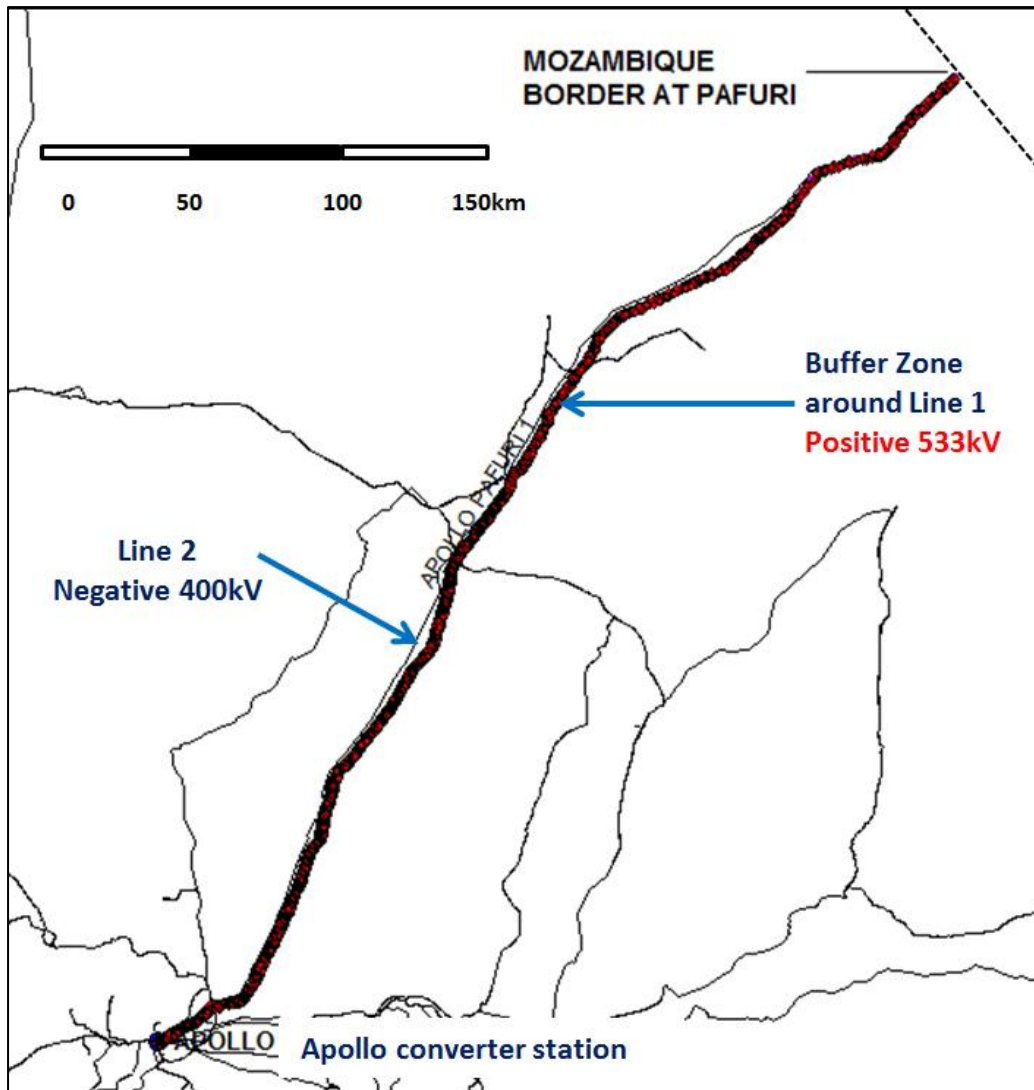


Figure 38: Graphical presentation of SAE analysis for the South African portion of Cahora-Bassa Line 1 for 1 October 2014 – 31 March 2015²⁶.

The individual strokes are visible in Figure 39, which shows the first 30 km of Line 1 from Apollo CS.

²⁶ Adapted from an extract from Vaisala FALLS®.

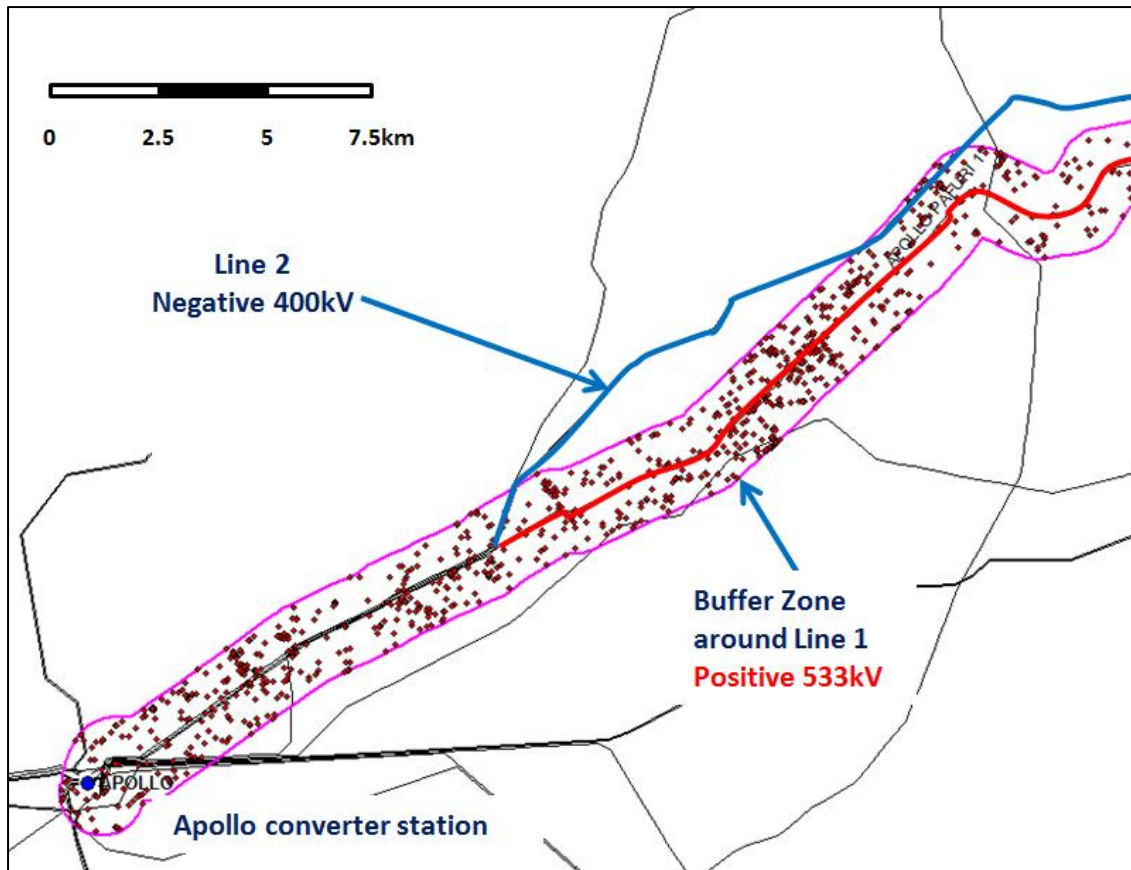


Figure 39: Graphical presentation of SAE analysis for Cahora-Bassa Line 1 near Apollo converter station for 1 October 2014 – 31 March 2015²⁷.

6.4.5 Information Available from Small Area Exposure Analysis

Running the SAE analysis tool for an asset produces statistics of the lightning activity during the period of consideration. The lightning statistics for this period are shown in the browser in Figure 40.

A		B		C		D1		D2							
expstats Browser															
Asset Name	Count	Count(-)	Count(+)	% Positive	Density	Min kA	Max kA	Mean kA	Exp. Factor	Min kA(-)	Max kA(-)	Mean kA(-)	Min kA(+)	Max kA(+)	Mean kA(+)
APOLLO CAHORA B	13 118	12 423	695	5.3	12.7245	2	151	16	205.236	2	151	16	10	116	21

Figure 40: Lightning statistics for the South African portion of Cahora-Bassa line for the period SAE for the period 1 October 2014 – 31 March 2015.

The following are salient aspects of the lightning exposure:

- A. Number of strokes: There were 13,118 strokes within the buffer region for Line 1.

²⁷ Adapted from an extract from Vaisala FALLS®.

- B. Percentage of positive strokes: Only 5.3% of the strokes were positive. All positive strokes below 10 kA are disregarded from the statistics, as there is potential that these Cloud-to-Ground (C-G) strokes may be misidentified with Cloud-to-Cloud (C-C) strokes. This skews the statistics slightly, in favour of a higher percentage of negative polarity strokes.
- C. The maximum, mean and minimum peak currents are given.
- D. As expected the mean positive stroke peak current (D1) is higher (21 kA) than that of the negative polarity (16 kA).

Graphical representations of sections of the Apollo-Pafuri Line 1 of the lightning exposure produced by the FALLS SAE Analysis tool for the period from the 1st of March 2006 to the 1st of March 2014 are shown in *Figure 41* and *Figure 42*. As before, each “dot” represents a lightning stroke. Interestingly, the density of the strokes along the transmission lines appears to be noticeably higher than the surrounding area, though this is to be expected, as tall objects such as power lines are associated with a greater probability of being struck by lightning due to having an “attractive potential” greater than the surrounding area.

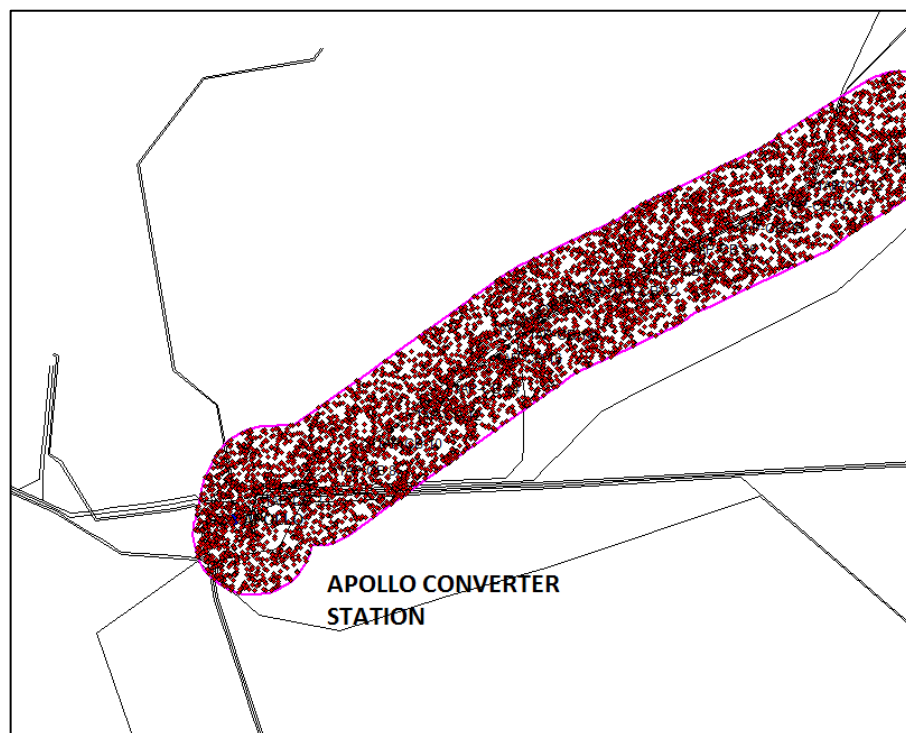


Figure 41: Graphical presentation of SAE Analysis for the Cahora-Bassa Line 1 near Apollo CS for the period SAE 1 March 2006 – 1 March 2014²⁸.

²⁸ Adapted from an extract from Vaisala FALLS®.

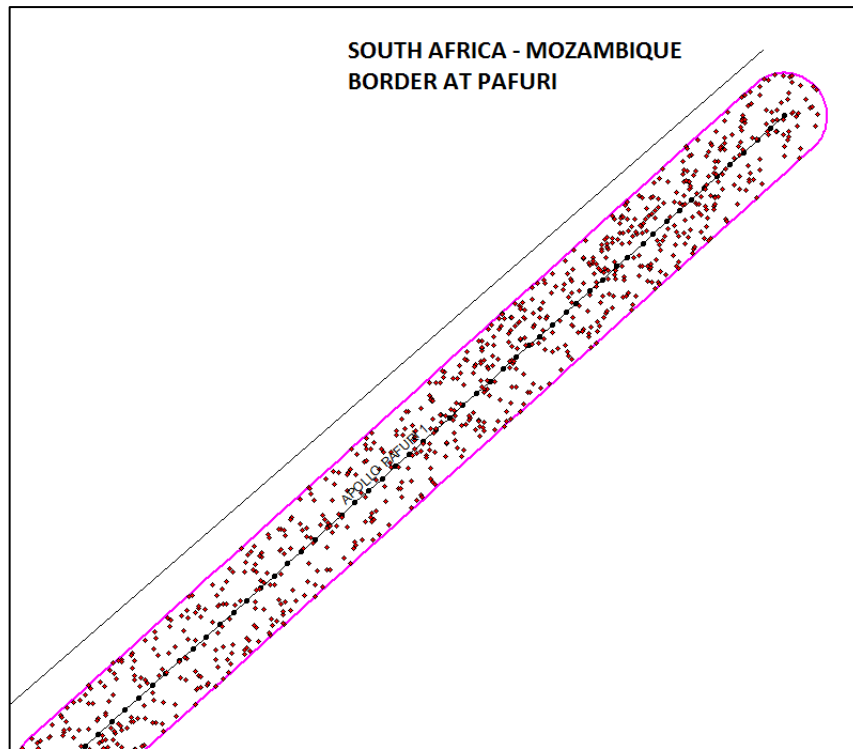


Figure 42: Graphical presentation of SAE Analysis for the Cahora-Bassa Line 1 near the South Africa - Mozambique border at Pafuri for the period SAE 1 March 2006 – 1 March 2014²⁹.

By comparing *Figure 41* and *Figure 42*, it can be seen that the lightning stroke density is significantly higher to the south of the line near the Apollo CS, compared to that near to the border with Mozambique.

These point events are used in the statistical analysis of the lightning exposure of the two Cahora-Bassa lines over the period of consideration from 1 March 2006 to 1 March 2014.

6.4.6 Input Data and Outputs for Small Area Exposure Analysis

The “Small Area Exposure Analysis” (SAE) Tool in the Vaisala FALLS software was used to determine the lightning statistics for the Cahora Bass HVDC transmission lines.

The input browser for the SAE Analysis tool is shown in *Figure 43* below. The significance of the various inputs and options are explained thereafter.

²⁹ Adapted from an extract from Vaisala FALLS ®.

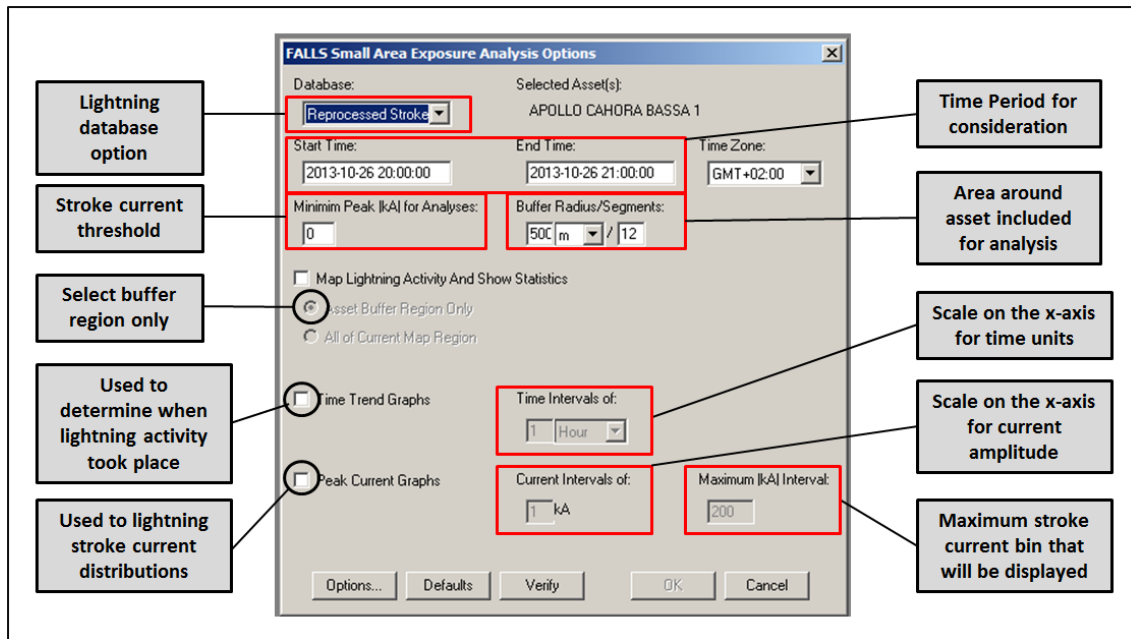


Figure 43: Small Area Exposure Analysis input screen³⁰.

Below follows a description of each input and what option should be selected for the SAE analysis.

Database Options

There are two sets of lightning databases, one for “Flashes” and the other for “Strokes”. Since accurate fault times are available, it is preferred to use the stroke database to find close correlations between lightning events and the recorded fault times. The following database options exist in the software:

1. “Real-time” databases – Lightning events are loaded into the database as they occur.
2. “Reprocessed” databases – These databases are manually loaded daily with all lightning events including delayed detection sensor reports that were affected by communication network availability.
3. “Spanned” databases – Spanned databases use all data available from the “Reprocessed” databases and then utilise real-time data at the end of the reprocessed data set.

³⁰ Adapted from SAE Browser from Vaisala FALLS®.

Therefore, “Reprocessed” databases will be more complete than “Real-time” databases, and are used for the correlation process.

Minimum Peak kA for Analyses

This specifies the minimum threshold modulus (since both polarities are included) of the stroke current that is to be considered in the analysis.

Buffer Radius

The buffer radius is a distance from the asset that defines the area that is to be included in the analysis. Due to accuracy limitations of the SALDN, it is recommended to use a minimum buffer radius of 1 km, however when investigating lightning activity that may have affected the asset, the buffer should be minimised, and 1 km is therefore suitable (Evert 2011).

Display Lightning Events and Statistics

The analysis is performed only in the buffer region by selecting “Asset Buffer Region Only” which is typically 1 km on either side of the line. Displaying “All of Current Map Region” is not suitable as this option considers all lightning activity within the region, whereas the investigation objective is to determine the lightning exposure of the asset. The option of displaying “All of the Current Map Region” is used for “Regional Statistical Analysis” in order to assess the lightning exposure over large areas, and is useful for siting new infrastructure, or identifying areas where the greatest opportunity for improvement exists (Smidt 2003).

Time trend graphs

Time trend graphs are a graphical presentation of lightning activity that allows the user to investigate time-related trends (Vaisala 2013). The total period for the analysis is between the entered “Start” and “End” time and is divided into the “Time Intervals” along the X-axis. The Y-axis plots the “count” or number of lightning events (either strokes or flashes) as shown in *Figure 44* below. The graphs are plotted for either negative or positive polarity, or both. In the graph below (*Figure 44*) colour is used to depict polarity. The blue portion of the bars represents positive polarity strokes, whilst the green represents strokes of negative polarity. It is apparent in this region that the positive polarity strokes make up a small proportion of the overall lightning exposure. The time trend graphs are useful for determining when lightning activity occurred.

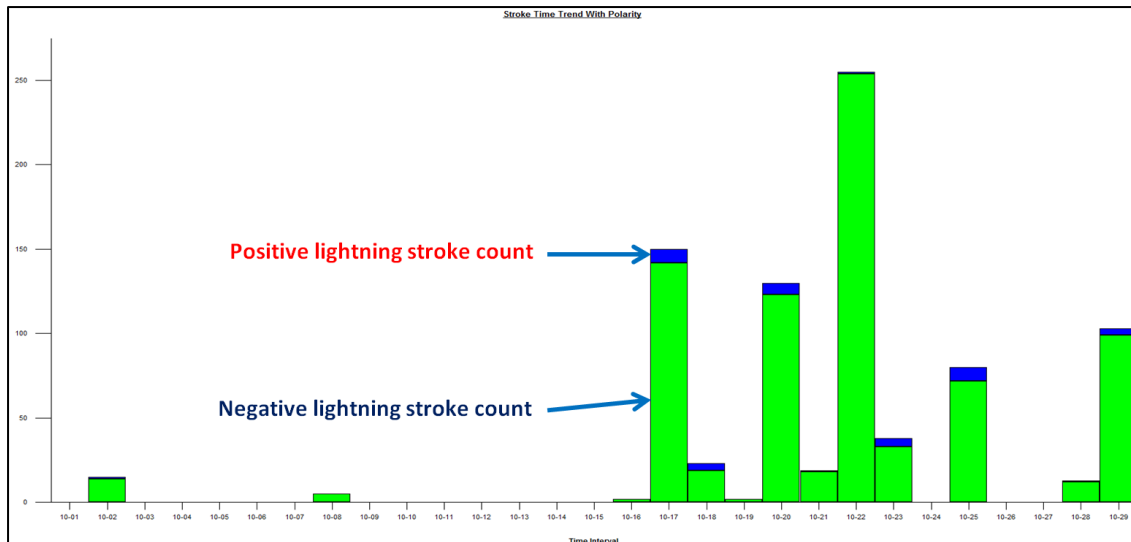


Figure 44: Stroke time trend for Cahora-Bassa Line 1 Apollo-Pafuri for the period from 1 October 2013 – 29 October 2013³¹.

As the graphs are displayed for the selected total time period for the analysis, an appropriate time interval must be selected for display purposes, e.g. for analysis periods of 1 month, a time interval of 1 day can be used to determine which days lightning activity occurred on.

If greater accuracy is required concerning the time of day when the lightning occurred, 6-hourly intervals can be selected for example, but smaller time intervals may be difficult to display in a way conducive for interpretation as there may be too much detail.

In *Figure 45*, the time trend graph has been used to ascertain which days of the winter months (in this case the “dry season”) there was lightning activity. This is useful in order to rule out lightning as a cause of faults during the dry season. There may be days in the dry season where there is lightning activity, although it must be noted that it is very limited, at roughly a 10th of the activity that occurs on thunderstorm days in the summer months.

³¹ Adapted from SAE output from Vaisala FALLS ®.

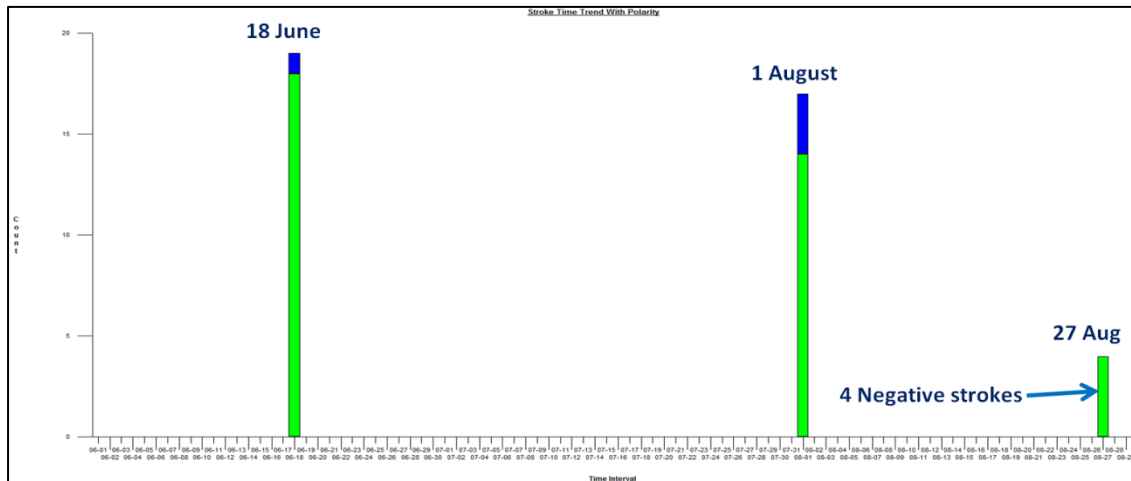


Figure 45: Stroke Time Trend Cahora-Bassa Line 1 Apollo-Pafuri from 1 June 2009 – 30 August 2009³².

In this research, time trend graphs were used to determine when lightning activity occurred. That is, in order to confirm if there was lightning activity during the period when a particular fault occurred. If there was no lightning, individual faults need not be further investigated for correlation with lightning strokes. This is particularly useful for faults, which occurred during the “dry season” where no lightning activity is expected. Although atypical, storm events may occur in the dry season. *Figure 46* below depicts the lightning activity for a 3-month period during the dry season from the 1st of June 2009 to the 30th of August 2009. As can be expected, there was very little overall lightning activity, however there were thunderstorms on the 18th of June, 1st of August and 27th of August. SAE Analysis can therefore be used to exclude all days where no thunderstorm activity occurred from the investigation.

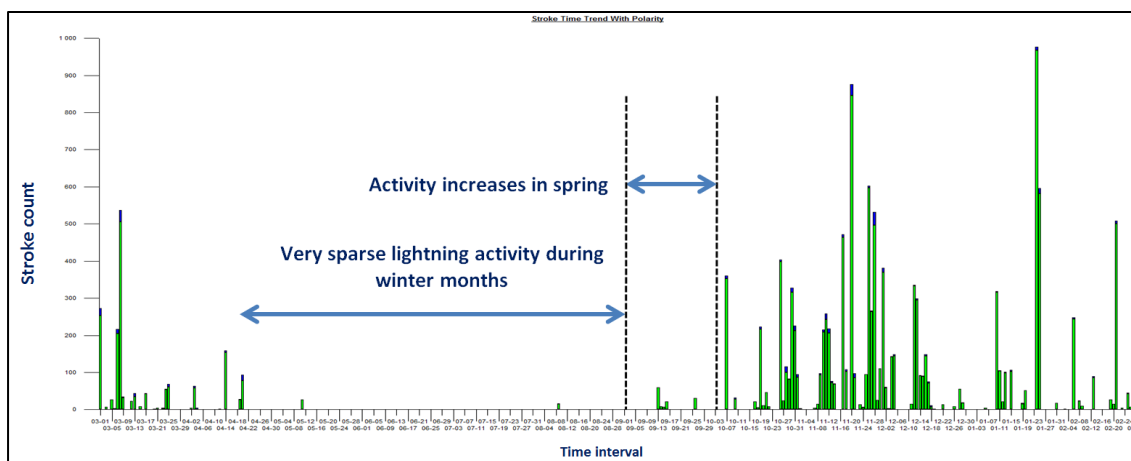


Figure 46: Stroke Time Trend for Cahora-Bassa Line 1, Apollo-Pafuri 1 March 2013 – 1 March 2014.³³

³² Adapted from SAE output from Vaisala FALLS ®.

For periods of analysis of a year, displaying time intervals of 1 day is the practical limit that can be displayed for interpretation. With this time interval, it is difficult to ascertain the date on which there may have been activity, as there are 365 segments on the horizontal axis.

Peak Current Graphs

The peak current graphs plot the distribution of the stroke count in relation to the stroke peak current or intensity. This distribution characterises the lightning activity within the buffer zone. The divisions on the X-axis represent the peak current levels expressed as bins associated with the stroke. The current intervals are user-selected and the recommended step increment is 1 kA (Evert 2011). The Maximum current interval is the highest amplitude current that will be individually displayed. Above this threshold, all larger magnitude strokes will be accumulated into a single stroke count bin. The maximum current interval must be set according to the nature of the investigation. Typically, there are relatively few strokes with amplitudes above 50 kA and the maximum interval can be set to this value. If it is necessary to investigate details about large amplitude, strokes the value can be set to say, 200 kA. It is extremely unlikely that there are any amplitudes exceeding 160 kA as shown in *Figure 47*.

The Y-axis is the stroke “count” or the number of strokes for a given peak current amplitude.

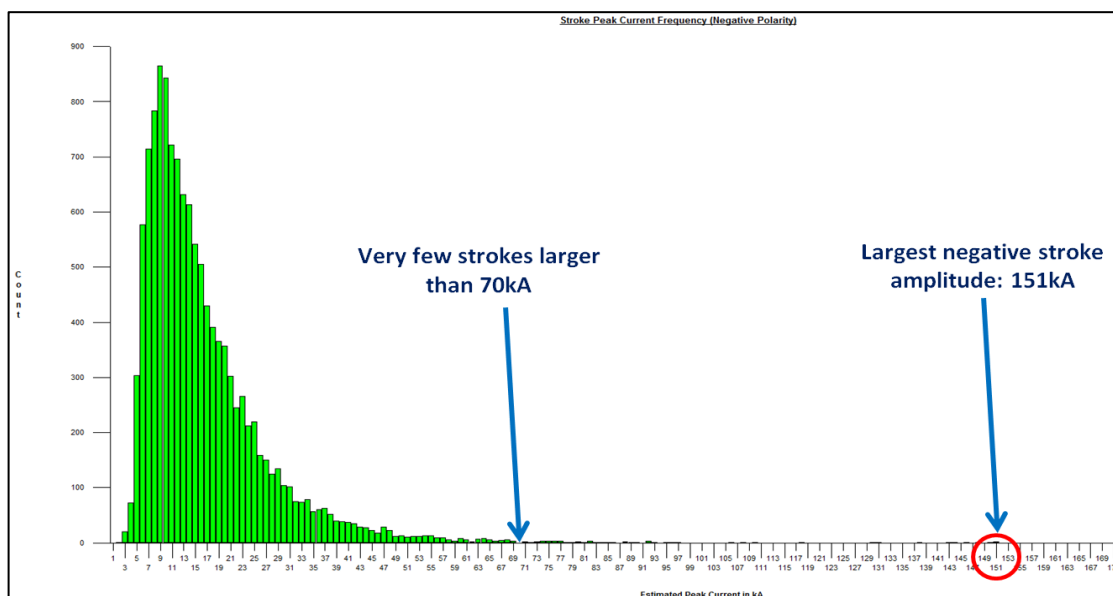


Figure 47: Peak Current Frequency for *negative polarity* strokes for Cahora-Bassa Line 1 Apollo-Pafuri for the period from October 2013 – 31 March 2015³⁴.

³³ Adapted from SAE output from Vaisala FALLS ®.

³⁴ Adapted from SAE output from Vaisala FALLS ®.

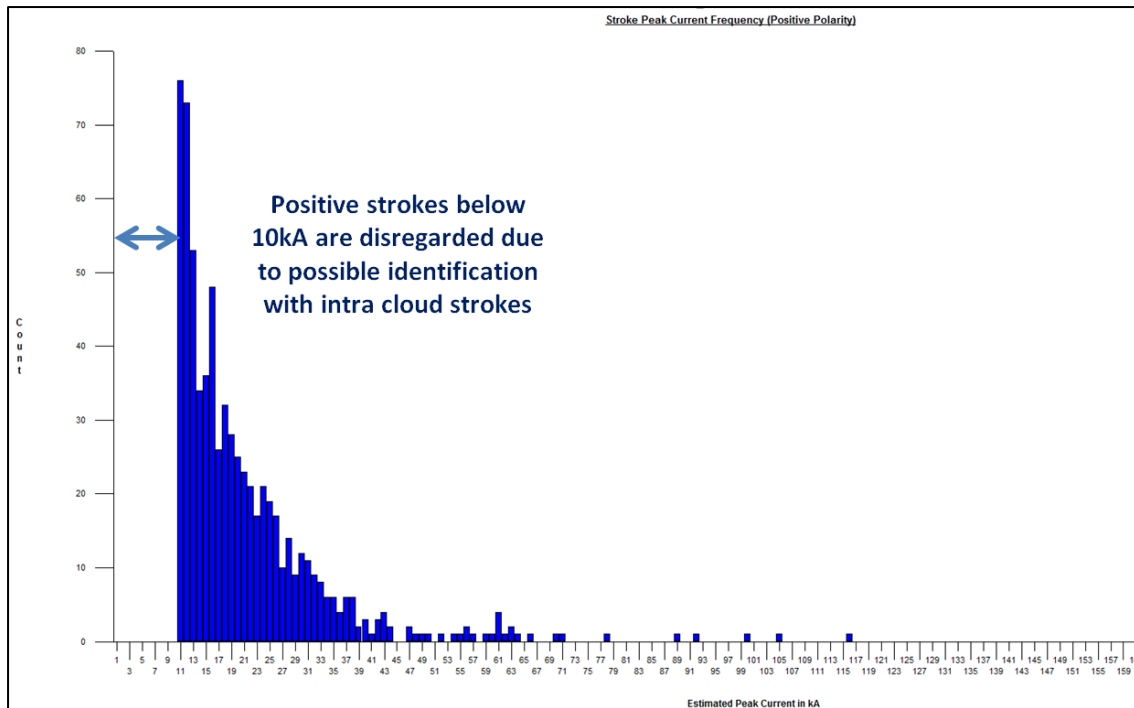


Figure 48: Peak Current Frequency for *positive polarity* strokes for Cahora-Bassa Line 1 Apollo-Pafuri for the period from 1 October 2013 – 31 March 2015³⁵.

The peak current graphs facilitate the comparison of the lightning exposure between the transmission lines for the positive and negative poles. The time trend graphs show the polarity of the lightning strokes but do not depict the magnitude. Therefore, the SAE Analysis can be used to compare the lightning exposure in terms of polarity.

This comparison forms the basis of the investigation, as in order to compare the effect of the HVDC Line polarity on the lightning performance, the lightning distribution within the buffer regions for the two lines must be very similar.

³⁵ Adapted from SAE output from Vaisala FALLS ®.

6.5 Methodology for Fault Correlation

The following section proposes a methodology for correlating line faults with lightning activity. This process is performed using the *Reliability Analysis* tool in the FALLS software introduced above.

6.5.1 Introduction to Fault Correlation with Lightning Activity

In order to correlate line faults with lightning events, both temporal and spatial comparisons must be performed. For the correlations to be considered positive, both temporal and spatial matches must be very close. Therefore, the fault correlation process depends on the accuracy of the time and position information, which will be compared.

Firstly, the recorded time of a fault from the line protection system is correlated with lightning stroke times from the LDN data. Therefore, the success of the time correlation depends on the accuracy of both the time stamp from the protection system as well as the reported stroke time from the LDN. The accuracy of both systems is discussed below.

Secondly, the locations of the time-correlated lightning strokes must be spatially correlated with the position of the line. The position of the transmission-line support towers is accurately known from the Global Positioning System (GPS) and is loaded into the simulation software. The stroke position is however not precisely known. The LDN provides so-called “confidence ellipses” as defined in **Chapter 2** (Background), which are ellipse shaped areas wherein which there is a finite probability that the lightning stroke in question occurred. All strokes with confidence ellipses that overlap the user-defined “buffer zone” around the line are considered for the analysis. Therefore, the accuracy of the LDN in detecting the positions of strokes is important. The operation and detection accuracy of the SALDN is described in **Chapter 2**.

LDN’s detect the electromagnetic pulses associated with lightning strokes, and use algorithms to group a number of strokes into a flash, based on detected time and reported location (Cummins et al. 1998a). Either lightning flashes or strokes can be correlated with faults. However, individual lightning strokes are used for fault correlation purposes, as the fault times are accurately known and can be correlated with individual strokes. In some cases, there may be several faults associated with multiple strokes of a single flash. These groups are considered a single fault event on the line.

Generally fault times correlate precisely (i.e. within one millisecond) with lightning stroke times. These differences arise from rounding-off of the fault times. However, occasionally small differences, of the order of 10's of milliseconds, between fault time and lightning stroke time are evident.

6.5.2 Definition of Buffer Zone and Confidence Ellipse

Buffer Zone for Lightning Analysis

The buffer zone is a user-defined area around an asset within which the impact of lightning discharges will be investigated. This allows for strokes that are too far from the line to interact, to be disregarded. The buffer zone is defined in terms of a radius around the asset as can be seen in *Figure 49* where a radius of 1 km around the Apollo-Pafuri Line 1 has been defined (the distance between the outside of buffer zone is 2 km). The buffer zone will result in an area parallel to the line with a fixed width of 1 km to be defined wherein which lightning activity will be considered.

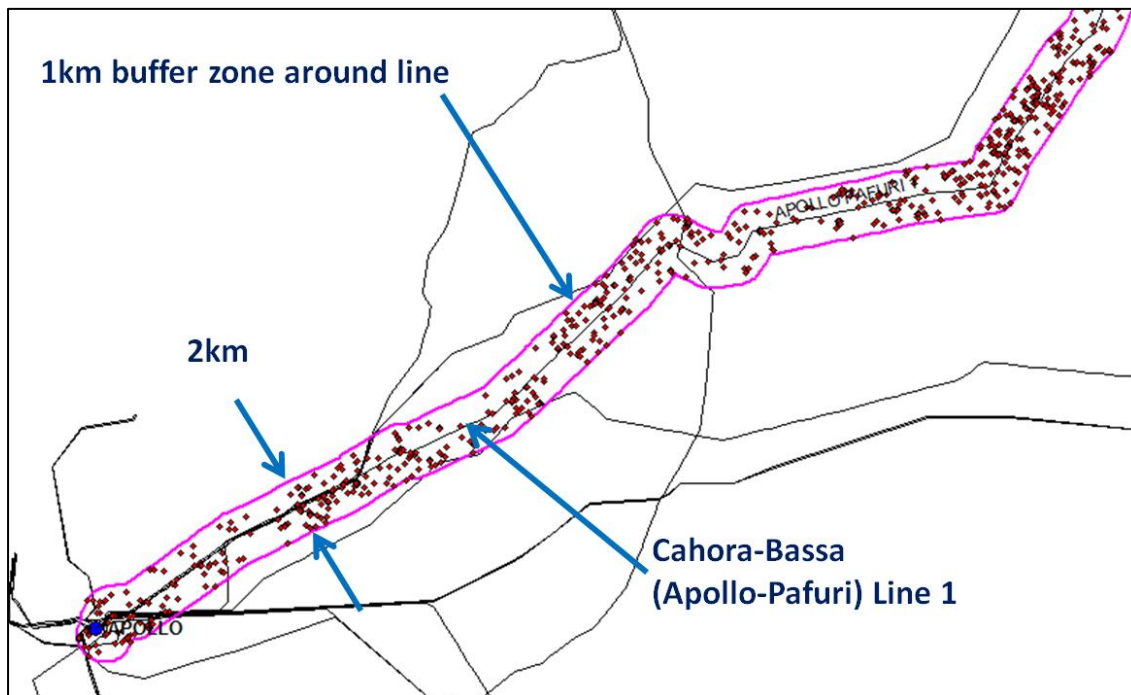


Figure 49: Example of 1 km buffer zone for Apollo-Pafuri Line 1 near Apollo CS³⁶.

Where the line section for investigation terminates at the border with Mozambique (*Figure 50*), it is apparent that the buffer zone is defined in terms of a radius as can be seen around

³⁶ Adapted from an extract from Vaisala FALLS®.

the final transmission line tower. Furthermore, discharges outside of the buffer zone are discarded, and only discharges within the buffer zone are displayed and considered in the statistical investigation.

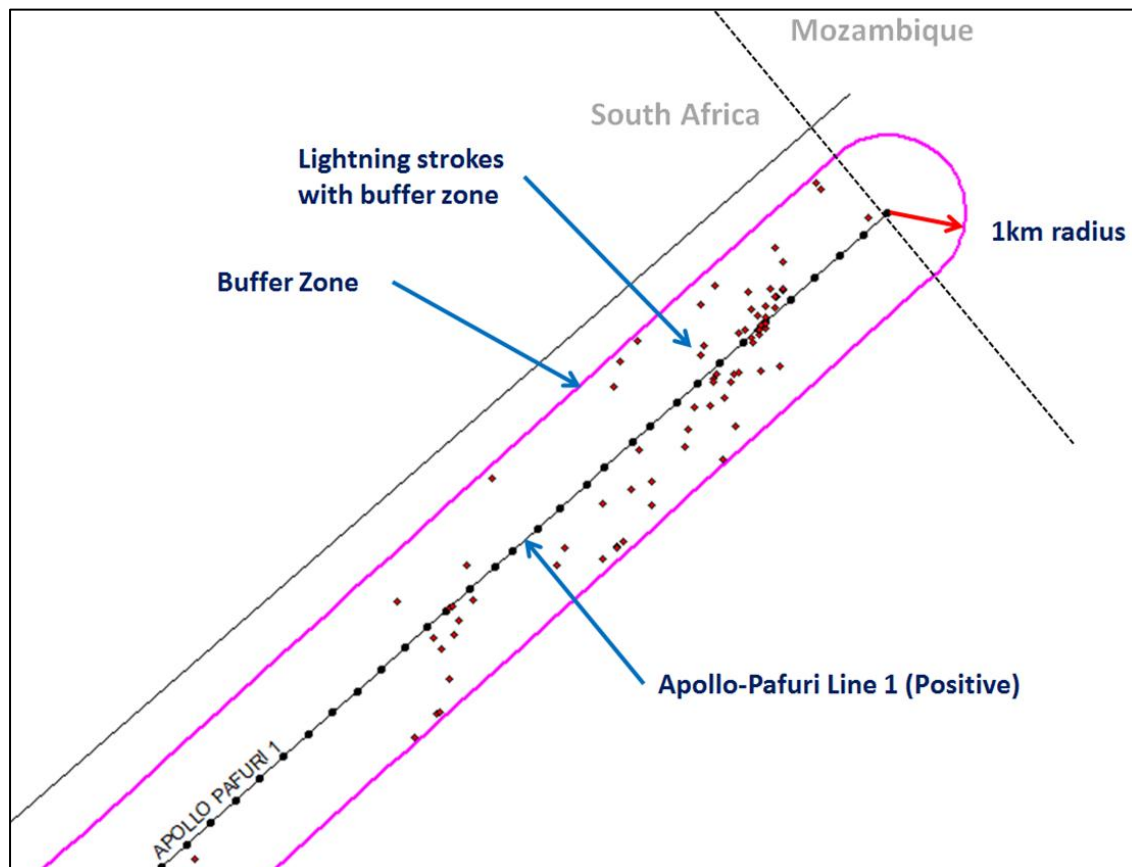


Figure 50: Example of 1 km buffer zone for Apollo-Pafuri Line 1 near to the Mozambique border³⁷.

Confidence Ellipse Associated with Lightning Strokes

Due to the nature of the detection of lightning discharges by the Lightning Detection Network (LDN), there is uncertainty in the detected position due to detection errors associated with individual sensors. This results in the reported position being displayed as an elliptical locus, instead of a precise point location, as can be seen in *Figure 51*. The centre of the ellipse is the optimal calculated location of the stroke but is normally not the actual stroke position due to the aforementioned detection errors. The shape and size of the confidence ellipse that is associated with the predicted location of the stroke primarily depends on the number of detecting sensors.

³⁷ Adapted from an extract from Vaisala FALLS®.

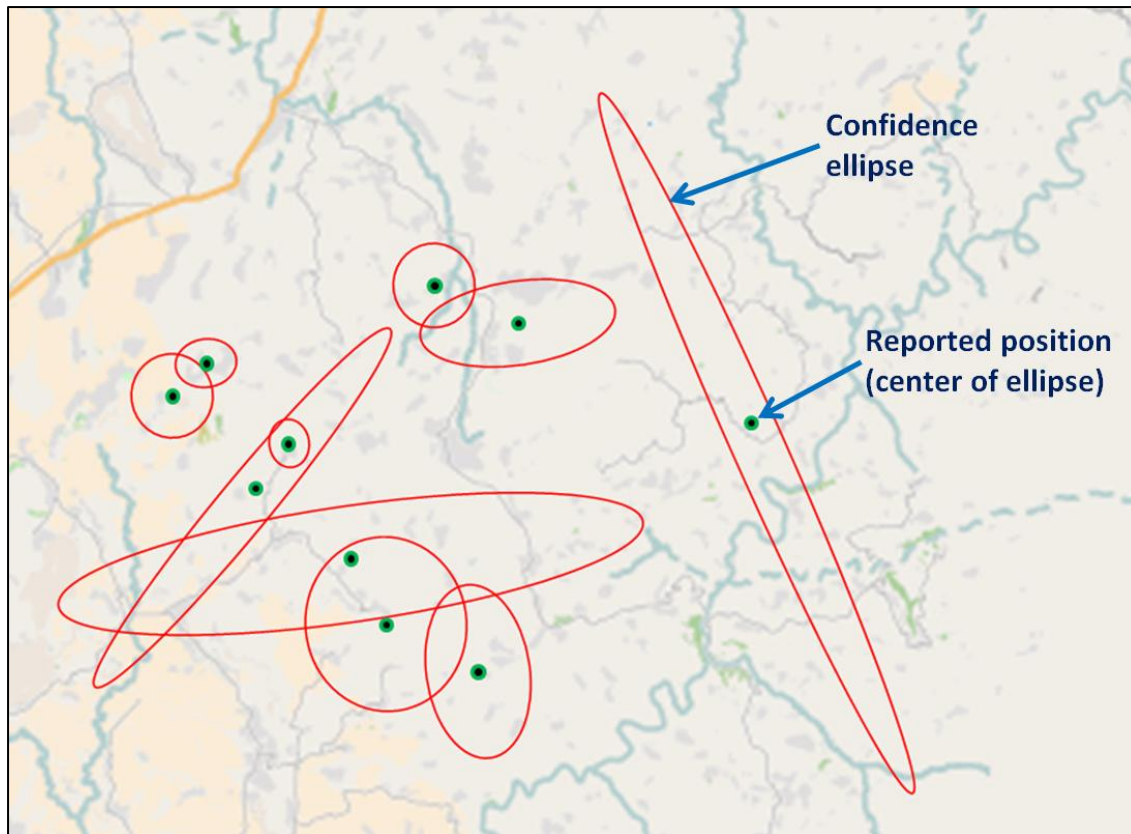


Figure 51: Confidence ellipses for selected strokes.

The FALLS software allows error ellipses with various levels of associated confidence, namely 50%, 90% and 99%, to be displayed. For statistical analysis of lightning activity, a 50% or “median” confidence ellipse is used. However, for fault correlation, a 99% confidence ellipse is recommended (Evert 2011), as there is a 50% probability with a median ellipse that the fault occurred outside of the ellipse, and it does not make it conducive for the correlation of fault events with lightning activity. The confidence ellipse that has been selected for fault correlation is for a 99% confidence level, meaning that there is 99% confidence that the true stroke location is within the 99% confidence ellipse.

Therefore, all strokes with confidence ellipses that overlap the buffer zone are considered potential strikes to the line. Strokes with ellipses that do not overlap the buffer zone are extremely unlikely to have terminated on the line unless within the “attractive radius” of the line. The default buffer zone that has been used is 1 km on either side of the line. This results in large numbers of spatially correlated strokes during times of high lightning activity and therefore increases the computation time required for the simulation. A smaller buffer zone less than 500 m was considered but it is not deemed prudent to utilise buffer zones, which are similar to the potentially large striking distance associated with large magnitude strokes.

It is also preferable to include more strokes in the process so as not to exclude potential strikes to the line by interpreting each correlated case based on factors other than the simple mathematical correlation used by the software.

In *Figure 52*, an example of fault correlation is depicted, in order to demonstrate the confidence ellipses associated with different strokes. Three different colours of ellipses are evident which are interpreted as follows: The grey ellipses are those that overlap the buffer zone, but are outside of the time tolerance for the fault correlation. The orange ellipses are those that fall within the temporal tolerance (called “Precision Interval” in FALLS) for the correlation. The red ellipse is the optimal correlation between the fault time and the lightning stroke time that falls within the buffer zone and is therefore spatially correlated with the line.

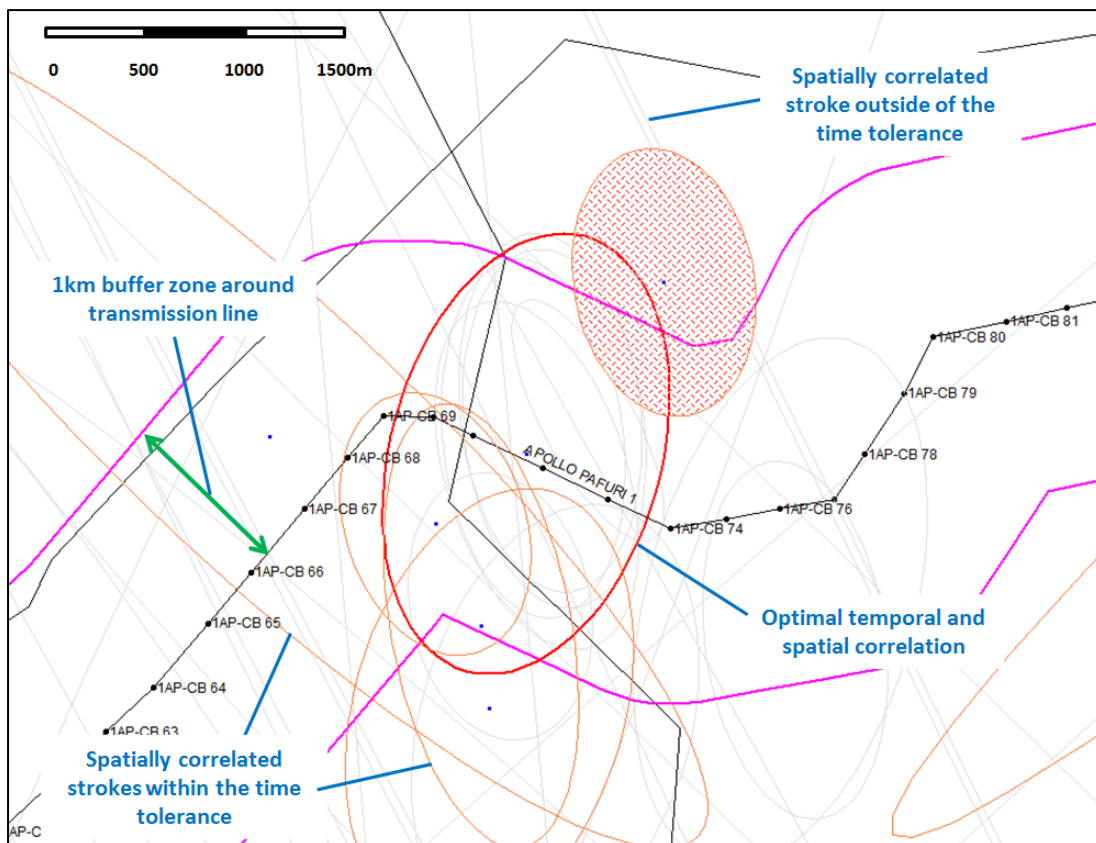


Figure 52: Example fault correlation depicting stroke confidence ellipses

6.5.3 Introduction to Reliability Analysis

The Reliability Analysis (RA) tool in FALLS provides a one-to-one correlation of events affecting the asset, such as transmission line faults, with lightning events. The analysis provides the location, amplitude and polarity of the correlated lightning event (Smidt 2003).

Therefore, RA has been used for the correlation of faults on the Cahora-Bassa HVDC lines with lightning stroke data from the South African Lightning Detection Network.

6.5.4 Input Data and Outputs for Reliability Analysis

The following section described the options and functionality of the Reliability Analysis tool in the Vaisala FALLS software. *Figure 53* shows the input browser for the Reliability Analysis. Fields labelled “A” to “D” are the same as for the Small Area Exposure Analysis and are explained in cross reference. Options “E” to “H” have been used for the correlations and are explained below *Figure 53*.

The screenshot shows the 'FALLS Reliability Analysis Options' dialog box. It contains various input fields and checkboxes for configuring the analysis. Callouts A through H point to specific features:

- A. Lightning database option:** Points to the 'Database:' dropdown menu, which is set to 'Reprocessed Stroke'.
- B. Time period for analysis:** Points to the 'Start Time:' and 'End Time:' date/time fields, which are set to '2013-12-14 00:00:00' and '2013-12-15 00:00:00' respectively.
- C. Stroke current threshold:** Points to the 'Minimum Peak (kA) for Analyses:' input field, which is set to '0'.
- D. Time period for analysis:** Points to the 'Time Zone:' dropdown menu, which is set to 'GMT+02:00'.
- E. Confidence for Ellipse:** Points to the 'Ellipse Confidence/Nodes:' dropdown menu, which is set to '99%'.
- F. Enter Fault details here:** Points to the 'Multiple' radio button and the 'Fault Entry...' button.
- G. Display all "Spatial Correlations":** Points to the 'Map Lightning Activity, correlating with buffered assets and fault times' checkbox, which is checked.
- H. Select "closest time":** Points to the 'Fault Correlation Rule:' dropdown menu, which is set to 'Closest time to fault is fault-correlated'.

Other visible options include 'Buffer Radius/Segments' (set to 1 km / 12), 'Fault Time/Precision (sec.)' (set to 1), 'Fault Type' (set to FAULT), and 'Time Trend Graphs' (unchecked). The 'Time Intervals of:' field is set to 1 Minute, and the 'Current Intervals of:' field is set to 1 kA. The 'Maximum (kA) Interval:' field is set to 50.

Figure 53: Reliability Analysis input screen indicating the selection of options for fault correlations.

The following options are significant for the fault correlations:

E – The confidence associated with the error ellipses used in the spatial correlation is selected here. The options are 50%, 90% or 99%. The confidence level that the true stroke position is within that ellipse is given by the selected “percentage confidence”.

For fault correlations, a 99% ellipse is selected such that there is a probability of 0.99 that the stroke occurred within the ellipse and therefore there is a high confidence in the spatial correlation.

F – The fault details are entered here by pressing the “Fault Entry...” button, which opens the following screen depicted in *Figure 54*, where the fault date and time is entered in “E1”, and the time interval for the correlation analysis is entered in “E2”. The time interval is referred to as the “Precision Interval” in the FALLS software and is the time tolerance around the entered fault time that will be considered for the correlation between the fault and the stroke times.

Asset Name	Date/Time (GMT+02:00)	Precision(sec)	Fault Type
APOLLO CAHORA	2010-10-30 19:04:21.661	000020.0000	FAULT

Asset List	Date	Time	Precision	Fault Type
APOLLO CAHORA	2016/02/05	00:00:00.000	60	FAULT

Figure 54: Manual fault entry screen for Reliability Analysis.

G – There are two options for the display of the spatially correlated ellipses. Either all spatially correlated lightning is displayed or alternatively only that which is within the time tolerance is displayed. This option is not critical to the outcome of the correlation, but the option for displaying all the spatially correlated lightning has been used for this analysis.

H – There are three options for the “Fault Correlation Rule”. The first option is that all “Time-correlated” lightning is classified as “Fault Correlated”. This has not been used, as the aim is to identify the causative stroke. The second option is that “Highest peak current” that is time correlated is classified as fault correlated. This is also not appropriate, as the aim is to identify which stroke has the closest time correlation and therefore the third option for the “Closest time to fault” has been selected.

6.5.5 Methodology for Identification of the Probable Stroke Resulting in the Fault

The most probable stroke to have caused a particular fault is identified by considering a combination of the temporal and spatial correlation. The temporal correlation is made between the fault time and the reported stroke time. The spatial correlation is between the transmission line coordinates and the confidence ellipse associated with a particular stroke. The evaluation of these correlations allows the most probable stroke to be identified and thereafter the likelihood that that stroke caused the fault in question to be estimated. In some cases, the most probable stroke may show correlations that mean the probability that the stroke caused the fault is low.

The amplitude of the stroke is another factor that influences the probability of a fault. If all other factors are the same, the probability of a flashover increases with increasing stroke amplitude. However, this probability also depends on the tower footing resistance; therefore, the amplitude of the stroke cannot be considered in determining the likelihood that a fault was caused by a particular stroke, and has been disregarded from the analysis as the tower footing resistances are not known.

The temporal and spatial correlations are classified in the comments for each graphical analysis in accordance with *Table 1* and *Table 3* respectively.

Temporal Correlation Classification

There is high confidence in the fault time from the protection system and the reported stroke time from the lightning data, therefore most faults that were caused by lightning should show near exact time correlations. Some faults on the Apollo fault database (Greyling 2015) were not recorded by the LFL, which may have been offline at the time, and therefore the time is not precisely known in these instances. In most cases, the time has been recorded to a resolution of seconds but in other cases, only the minutes have been captured for the fault.

Table 1: Key for the classification of temporal correlation.

Correlation classification	Criteria for temporal correlation ranking
Exact (Green)	The fault time and reported stroke time are the same (less than 2 ms, the difference is only due to rounding of the LFL fault time)
Close (Orange)	The fault time and reported stroke time are the close (less than 200 ms)
Poor (Red)	The time correlation is “poor” (>200 ms) <u>OR</u> The fault time is not precisely known (up to second tolerance)

Spatial Correlation Classification

In the RA analysis in FALLS, all strokes with confidence ellipses that overlap the buffer zone are considered to be spatially correlated, however this does not mean that such strokes terminated on the line. The buffer zone that has been used is either 500 m or 1000 m (as recommended by Evert 2011), some strokes that overlap the buffer zone may be a considerable distance away from the line yet are still included in the correlation. Since the attractive radius of the shield wire or pole conductors under each approaching downward leader is not known, a conservative minimum buffer radius of 500 m was used so as not to exclude any strokes that could have potentially terminated on the line.

As 99% confidence ellipses have been used in the correlation studies, stroke ellipses that do not overlap the transmission line or do not approach within the “striking distance”, are unlikely to have terminated on the line. Calculation of the striking distance can be used as a cursory determination of whether a stroke could potentially have terminated on the line. The striking distance is a function of the stroke peak current amplitude and therefore large amplitude strokes may have considerable striking distances. The relationship used by IEEE in Std. 998 (2012) for direct lightning stroke shielding protection has been used to calculate the striking distance. The relationship adopted by the IEEE yields conservative values. In order to classify these strokes as either “Fair” or “Poor” spatial correlations, in cases where the confidence ellipse does not overlap the line, the striking distance must be compared to the distance between the line and the ellipse.

The equation for the striking distance (D_s), in terms of the stroke current (I), for the conductor and shield wire is as follows:

$$D_s = 8 I^{0.65} \quad \text{Equation (4)}$$

Striking distances are presented in *Table 2*. An estimate of striking distance can be calculated from the correlated stroke current in accordance with *Equation (4)* (Column 7 in *Table 2*). This equation gives a conservative value for the striking distance, which could be a little as a half of that predicted by other models (IEEE 998 2012). Therefore, double this distance is deemed as a “Working Striking Distance” that can be compared to the distance between the confidence ellipse and the line (Column 8 in *Table 2*). If the comparison is close, it is considered that there is a fair probability that the stroke could have terminated on the line.

Table 2: Striking distances associated with fault-correlated strokes.

1	2	3	4	5	6	7	8
Fault No.	Line Polarity	Date	Fault Time	Stroke Current & Polarity	Tower Location (Probable)	Striking Distance IEEE 998	Working Striking Distance
						[m]	[m]
1.	1 (+)	19 01 2009	23:13:38:108	-18kA	72	52.36	104.72
2.	1 (+)	19 01 2009	23:13:41:151	-7kA	116, 117	28.34	56.68
3.	1 (+)	20 01 2009	00:50:42:744	-17kA	442, 443	50.45	100.90
4. a	1 (+)	17 02 2009	20:28:40:024	-26kA	76	66.50	133.00
5.	1 (+)	17 02 2009	20:51:17:543	-8kA	68	30.91	61.82
6.	2 (-)	01 12 2009	01:28:52:564 & 573	-11kA	771	38.02	76.04
7.	1 (+)	16 01 2010	01:16:39:590	-24kA	74	63.13	126.26
8.	1 (+)	09 10 2010	15:16:42:625	-6kA	389	25.64	51.28
9.	1 (+)	09 10 2010	15:22:10:571	+14kA	344	44.47	88.94
10.	1 (+)	09 10 2010	15:24:13:888	-22kA	361	59.66	119.31
11.	1 (+)	09 10 2010	15:26:18:488	-17kA	384	50.45	100.90
12.	1 (+)	27 10 2010	09:21:40:248	-9kA	12, 13	33.37	66.74
13. a	1 (+)	30 10 2010	19:04:20:427	-18kA	71,72	52.36	104.72
14.	1 (+)	30 10 2010	19:04:21:661	-9kA	74	33.37	66.74
15.	1 (+)	07 11 2010	00:37:25:390	-8kA	506	30.91	61.82
16.	1 (+)	11 12 2010	18:36:03:593	-43kA	69	92.22	184.45
17.	1 (+)	24 12 2010	03:04:35:625	-40kA	70	87.99	175.98
18.	1 (+)	16 03 2010	11:03:24:535	-31kA	39	74.55	149.11
19.	1 (+)	03 10 2010	13:49	-64kA	308, 309	119.43	238.86
20.	1 (+)	26 10 2013	43:26.0	-24kA		63.13	126.26
21.	1 (+)	26 10 2013	43:26.0	-24kA	72	63.13	126.26
22.	1 (+)	26 10 2013	55:38.0	-21kA	72	57.88	115.76
23.	1 (+)	12 11 2013	09:54.6	-18kA	72	52.36	104.72
24.	2 (-)	28 11 2013	16:48:05:550	-9kA	56 -62	33.37	66.74
25.	1 (+)	14 12 2013	20:52:49:493	-27kA	39	68.15	136.30
26.	1 (+)	15 01 2014	18:30:09:008	-17kA	72	50.45	100.90

The spatial correlations are classified in accordance with the criteria in *Table 3*.

Table 3: Key for the classification of spatial correlation.

Correlation classification	Criteria for temporal correlation ranking
Good (Green)	The center of 99% confidence ellipse is close to the transmission line, within the buffer zone <u>OR</u> The 99% confidence ellipse overlaps the transmission line partially
Fair (Orange)	The 99% confidence ellipse does not overlap the transmission line but is within the striking distance <u>OR</u> The confidence ellipse is very large due to few sensors involved in detecting the stroke (<4)
Poor (Red)	The confidence ellipse overlaps the buffer zone marginally but is not close to the striking distance

The combination of the temporal and spatial classifications can be used to categorise the likelihood of a particular stroke causing the fault in question according to the criteria in *Table 4*.

Table 4: Categorisation of the likelihood that a stroke caused a fault.

		Temporal correlation		
		Poor	Close	Exact
Spatial correlation	Good	Medium	High	Very High
	Fair	Low	Medium	High
	Poor	Very Low	Low	Medium

All strokes that are classified as either a “Medium, High” or “Very High” likelihood are reported in the summary of the correlation results. Strokes that have been classified as “Low” or “Very Low” are considered unlikely to have caused the faults, and have been disregarded from the overall performance statistics.

7. Results and Discussion

The comparison between the lightning exposure of the two Cahora-Bassa HVDC transmission lines, is given for an 8 year period. Fault data was available for seven years and the results of the correlations between faults and lightning activity are provided for this 7-year period. Various significant trends in the results are described. Several specific examples of the fault correlations are discussed in detail.

7.1 Introduction

This chapter is comprised of the presentation of the results of two main research aspects.

The first is the comparison between the lightning exposures of the two poles of the Cahora-Bassa transmission line for an 8-year period and there is a discussion around general trends associated with the lightning exposure.

The second aspect reviews the results of all the lightning correlated faults for the Cahora-Bassa Lines over a 7-year period. Specific examples are explored in detail and peculiarities are explained. Probable causes of the faults are discussed.

A specific section of Line 1 has been identified where the lightning fault rate is extraordinarily high. This section is anomalous as it only comprises a few hundred meters of the line length, yet it is along this section that about half of the total faults of the entire 1000 km line occur. The environmental influence and possible additional causes for the high fault rate are discussed.

7.2 Comparison of the Lightning Statistics for the Two Cahora-Bassa Lines

The lightning exposure within a buffer zone of 1 km around each line was determined by the FALLS SAE analysis. The exposure was determined by SAE analysis for the 8-year period from the 1st March 2006 to the 1st March 2014 for which SALDN data was available at the time. The analysis was performed for Line 1 and Line 2 separately. The time trend graph for Line 1 shown in *Figure 55* indicates the periods where there was lightning activity during the 8-year period (predominantly during the rainy season).

This graph shows the overall cyclical nature of the lightning activity while highlighting the significant differences in the distribution between years. For each year, the end of December is used as an indication of time reference.

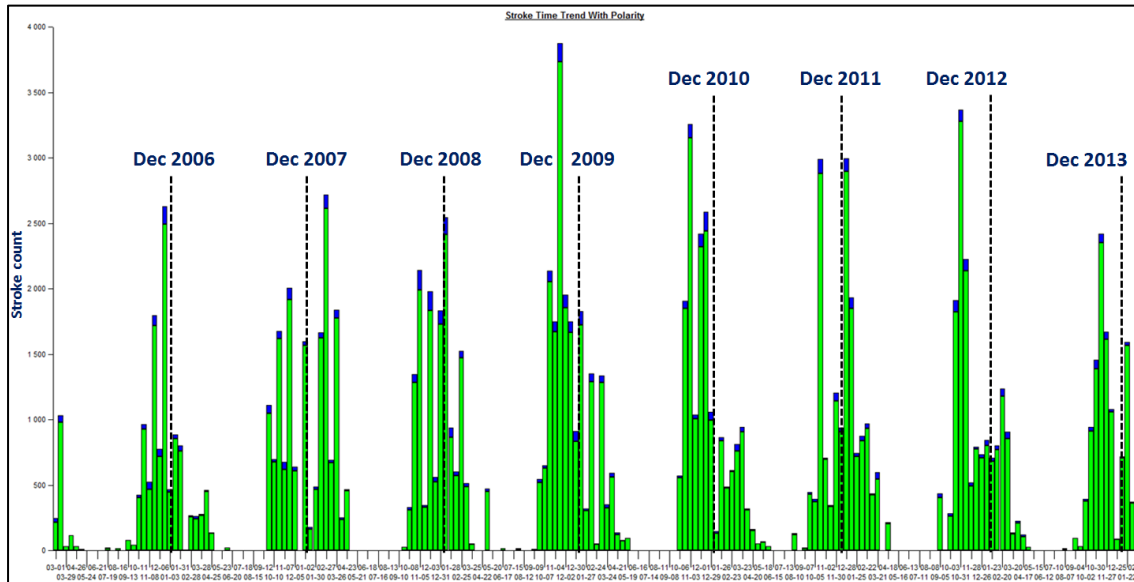


Figure 55: SAE analysis for Apollo-Pafuri Line 1 for the 8-year period from the 1st March 2006 to the 1st March 2014³⁸.

The comparison of the lightning exposure was performed separately for positive and negative stroke polarities between the two lines. The SAE analysis provides the statistics of the lightning exposure in terms of the stroke count versus the lightning peak current amplitude.

The stroke peak current distribution is displayed in terms of the lightning stroke frequency versus peak current amplitude, as depicted in *Figure 56* and *57*. The count for each integer peak current value is referred to in this discussion as “bins”. There are two distributions per line, one for each lightning stroke polarity. This statistical analysis provided by the FALLS software allows the lightning exposure of the two poles to be compared.

The distributions for negative strokes for the two lines are shown in *Figure 56* and *Figure 57*.

³⁸ Output from Vaisala FALLS ®.

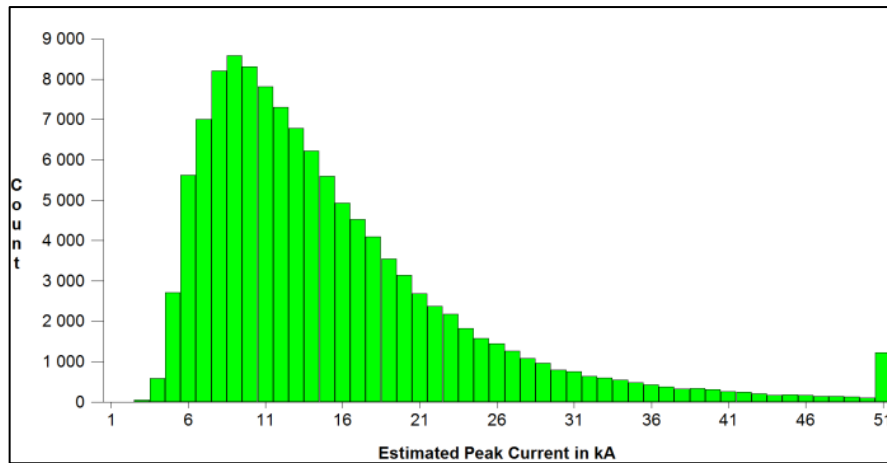


Figure 56: *Positive pole (Line 1) stroke peak current frequency for strokes of negative polarity*³⁹.

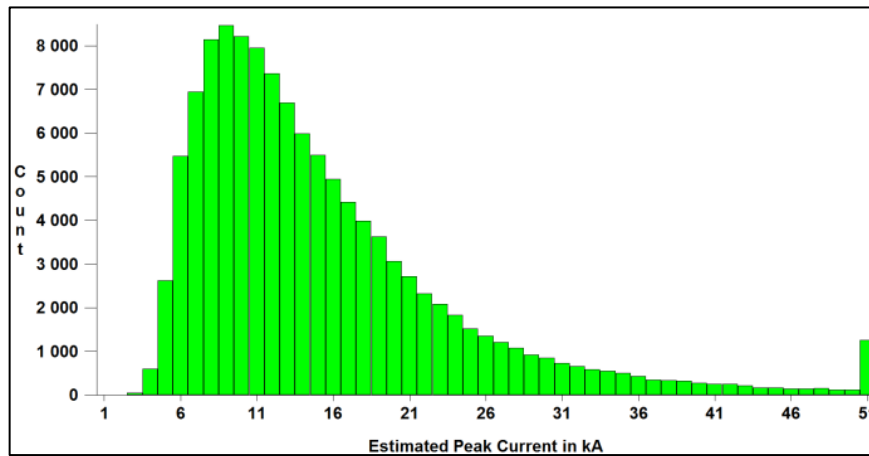


Figure 57: *Negative pole (Line 2) stroke peak current frequency for strokes of negative polarity*⁴⁰.

Upon visual inspection, the two distributions appear to be very similar. This similarity is confirmed by calculating the “average difference” across the stroke amplitudes between the distributions for Line 1 and Line 2.

This difference in the distribution of negative stroke count per peak current amplitude is depicted in *Figure 58*. Due to the probabilistic nature of flashover due to lightning, it is conducive to make an “overall comparison” between the stroke distributions of the two lines. The “average difference” is considered an optimal comparison. This average difference is most meaningful when expressed as a percentage. The difference between the two distributions is marginal with an average percentage difference across the amplitude bins of 1.01% and a standard deviation of 6.77%.

³⁹ Output from Vaisala FALLS ®.

⁴⁰ Output from Vaisala FALLS ®.

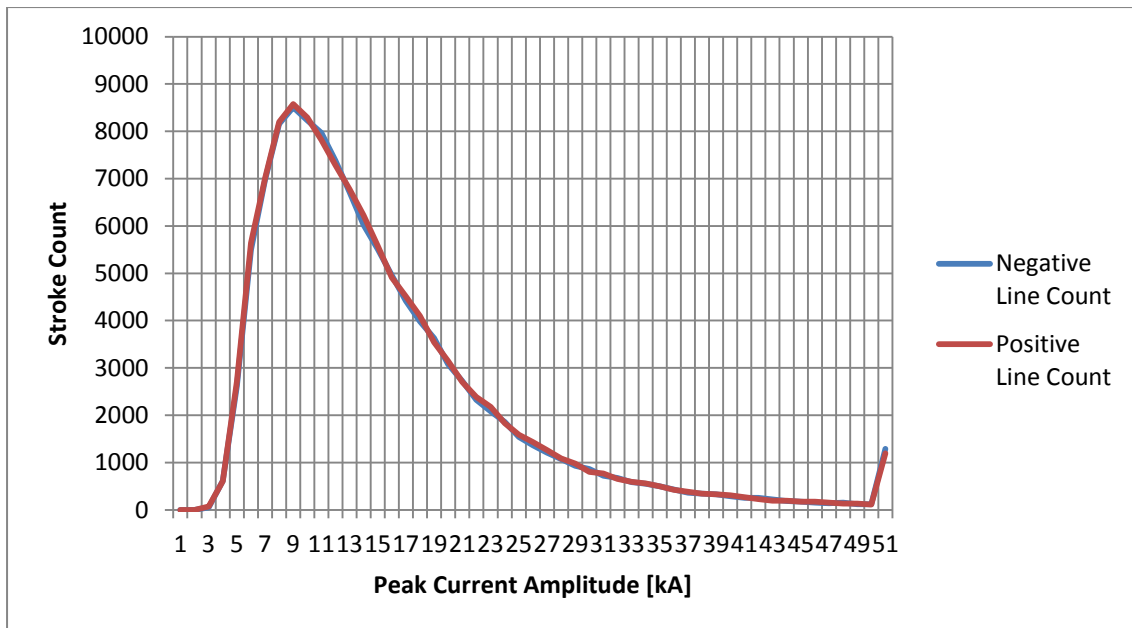


Figure 58: Comparison between *negative* stroke count for *positive* pole (Line 1) and *negative* pole (Line 2).

The stroke count distributions for positive polarity strokes for the two lines are shown in Figure 59 and Figure 60.

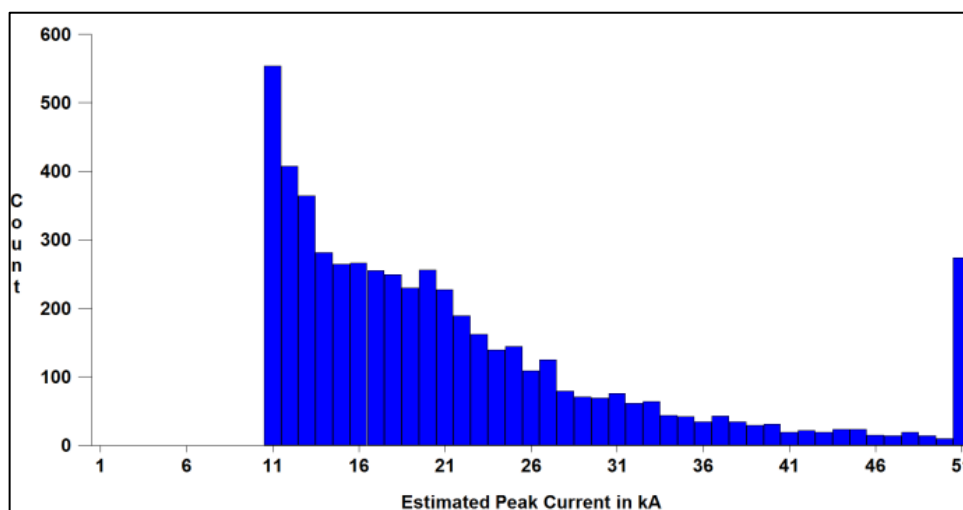


Figure 59: *Positive* pole 1 (Line 1) stroke peak current frequency for strokes of positive polarity⁴¹.

⁴¹ Output from Vaisala FALLS ®.

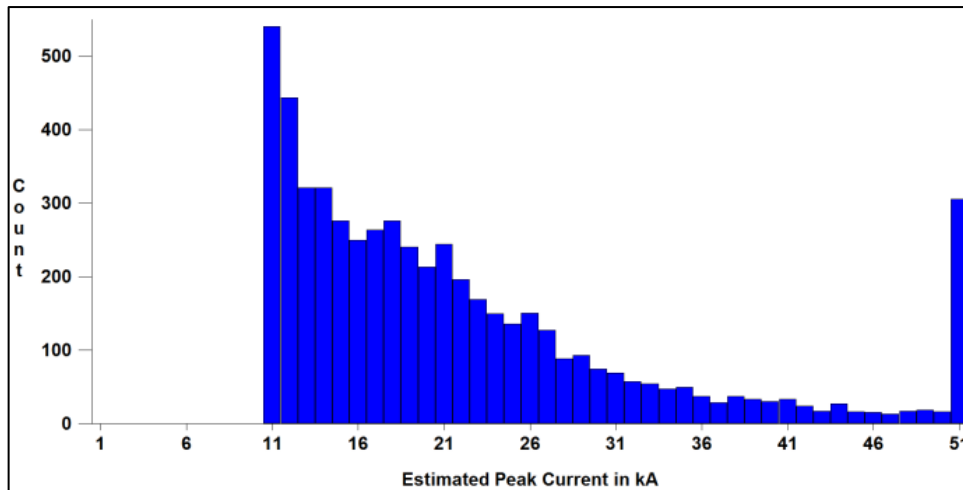


Figure 60: *Negative pole (Line 2) stroke peak current frequency for strokes of positive polarity*⁴².

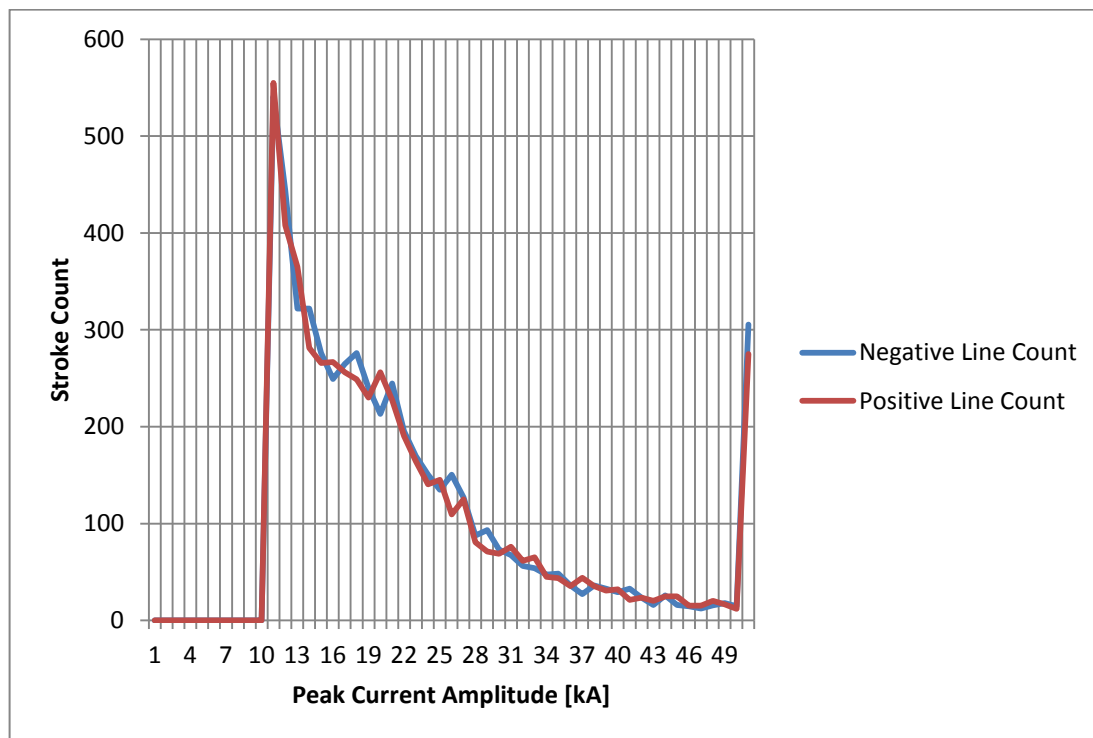


Figure 61: Comparison between *positive* stroke count for *positive* pole (Line 1) and *negative* pole (Line 2).

As only 5% of the values are used in producing the distributions, the distributions for the positive strokes are not as “smooth” as the distributions for the negative stroke polarity. The distributions appear unexpectedly dissimilar, as can be seen in *Figure 61*. Despite the differences across stroke amplitudes, between the two distributions, being larger than for the negative stroke count, the *average* difference between the two distributions is marginal.

⁴² Output from Vaisala FALLS ®.

The average percentage difference across the amplitude bins is the same as for the negative distribution, and is relatively small at 1.01% with a standard deviation of 17.33%.

Comparison of the stroke peak current frequency between the two lines for both positive and negative stroke polarities are shown in *Figures 56, 57, 59 and 60 respectively*. The comparison indicates that the lightning exposure for the two lines is very similar over the 8-year period of analysis. Therefore, the lightning-correlated faults for the two lines are compared in the following section, in order to determine the influence of the polarity on the lightning induced fault rate.

7.3 Results of the Fault Correlations

The results of the fault correlations for the 517 km South African portion of the Cahora-Bassa HVDC Lines, between Apollo CS and the Pafuri Border with Mozambique, are given in *Table 5* below.

Table 5: Summary of the fault correlation on the Cahora-Bassa HVDC Lines for the period between the 17 September 2008 and 31 August 2014.

Fault No.	Line Polarity	Fault Date	Fault Time from protection system	Stroke Time and Correlation from FALLS	Spatial Correlation from FALLS	Stroke Current & Polarity	No. of Detecting Sensors	Tower Location (Probable)
1.	1 (+)	19 01 2009	23:13:38:108	23:13:38:108	Good	-18 kA	11	72
		19 01 2009	23:13:38:193	23:13:38:193	Good	-9 kA	3	74
		19 01 2009	23:13:38:232	23:13:38:232	Good	-9 kA	3	73
		19 01 2009	23:13:38:395	23:13:38:395	Good	-11 kA	3	73
		19 01 2009	23:13:38:438	23:13:38:438	Good	-9 kA	5	73
2.	1 (+)	19 01 2009	23:13:41:151	23:13:41:151	Fair	-7 kA	2	116 - 117
3.	1 (+)	20 01 2009	00:50:42:744	00:50:42:744	Good	-17 kA	2	442 - 443
4.	1 (+)	17 02 2009	20:28:40:024 a)	20:28:40:024	Good	-26 kA	12	76
			20:28:40:138 b)	20:28:40:138	Good	-17 kA	2	73 - 74
5.	1 (+)	17 02 2009	20:51:17:543	20:51:17:543	Fair	-8 kA	2	68
6.	2 (-)	01 12 2009	01:28:52:564 & 573	01:28:52:645	Good	-11 kA	5	771
7.	1 (+)	16 01 2010	01:16:39:590	01:16:39:617 01:16:39:677 01:16:39:744	Fair	-16 kA -15 kA -24 kA	10 8 8	73 82 74
8.	1 (+)	09 10 2010	15:16:42:625	15:16:41:982 15:16:42:062 15:16:42:161 15:16:42:200 15:16:42:551	Fair	-32 kA +25 kA -15 kA -11 kA -6 kA	8 10 8 7 3	396 392 389 389 389
9.	1 (+)	09 10 2010	15:22:10:571	15:22:10:571	Good	+14 kA	5	344
10.	1 (+)	09 10 2010	15:24:13:888	15:24:14:207 ¹	Fair	-22 kA	2	361
11.	1 (+)	09 10 2010	15:26:18:488	15:26:18:487	Fair	-17 kA	3	384
12.	1 (+)	27 10 2010	21:21:40.248	21:21:40.249 21:21:40.323 21:21:40.396 21:21:40.768	Good	-9 kA -13 kA -21 kA -10 kA	3 7 12 4	12 - 13 13 12 13
13.	1 (+)	30 10 2010	19:04:20:427 a)	19:04:20:427	Good	-18 kA	4	71 - 72
			19:04:20:427 b)	19:04:20:427	Good	+11 kA	2	126
14.	1 (+)	30 10 2010	19:04:21:661	19:04:21:660	Poor	-9 kA	4	74
15.	1 (+)	07 11 2010	00:37:25:390	00:37:25:389	Good	-8 kA	3	506
16.	1 (+)	11 12 2010	18:36:03:593	18:36:03:593	Poor	-43 kA	12	69
17.	1 (+)	24 12 2010	03:04:35:625	03:04:35:626	Good	-40 kA	12	70
18.	1 (+)	16 03 2011	11:03:24:535	11:03:24:535	Good	-31 kA	7	39
19.	1 (+)	03 10 2011	13:49:45:00	13:49:45:191 ²	Good	-64 kA	15	308 - 309
20.	1 (+)	26 10 2013	00:44:00:000	00:44:20:557 ²	Good	-24 kA	9	431 - 432
21.	1 (+)	26 10 2013	20:43:25:995	20:43:25:995	Good	-24 kA	9	72
22.	1 (+)	26 10 2013	20:55:37:955	20:55:37:955	Good	-21 kA	7	72
23.	1 (+)	12 11 2013	17:09:54:590	17:09:54:590	Good	-18 kA	8	72
24.	2 (-)	28 11 2013	16:48:05:550	16:48:05:551	Good	-9 kA	3	56 - 62
25.	1 (+)	14 12 2013	20:52:49:493	20:52:49:622	Fair	-27 kA	12	39
26.	1 (+)	15 01 2014	18:30:09:008	18:30:09:008	Good	-17 kA	8	72

Legend:

RED indicates positive HVDC transmission line, and positive lightning stroke polarities.

BLUE indicates negative HVDC transmission line, and negative lightning stroke polarities.

Stroke times in **GREEN** are "exact" time correlations (<2 ms, the difference is only due to rounding-off of the LFL fault time).

Strokes times in **YELLOW** indicate "close" time correlations (≤200 ms).

Strokes times in **PINK** indicate "poor" (>200 ms, see Note 1) or uncertain time correlations (See Note 2 below).

Strokes times in **GREY** indicate multiple strokes of a single flash that are not fault correlated

Notes:

1. Fault number 10 shows a difference of 319 ms between the fault time and the closest stroke time. This is discussed further under 7.4 for “fault 10” below.
2. Fault number 19 and 20 were obtained from database records from the Apollo staff, and was not reported by the LFL linked to the protection system. Although reasons for this are uncertain, it is possible that the LFL system was not operational at this time, resulting in the time of the fault not being accurately known.

Table 5 was compiled from the information presented in Appendices A and B. **Appendix A** contains a tabular summary of the lightning correlation results for each fault recorded by the line protection scheme. **Appendix B** contains the graphical FALLS “Reliability Analysis” correlation for each fault.

7.4 Discussion around correlations that are not ideal

The following is a discussion around fault correlations that are not ideal and therefore require further interpretation of the circumstances that contribute to the correlations. These faults are numbered in accordance with the faults listed in *Table 5*. The discussions should be read in conjunction with the corresponding graphical correlations with the same fault number in **Appendix B**.

About two thirds of the faults in *Table 5* show what can be considered “ideal correlations”. Fault correlations are considered “ideal” if the following two criteria are met:

- a. Temporal correlation: The time correlation between the fault time and the lightning stroke time is less than 2 ms.
- b. Spatial correlation: The 99% confidence ellipse of the stroke overlaps the transmission line.

In most of these cases, there have also been a large number of reporting LDN sensors and therefore the confidence in the reported stroke position is high.

The following is an example of a fault correlation that is classified as “ideal”. There were nine reporting LDN sensors for this correlated stroke. The fault time and the time of the correlated stroke are the same.

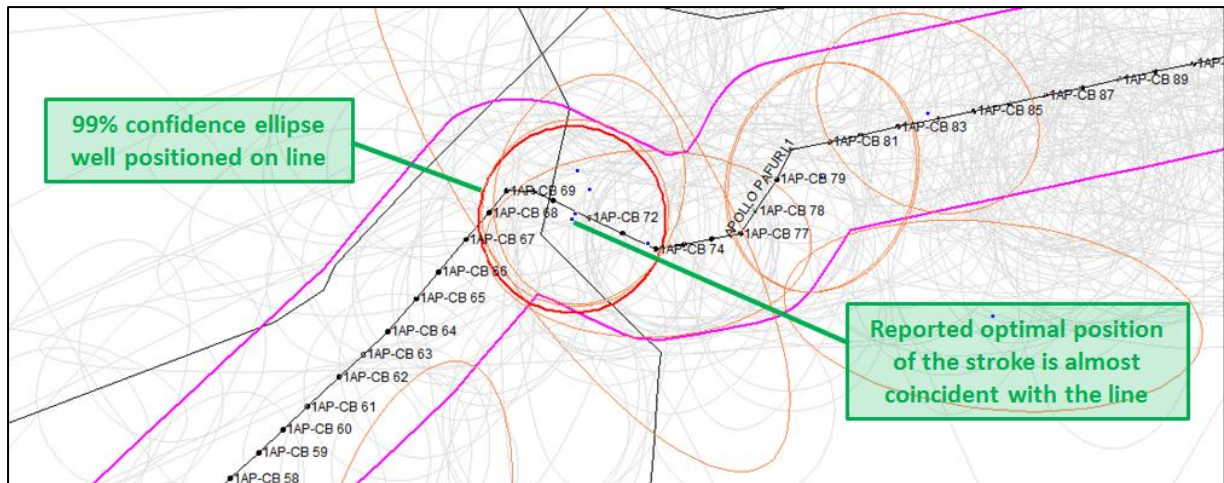


Figure 62: Ideal spatial correlation between line and reported stroke position

The following are fault correlations in *Table 5* that are considered not ideal. The criteria for classification of the correlation, in the methodology for fault correlation, are applied for the temporal and spatial matching in order to categorise the likelihood that the correlated stroke resulted in the fault. The likelihood that a stroke resulted in a fault is classified as either *low*, *medium* or *high*. Strokes that are regarded as of low probability have been disregarded from the overall statistics of the line.

Fault 2 (refer to *Figure B.2*)

In this case, the temporal correlation is exact. There were only two reporting sensors although the confidence ellipse overlaps the line; the uncertainty in the stroke position is large. The overall likelihood that this stroke resulted in the fault is *medium*.

Fault 6 (refer to *Figure B.7*)

There is a difference of 72 ms in the temporal correlation between the fault time and the stroke. This correlation is considered fair, based on the criteria in the methodology. The spatial correlation is good. The overall likelihood that this stroke resulted in the fault is considered *medium*.

Fault 10 (refer to *Figure B.11*)

This fault has been correlated according to the following criteria used by FALLS Reliability Analysis:

- a. Fault time is within the time interval for analysis around the fault time
- b. 99% confidence ellipse coincided with buffer zone around the line

However, each correlation is considered in detail in order to determine the probability of correlation. The following comments can be made about this correlation:

Temporal correlation: As the *319 ms* time interval between the fault and the stroke times is significant, the time correlation is considered poor.

Spatial correlation: As there were only two sensors reporting this stroke, the confidence ellipse is approximately 10 km along the major axis, therefore the confidence is the spatial correlation is low.

The probability that this stroke resulted in the fault in question is *low* and this correlation has been disregarded from the performance statistics.

Fault 14 (refer to *Figure B.15*)

The fault time is 19:04:21:660 and the stroke time is 19:04:21:660526600. Hence, the temporal correlation is exact.

Although the confidence ellipse overlaps the buffer zone, the boundary of the ellipse is still approximately 600 m from the line and this is outside of the optimistic striking distance of a 9 kA stroke of about 70 m. Therefore, the overall likelihood that this stroke resulted in the fault is *medium*.

Fault 16 (refer to *Figure B.17*)

The temporal correlation is exact, at 18:36:03:583 for both the fault and the correlated stroke.

Although the confidence ellipse overlaps the buffer zone, the boundary of the ellipse is still a distance of approximately 200 m from the line. The striking distance is calculated to be 92 m by the equation adopted by IEEE998 2012 for the stroke amplitude of 43 kA. This distance is conservative and according to other Electro-Geometric Models could be as much as double. In addition, this does not take into account HVDC polarity effects, which may affect the striking distance. Therefore, the line is considered to be within the potential striking distance. The overall likelihood that this stroke resulted in the fault is *medium*.

Fault 19 (refer to *Figure B.20*)

The time of the fault is only known to the second resolution, i.e. 13:49:45. Although the times match to this resolution, the lightning activity cannot be precisely time-correlated with the fault.

Despite this, the spatial correlation of the stroke error ellipse with the line is good, with the ellipse overlapping the line significantly. Therefore, the overall probability that this stroke caused the fault is *high*.

Fault 20 (refer to *Figure B.21*)

The time of the fault is known to the minute resolution, i.e. 00:44:00; therefore, there is uncertainty in the temporal correlation.

The spatial correlation of the stroke error ellipse with the line is favourable with the centre of the ellipse close to the line. Therefore, the overall probability that this stroke caused the fault is considered *medium*.

Fault 25 (refer to *Figure B.26*)

The time of the fault is *129 ms* before the closest time correlated stroke. Therefore, the temporal correlation is fair.

The stroke error ellipse touches the line and therefore the spatial correlation is good. The overall probability that this stroke caused the fault is classified as *medium*.

Conclusion

Based on the above discussions, fault numbers 2, 6, 14, 16, 19, 20 and 25 are considered to be of a medium or high likelihood to have been caused by the correlated stroke.

7.5 Distribution of correlated stroke amplitudes

The distribution of stroke amplitudes that have been correlated with line faults can be shown graphically in *Figure 63*.

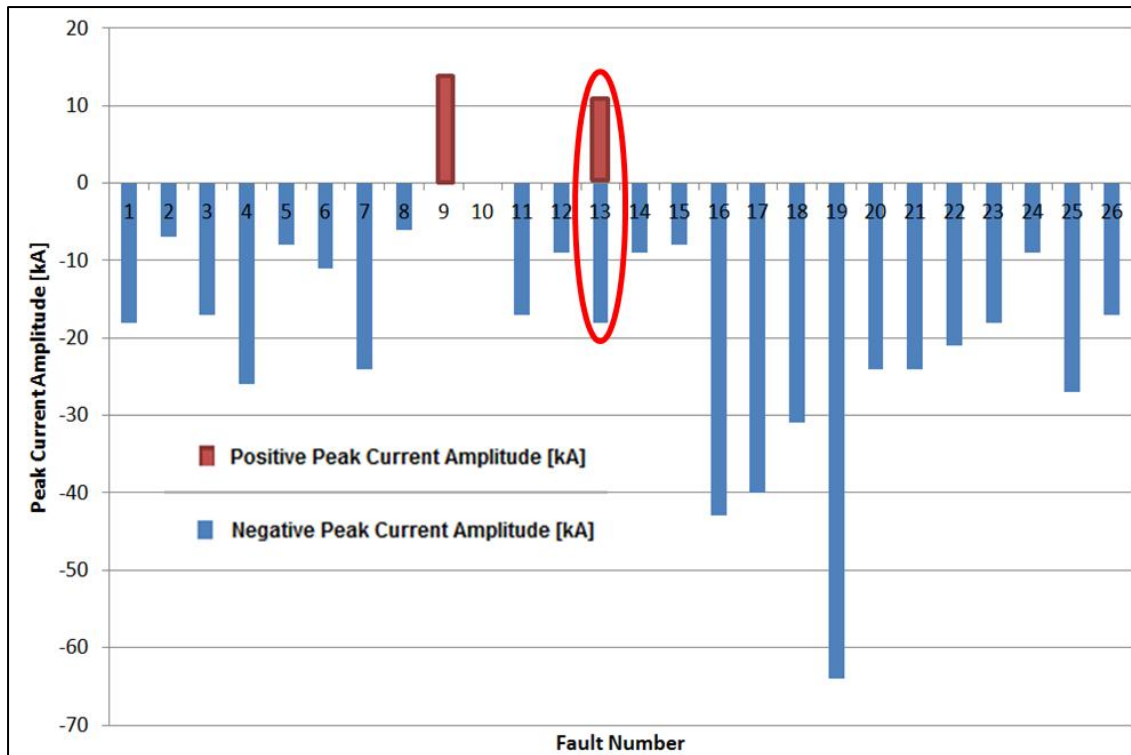


Figure 63: Peak current amplitude and polarity of the fault-correlated strokes.

Fault number 13 encircled with the red ellipse, is comprised of two lightning stroke events that occurred in locations far apart on the line but at the same time. There was a negative 18 kA stroke near tower 71 and a positive 11 kA stroke near tower 126. According to the lightning database, these strokes occurred at precisely the same time 19:04:20:427 on the 30th October 2010. Fault number 10 has been classified as having a low probability of causing the fault and has been disregarded from the fault statistics and is depicted removed from *Figure 63*.

7.6 Discussion of the Results of Fault Correlations

The results are discussed with particular emphasis on trends related to polarity.

7.6.1 Total Number of Lightning Correlated Line Faults

The total correlated lightning faults over a 7-year period are 25. Some of these reported faults are actually comprised of several line faults occurring in close proximity on a section of line between several towers, which seem to have been caused by subsequent return strokes of a single lightning flash. As the successive faults are likely caused by strokes of a single flash, the faults are grouped together and reported as a single fault incident.

A significant example of this is the series of faults that occurred on the 19 January 2009, which is investigated in *Specific Example 2*.

7.6.2 Influence of Polarity on the Incidence of Faults

The HVDC scheme is comprised of two “poles” which are independent power lines of positive and negative polarity. Similarly, cloud-to-ground lightning strokes are also either of positive or negative polarity. There are two failure modes for lightning induced faults on transmission lines, namely “shielding failure” and “back-flashover”. The combination of the line and stroke polarities and failure modes results in eight permutations of polarity interaction. These combinations cannot be investigated at this stage because faults due to the two failure mechanisms have not been differentiated.

7.6.3 Line Polarity

Of the total lightning correlated faults, twenty-three (92%) are on the positive line (Line 1), and two (8%) are on the negative line (Line 2). The positive polarity appears to be more affected by lightning activity. The mode of failure being either back-flashover or shielding failure has not been determined. The polarity of the line may influence the probability of failure in relation to the lightning polarity depending on the mode of failure. Therefore at this stage it cannot be determined if the positive line polarity increases the probability of strike by negative downward leader.

7.6.4 Stroke Polarity

Of the faults of the positive line, 21 out of 23 (91%) were due to strokes of negative polarity which is consistent with the proportions of positive and negative polarity lightning activity determined by the Area Exposure Analysis.

Only two (8%) out of 25 correlated faults are due to positive strokes, which corresponds with the overall lightning exposure statistics from the SAE analysis for the 8-year period, where between 5% and 10% are positive strokes.

7.6.5 Stroke Amplitude

Some faults are caused by unexpectedly low amplitudes. Correlated faults in *Table 5* show positively correlated faults for stroke peak amplitudes as low as 7 kA.

This is anomalous as this is significantly lower than what is expected to result in flashovers for transmission lines. There are two mechanisms whereby lightning may result in faults on transmission lines:

- a) Back-flashover - These faults are due to strokes attaching to the shield wire or tower, that result in insulator flashovers due to high structure footing resistances.
- b) Shielding failure – These faults arise from strokes bypassing the shield wire and terminating on the pole conductor bundle.

Figure 64 depicts the fault on Hydro Manitoba’s Nelson River HVDC Transmission Lines between 1998 and 2000. The “bimodal” fault distribution suggests that the outages are related to the two modes of failure, namely, shielding failures and back-flashover (Shelemy & Swatek 2001). In this case, relatively low stroke amplitudes of 15 kA, 25 kA and 35 kA resulted in faults that are presumed to be due to shielding failure. It is suggested that the large amplitudes of 105 kA and 135 kA resulted in faults due to back-flashovers.

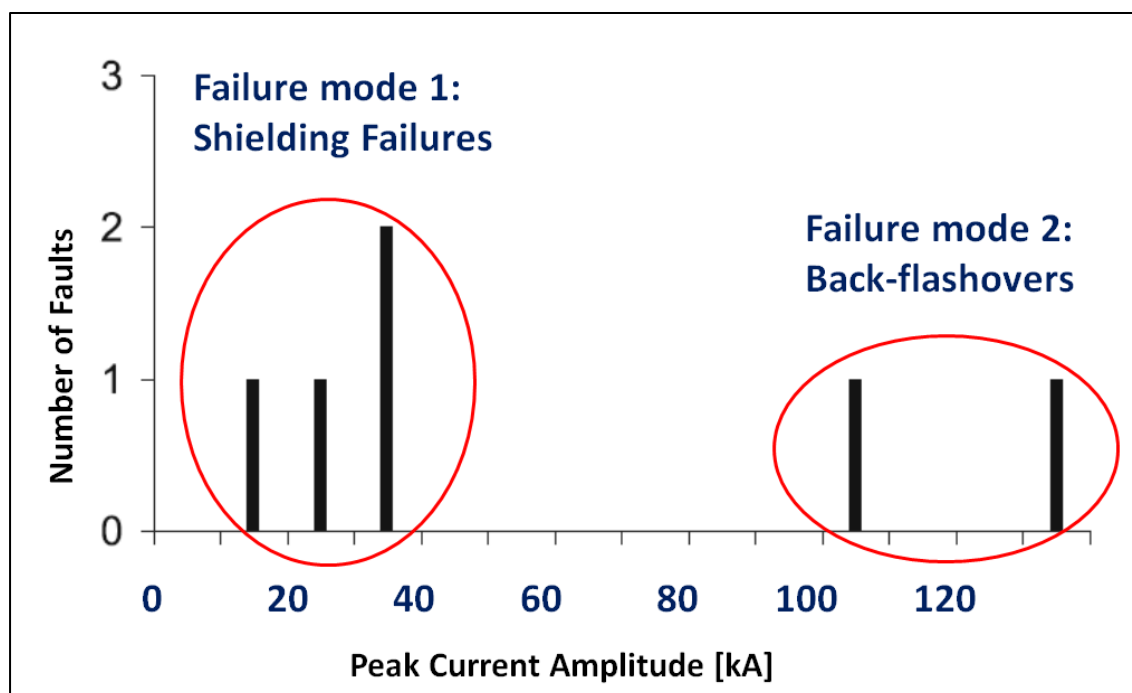


Figure 64: Faults on the Nelson River HVDC transmission lines between 1998 and 2000⁴³.

The Nelson River results appear to be what may be expected if the insulation coordination for a transmission line is appropriately designed.

⁴³ Adapted from Shelemy & Swatek (2001).

“Appropriately designed” means that there is an acceptably low probability of faults occurring that result in the target fault rate, usually expressed as faults/100 km/year being met. The target for fault rate depends on the particular application and the main factors being power rating, and impact of outages. The target fault rate is the rate, which is economically feasible whilst achieving acceptable technical performance (Kiessling et al. 2002; Eskom 2005),

The fault amplitude distribution for the Cahora-Bassa Lines is dissimilar and contains unexpectedly many faults due to relatively low amplitudes as can be seen in *Figure 65*. Twenty-two out of twenty-five faults (88%) occurred for stroke amplitudes below 35 kA.

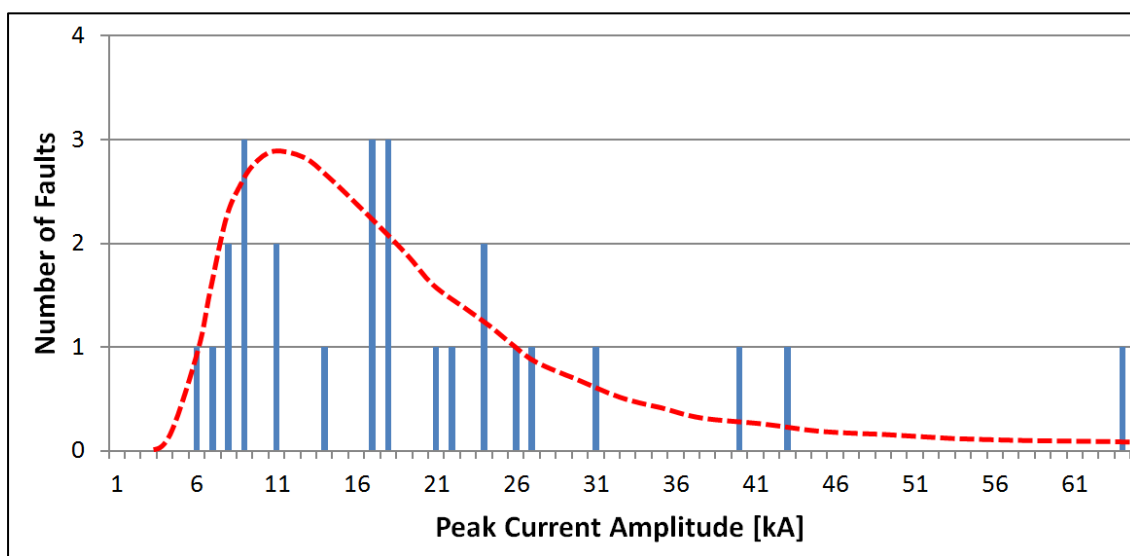


Figure 65: Number of lightning correlated faults vs. peak stroke amplitude for the period from August 2008 to August 2014.

The distribution of faults is spread across the amplitudes, and appears to loosely mimic the distribution of the number of strokes versus the peak current amplitude for Line 1. This is shown in the similarity between *Figure 65* and *Figure 66*. The envelope of the stroke peak current frequency has been superimposed on the number of faults vs. peak current amplitude to highlight this. This indicates that there is a similar probability of failure across all amplitudes.

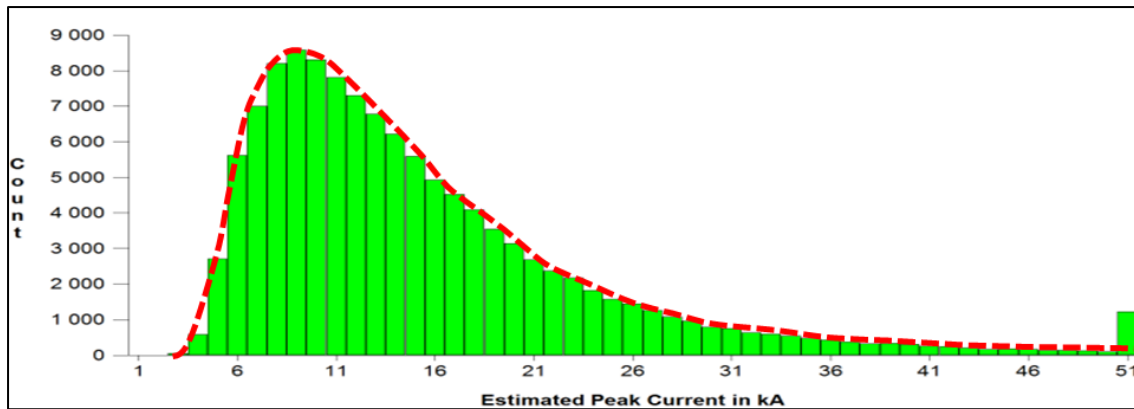


Figure 66: Positive pole (Line 1) *negative* polarity stroke peak current frequency.

Further investigation is required to determine the reason for the unexpected distribution of fault amplitudes; however, preliminary assessment indicates two possible modes of failure:

- a) Back-flashover – Small amplitude strokes intercepted by the shield wire yet still resulting in faults due to exceptionally high structure footing resistances.
- b) Shielding failure – Low amplitude strokes below the “coordination current” that may bypass the shield wire and terminate on the pole conductor.

The first reason is more probable as in most of the cases of relatively low amplitude strokes that result in faults, are due to tower footing resistances are high. Measurements taken confirmed high tower footing resistances.

The second reason is less likely as the insulator lightning impulse withstand level is high (1800 kV) and the quad conductor bundle surge impedance is relatively low due to four 31.8 mm diameter sub-conductors with a spacing of 450 mm (Holtzhausen et al. 2007). The high impulse withstand level is a product of the high insulator creepage that is required for the suppression of leakage current for adequate pollution performance.

7.7 Specific Examples of Fault Correlations

The process of fault correlation and the interpretation of the results are explored by means of the following specific examples.

7.7.1 Specific Example 1: Fault for 15 January 2014

The first example is where the fault correlation is ideal, and there is a high degree of confidence that the fault was caused by the identified lightning stroke.

The time of the fault and the correlated lightning stroke are both recorded as 18h30:09:008, whilst the spatial correlation is favourable as shown in *Figure 67*.

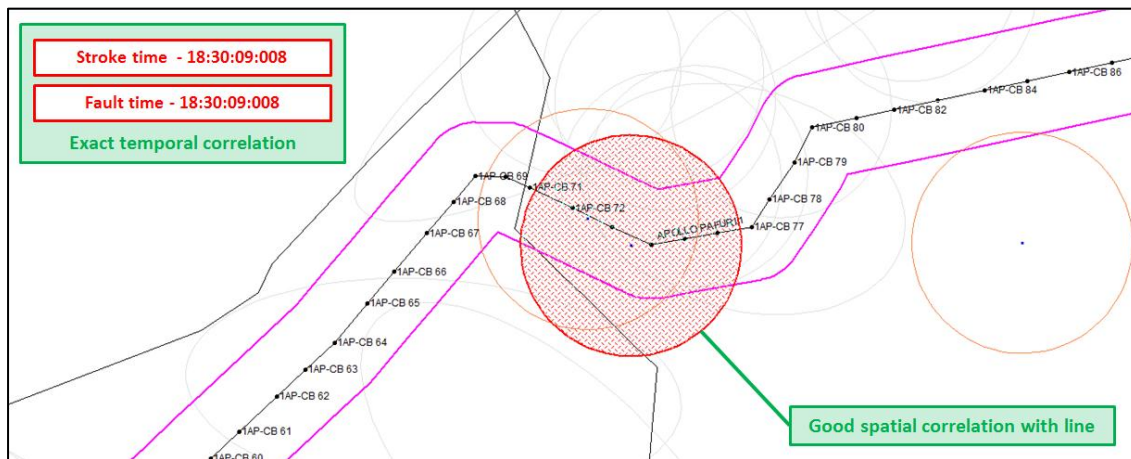


Figure 67: Ideal correlation for fault number 26 on the 15 January 2014.

7.7.2 Specific Example 2: Faults for 19 January 2009

On the 19th of January 2009, there were six line faults reported by the protection system that correlated with lightning strokes are shown in *Table 6*.

Table 6: Fault correlation result for faults occurring on the 19 January 2009 on Cahora-Bassa Line 1.

Fault Number	Line Polarity	Date	Fault Time	Stroke Time & Correlation	Inter-stroke interval	Stroke Current & Polarity	Location (Probable)
1a	1 (+)	19 01 2009	23:13:38:108	23:13:38:108	85 ms 39 ms 163 ms 43 ms	-18 kA	Tower 72
1b		19 01 2009	23:13:38:193	23:13:38:193		-9 kA	Tower 74
1c		19 01 2009	23:13:38:232	23:13:38:232		-9 kA	Tower 73
1d		19 01 2009	23:13:38:395	23:13:38:395		-11 kA	Tower 73
1e		19 01 2009	23:13:38:438	23:13:38:438		-9 kA	Tower 73
2	1 (+)	19 01 2009	23:13:41:151	23:13:41:151		-7 kA	Tower 116, 117

There were six faults reported on this day. All six of the faults demonstrate an “exact correlation” in time where the reported time from the LDN corresponds precisely with the protection time stamp to the millisecond as shown in the table. An “exact correlation” is defined as one where the difference in time between the fault time and the stroke is less than 2 ms.

The first five faults between 23:13:38:108 and 23:13:38:438 are separated by several 10's of milliseconds and are probably due to subsequent strokes of a single flash. The arithmetic mean of the inter-stroke time interval for this series of five strokes is 82.5 ms. Inter-stroke time intervals observed in various geographical regions around the globe have not been found to vary greatly and the arithmetic mean ranges between 64.3 and 87 ms (Cooray 2010). Therefore, the inter-stroke interval is within the normal range. The reported stroke location for each stroke is not identical, but is proximate between towers 71 and 74 as shown in *Figure 68*. The subsequent strokes in a flash are known to vary in position by up to several hundred meters or more. Furthermore, since these individual stroke events are concentrated in a relatively small area, the supposition that the strokes are related within a single flash is further substantiated.

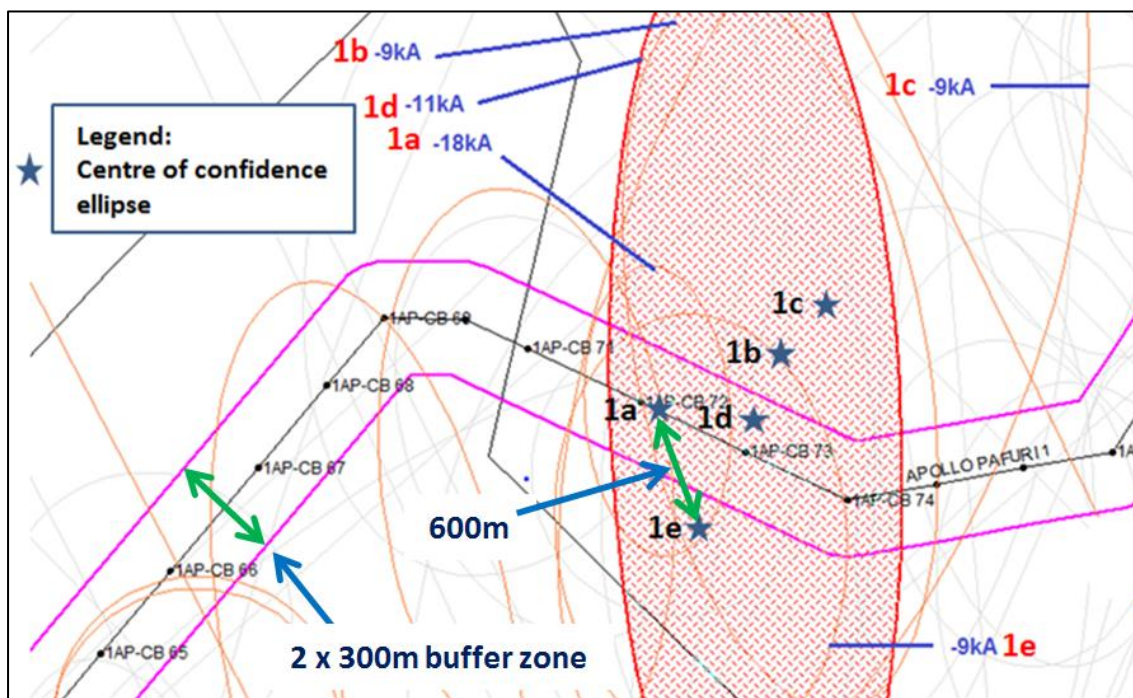


Figure 68: Graphical Reliability Analysis for 19 January 2009 depicting confidence ellipses for the 5 fault-correlated strokes between 23:13:38:108 and 23:13:38:438.

Figure 69 is an extract from the Line Fault Locator (LFL) download for all faults occurring on the 19th of January 2009. There are 15 faults reported on “Pole 1” which is the positive line. These faults occurred between 23:13:32:849 and 23:13:41:151.

ts_lightning Browser

				Fault time from protection system	Lightning Stroke Detection Time			
	Corr	ID	Asset Name	TimeCorr Fact	Fault Time GMT+02:00	Precision(s)	Time GMT+02:00	PkCurr(kA)
☐	F	2	APOLLO CAHORA BASSA	0.565651	2009-01-19 23:13:32.849	60	2009-01-19 23:13:06.788	-9
☐	F	3	APOLLO CAHORA BASSA	0.603363	2009-01-19 23:13:32.849	60	2009-01-19 23:13:09.051	-8
☐	F	4	APOLLO CAHORA BASSA	0.677423	2009-01-19 23:13:32.849	60	2009-01-19 23:13:13.494	-7
☐	F	5	APOLLO CAHORA BASSA	0.6867	2009-01-19 23:13:32.849	60	2009-01-19 23:13:14.051	-10
☐	F	6	APOLLO CAHORA BASSA	0.743992	2009-01-19 23:13:32.849	60	2009-01-19 23:13:17.489	-10
☐	F	7	APOLLO CAHORA BASSA	0.744306	2009-01-19 23:13:32.849	60	2009-01-19 23:13:17.507	-12
☐	F	8	APOLLO CAHORA BASSA	0.745833	2009-01-19 23:13:32.849	60	2009-01-19 23:13:17.599	-17
☐	F	9	APOLLO CAHORA BASSA	0.808625	2009-01-19 23:13:32.849	60	2009-01-19 23:13:21.366	-10
☐	F	10	APOLLO CAHORA BASSA	0.816257	2009-01-19 23:13:32.849	60	2009-01-19 23:13:21.824	-11
☒	T	11	APOLLO CAHORA BASSA	0.987263	2009-01-19 23:13:32.849	60	2009-01-19 23:13:32.085	-13
☐	F	12	APOLLO CAHORA BASSA	0.921141	2009-01-19 23:13:32.849	60	2009-01-19 23:13:37.581	-8
☐	F	13	APOLLO CAHORA BASSA	0.913479	2009-01-19 23:13:32.849	60	2009-01-19 23:13:38.040	-16
☐	F	14	APOLLO CAHORA BASSA	0.912353	2009-01-19 23:13:32.849	60	2009-01-19 23:13:38.108	-18
☐	F	15	APOLLO CAHORA BASSA	0.910984	2009-01-19 23:13:32.849	60	2009-01-19 23:13:38.190	-5
☐	F	16	APOLLO CAHORA BASSA	0.910941	2009-01-19 23:13:32.849	60	2009-01-19 23:13:38.193	-9
☐	F	17	APOLLO CAHORA BASSA	0.91028	2009-01-19 23:13:32.849	60	2009-01-19 23:13:38.232	-9
☐	F	18	APOLLO CAHORA BASSA	0.907571	2009-01-19 23:13:32.849	60	2009-01-19 23:13:38.395	-11

Figure 71: Extract of the output browser for Reliability Analysis showing all spatially correlated strokes between 23:13:06:788 and 23:13:38:395.

The graphical representation of the RA for the fault occurring at 23:13:32:849 is depicted in *Figure 72*. The “best correlation” is shown as a bold red ellipse. This stroke is the closest time correlation to the fault time but the 99% confidence ellipse does not overlap with the transmission line and therefore it is unlikely that this stroke terminated on the line. All other spatially correlated strokes within the time tolerance are displayed as orange confidence ellipses.

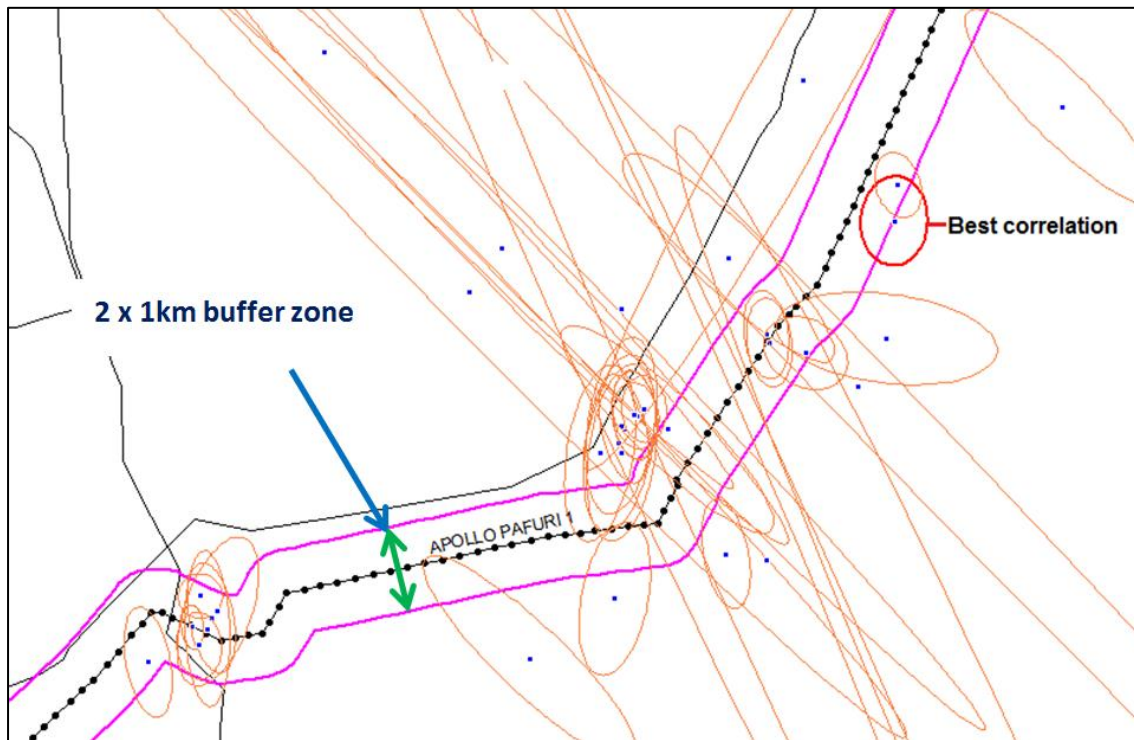


Figure 72: Graphical Reliability Analysis depiction for the fault occurring at 23:13:32:849.

Due to the poor temporal correlation between the fault and the stroke time, and the poor spatial correlation between the line and the confidence ellipse of the stroke indicated above, the fault is considered unrelated to lightning activity.

For reasons of efficiency, the RA was not performed for each of the 15 reported protection system faults. The subsequent 14 faults were analysed by means of a single RA analysis. Since the faults are within a very short period of less than 5 seconds, a single RA can be used to check for correlation on all 14 faults. *Figure 73* shows the output browser for RA for all spatially correlated strokes between 23:13:33:494 and 23:13:41:151. The RA has been set to display all spatially correlated strokes for 60 seconds before and after the fault time. This period is referred to as the “Precision interval” and is indicated by the “Precision” column highlighted in the output browser. As lightning strokes during this period were frequent, there are a large number of spatially correlated strokes. Therefore, only a few strokes have been selected for display purposes.

ts_lightning Browser								
Corr	ID	Asset Name	TimeCorr Fact	Fault Time GMT+02:00	Precision(s)	Time GMT+02:00	PkCurr(kA)	NumSer
☐	F	11 APOLLO CAHORA BASSA	0.584856	2009-01-19 23:13:38.403	60	2009-01-19 23:13:13.494	-7	2
☐	F	12 APOLLO CAHORA BASSA	0.594134	2009-01-19 23:13:38.403	60	2009-01-19 23:13:14.051	-10	3
☐	F	13 APOLLO CAHORA BASSA	0.651425	2009-01-19 23:13:38.403	60	2009-01-19 23:13:17.489	-10	4
☐	F	14 APOLLO CAHORA BASSA	0.651739	2009-01-19 23:13:38.403	60	2009-01-19 23:13:17.507	-12	5
☐	F	15 APOLLO CAHORA BASSA	0.72369	2009-01-19 23:13:38.403	60	2009-01-19 23:13:21.824	-11	5
☐	F	16 APOLLO CAHORA BASSA	0.986292	2009-01-19 23:13:38.403	60	2009-01-19 23:13:37.581	-8	2
☐	F	17 APOLLO CAHORA BASSA	0.995081	2009-01-19 23:13:38.403	60	2009-01-19 23:13:38.108	-18	11
☐	F	18 APOLLO CAHORA BASSA	0.996449	2009-01-19 23:13:38.403	60	2009-01-19 23:13:38.190	-5	2
☐	F	19 APOLLO CAHORA BASSA	0.996492	2009-01-19 23:13:38.403	60	2009-01-19 23:13:38.193	-9	3
☐	F	20 APOLLO CAHORA BASSA	0.997153	2009-01-19 23:13:38.403	60	2009-01-19 23:13:38.232	-9	3
☒	T	21 APOLLO CAHORA BASSA	0.999863	2009-01-19 23:13:38.403	60	2009-01-19 23:13:38.395	-11	3
☐	F	22 APOLLO CAHORA BASSA	0.999416	2009-01-19 23:13:38.403	60	2009-01-19 23:13:38.438	-9	5
☐	F	23 APOLLO CAHORA BASSA	0.984371	2009-01-19 23:13:38.403	60	2009-01-19 23:13:39.341	-12	2
☐	F	24 APOLLO CAHORA BASSA	0.960757	2009-01-19 23:13:38.403	60	2009-01-19 23:13:40.758	-34	3
☐	F	25 APOLLO CAHORA BASSA	0.955639	2009-01-19 23:13:38.403	60	2009-01-19 23:13:41.065	-3	2
☐	F	26 APOLLO CAHORA BASSA	0.954206	2009-01-19 23:13:38.403	60	2009-01-19 23:13:41.151	-7	2

Figure 73: Tabular output browser for Reliability Analysis for 19 January 2009 showing all spatially correlated strokes between 23:13:33:494 and 23:13:41:151.

Comparing the download from the LFL and the output of the RA, it is evident that there are six correlated faults, which are highlighted in green in *Figure 74*. The remaining seven fault time stamps that do not correlate with lightning strokes are highlighted in yellow.

Line	Date	Fault time from LFL	Lightning Correlation Result
1	19 01 2009	23 13 38.108	Perfect time correlation with -18kA
1	19 01 2009	23 13 38.117	No correlation
1	19 01 2009	23 13 38.193	Perfect time correlation with -9kA
1	19 01 2009	23 13 38.202	No correlation
1	19 01 2009	23 13 38.232	Perfect time correlation with -9kA
1	19 01 2009	23 13 38.241	No correlation
1	19 01 2009	23 13 38.395	Perfect time correlation with -11kA
1	19 01 2009	23 13 38.404	No correlation
1	19 01 2009	23 13 38.438	Perfect time correlation with -9kA
1	19 01 2009	23 13 38.447	No correlation
1	19 01 2009	23 13 38.493	No correlation
1	19 01 2009	23 13 38.602	No correlation
1	19 01 2009	23 13 41.151	Perfect time correlation with -7kA

Figure 74: Summary of lightning correlated faults for the 19th of January 2009.

It is notable that the stroke amplitudes ranging between 7 kA and 18 kA are unexpectedly low to have resulted in line faults. As the line impulse insulation level is high (1800 kV), stroke amplitudes of this magnitude will only result in line faults if the tower footing resistance is excessively high. The possibility of high footing resistances must be further investigated in order to confirm if this is the cause of these faults.

In addition, all strokes are of negative polarity, which is opposite to the positive line voltage. Negative impulses are more likely to result in flashovers on the positive line by the back-flashover mechanism, as the opposite polarities result in additive voltage stress across the line insulation.

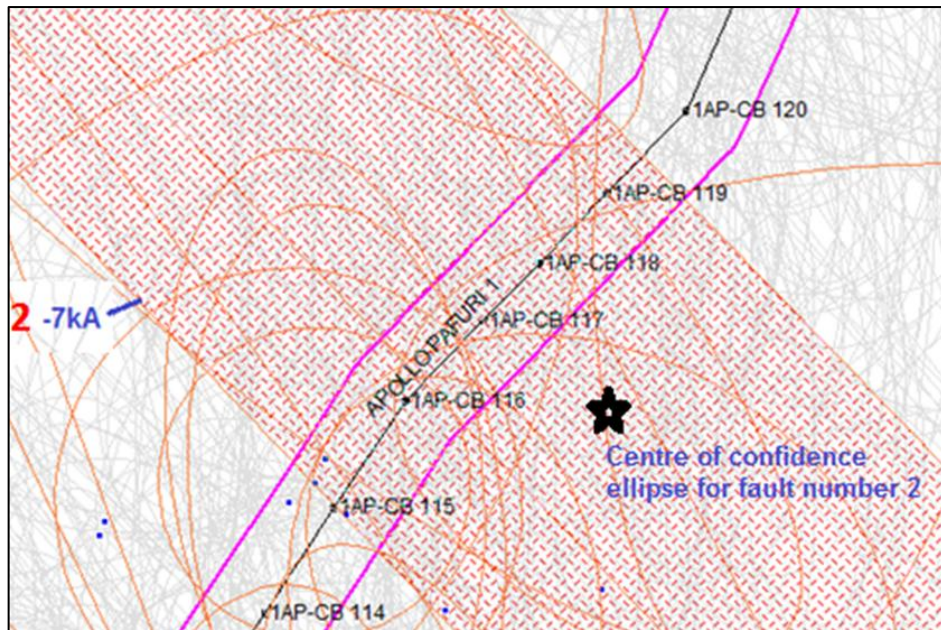


Figure 75: Graphical Reliability Analysis output for the fault occurring at 23:13:41:151 on the 19th of January 2009.

The sixth fault was shown to correlate with a negative stroke of amplitude of 7 kA and a probable strike position between Tower 116 and 117 as shown in *Figure 75*. Only two LDN sensors were involved in the stroke detection and hence the 99% confidence ellipse is relatively large. The sixth fault, which occurred at 23:13:41:151, is distinct from the group of five faults between 23:13:38:108 and 23:13:38:438, both temporally and spatially, and is therefore considered a separate fault incident. Approximately 2.7 seconds had elapsed between the group of five faults and the sixth fault. Furthermore, the reported position of the sixth fault is between tower 114 and 120 whereas the group of five faults occurred between towers 71 and 74.

This example is significant because it shows a number of strokes within a flash that are correlated with protection system time-stamps.

7.7.3 Specific Example 3: Faults for 16 January 2010

On the 16th of January 2010, a single fault on Line 1 was recorded by the protection system as shown in *Figure 76*.

"2010.01.16","01:16:40:690","Fault Time 39 sec, 590288200 ns, Pole 1"

Figure 76: LFL download reporting a single line fault on Line 1 occurring on the 16th January 2010.

The fault time from the protection system is interpreted as 01:16:39:590 as explained in “Specific Example 1”. The FALLS RA Tool was used to determine if there were any lightning strokes that correlated with this fault time.

The FALLS analysis shows that there were two flashes close to the fault time. The first flash is comprised of two strokes at 01:15:25:562 and 01:15:25:600. The second flash is comprised of three strokes occurring at 01:16:39:617, 01:16:39:677 and 01:16:39:744. The strokes occurring at 01:16:39:617 and 01:16:39:677 are closest to the fault time of 01:16:39:590. In addition, the strokes are spatially well correlated with the line, as their confidence ellipses overlap the buffer zone but only come within about 500 m of the transmission line, as can be seen in Figure 77. The stroke at 01:16:39:744 shows good spatial correlation but is 150 ms after the reported fault time. This last stroke is considered the most probable stroke to have resulted in the fault. It is likely that this fault is correlated with lightning, as there are multiple strokes around the time of the fault. The centroid of the triangle formed by these three strokes corresponds closely with the position of the line.

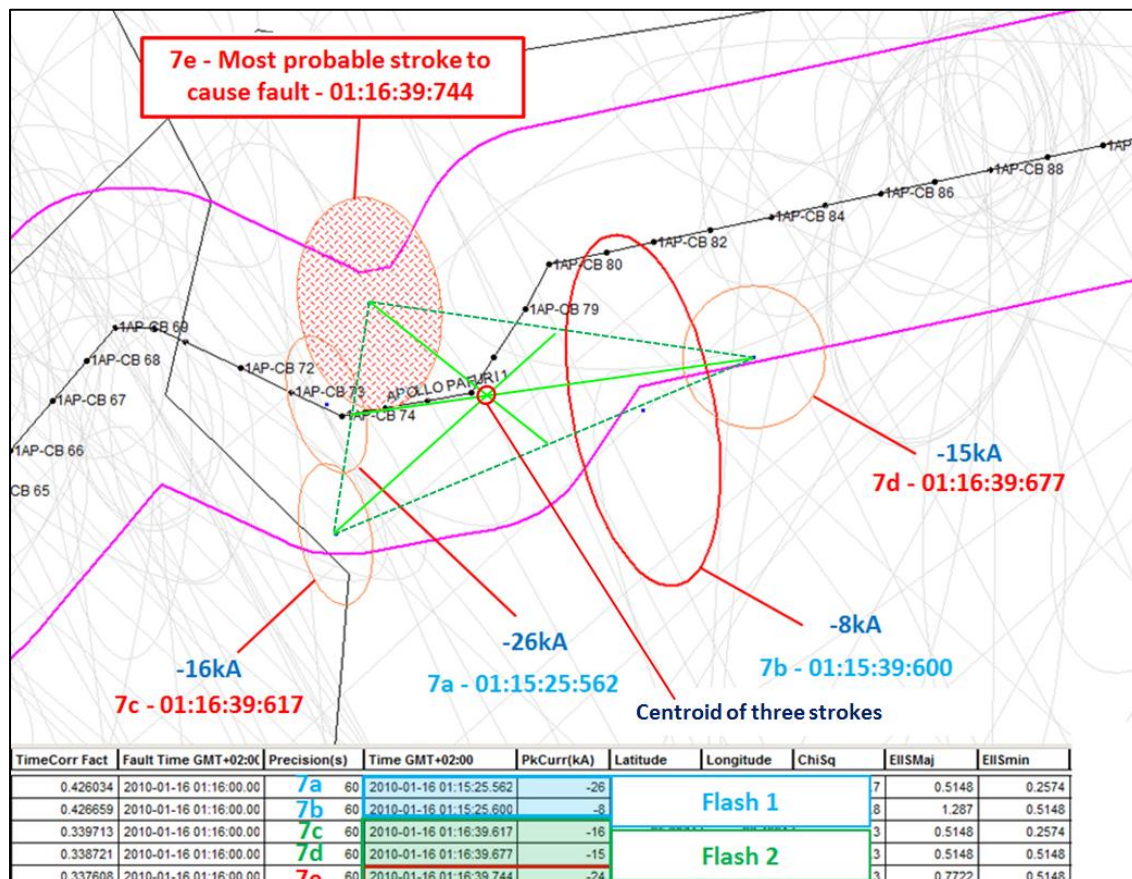


Figure 77: Graphical Reliability Analysis for fault occurring on 16th January 2010.

7.7.4 Specific Example 4: Faults for 30 October 2010

Fault correlation

This is an unusual case (and unique in this investigation) where the LFL system reported a single fault occurring at 19:04:20.427 on the 30th October 2010, but there are two separate strokes that occurred a significant distance apart (approximately 20 km), that are time correlated with this fault. The first stroke occurred close to tower 71 ("Stroke 71") with an amplitude of -18 kA. The second correlated fault took place near tower 126 ("Stroke 126"), with an amplitude of +11 kA. Stroke 71 and stroke 126 are clearly two distinct lightning events. The reported time from FALLS for both strokes is precisely 19:04:20.427 as can be seen in the output browser below the graphical presentation of the RA in the lower part of *Figure 78*.

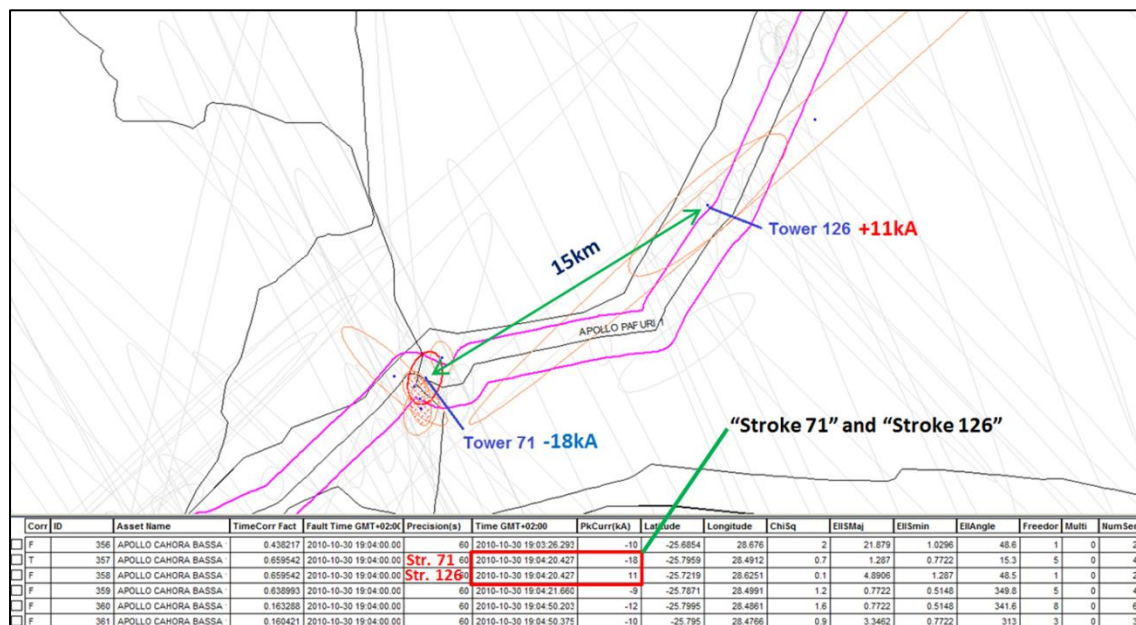


Figure 78: Graphical Reliability Analysis for 30 October 2010 showing two correlated stroke positions.

Determination of Probable Causative Stroke

It is not possible to conclusively determine which of the two strokes resulted in the line fault. In some cases, visual line inspections can reveal the position of the line fault by means of evidence of flash marks on the insulators. This is determined by electric arc damage to metal end fittings similar to marks that are caused by arc welding, or by arc by-products on the insulation material. In this case, the fault occurred more than 5 years ago and it is unlikely that any evidence of arc by-products would remain at this stage,

even under close visual examination. Arc damage to the end fittings would still remain but cannot be determined without a line outage or live-live techniques permitting close inspection. Furthermore, the line has since been “reinsulated” with silicone rubber long-rod insulators, which have replaced the original glass disc insulator strings.

It is considered that the stroke occurring close to tower 71 is the stroke most likely to have resulted in the line fault, due to one of the possible breakdown mechanisms, namely back-flashover and shielding failure:

a) Back-flashover mechanism – “Stroke 71” is more likely to have caused a line fault for two reasons. Firstly, the stroke amplitude is nearly 40% higher (-18 kA vs. +11 kA) and it is of the opposite polarity to the line polarity, resulting in greater stress across the line insulation and a higher probability of back-flashover. Secondly, the tower footing resistances in the vicinity of tower 71 are unusually high due to local geological conditions and therefore tower-top voltage increases would be proportionately high and more likely to result in back-flashovers.

b) Shielding-failure – As the stroke and line have opposite polarities, it is likely that the probability of shielding failure associated with this stroke is higher than that of a stroke of the same polarity as the line. This is because opposite polarities result in a greater potential for induced streamers from the pole conductor, which effectively increase the probability of shielding failure. However, the opposite polarities result in lower voltages developed across the line insulation and therefore reduce the probability of flashover.

The stroke occurring close to tower 126 is spatially correlated with the line, with the most probable reported location coincident with the line. This positive stroke is considered less likely to have resulted in a line fault. The centroid of the triangle formed by these three strokes corresponds closely with the position of the line.

7.8 Discussion of Anomalous Area with High Fault Rate

Out of the combined 25 line faults on both lines, 23 faults occurred on Line 1, which is the positive pole. Out of these 23 faults on Line 1, 11 faults occurred over a short section of about 3500 m comprised of 8 towers between towers 68 and 76 and is highlighted in *Figure 79* within the red ellipse.

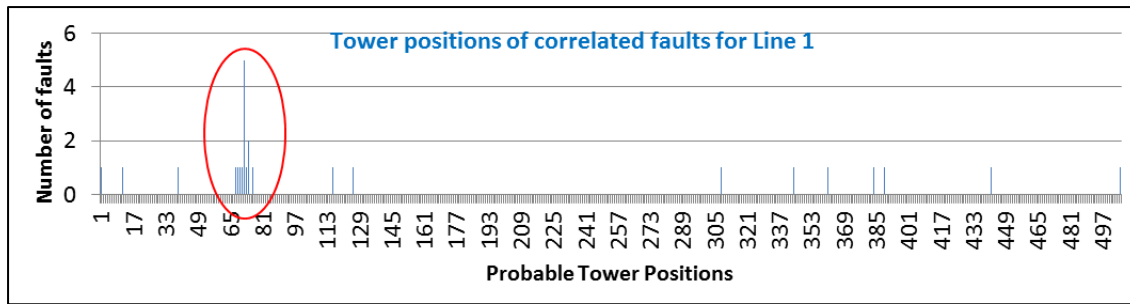


Figure 79: Probable tower positions for faults on Line 1 from August 2008 to August 2014.

The route of the two lines is 517 km long, running from Apollo CS to the Mozambique border and therefore, the combined line length results in over a thousand kilometres of exposure. It is remarkable that such a high proportion of the lightning related faults are concentrated in a very small area and only on one of the two lines. The section in question, between towers 68 and 76 and its position relative to Apollo CS are illustrated in *Figure 80*. The majority of the faults in this anomalous area occur between towers 69 and 74. This position is approximately 25 km along the line northeast of Apollo CS.

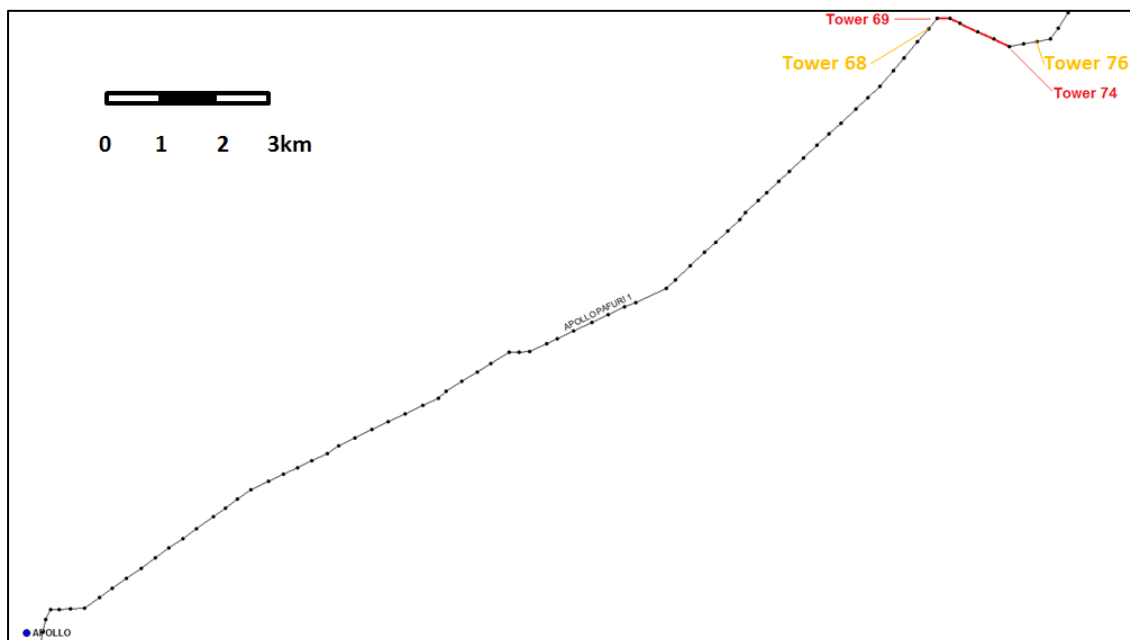


Figure 80: Affected Line 1 section between towers 68 and 76⁴⁴.

This section of Line 1 is adjacent to the N4 (Pretoria – Witbank) highway as can be seen in *Figure 81*. Line 1 crosses the N4 highway at this point, between towers 77 and 78, and continues in a North-easterly direction.

⁴⁴ Adapted from line asset depiction in Vailsala FALLS ®

This section of Line 1 is referred to as the “N4 spot” by the operational staff at Apollo CS, due to the numerous associated lightning faults at this position, over the years. There have been several investigations into suspected lightning faults, which occurred in this particular area. Miya (2014a, 2014b) compiled detailed investigative reports for two line faults that occurred in October 2013.



Figure 81: Aerial view of the affected Line 1 section between towers 69 and 74⁴⁵.

Several possible contributing factors result in the very high fault rate on this section of line:

- a) *High structure footing resistances* - This section can clearly be seen to cross a rocky outcrop. This geological feature probably results in very high local soil resistivity and therefore structure footing electrode resistances.
- b) *High relative elevation* – The towers of this section are generally elevated above the surrounding area due to the rocky outcrop. Tower 69 is particularly exposed.

7.8.1 Structure Footing Resistances

A common cause of a high fault rate on a transmission line due to lightning is high tower footing resistances. Often high footing resistances are related to more elevated positions, which increase lightning exposure, thus exacerbating the problem. The tower footing resistance of tower 69 was measured using a Low Frequency (LF) measurement technique in May 2014 (Pretorius 2014a).

⁴⁵ Adapted from Miya (2014a).

A LF technique is appropriate in this case because the shield wire is insulated from the structures and therefore, from an earthing point of view, each tower electrode is “independent”. If, however the shield wire were bonded to the structures, a High Frequency (HF) technique using a specialised instrument would be applicable. This is because the measurement of an individual tower cannot be performed without the undue influence of the adjacent tower electrodes. The use of a HF technique aims to obtain an indication of the local tower footing resistance as by using a high frequency, the relatively high impedance of the shield wire compared to the tower footing impedance means that the adjacent tower electrodes are largely excluded.

The instrument used was the four terminal earth tester, “Megger DET 2/2” shown in *Figure 82*, and the test was repeated along several trajectories and thereafter averaged to obtain 835 Ω (Pretorius 2014a).

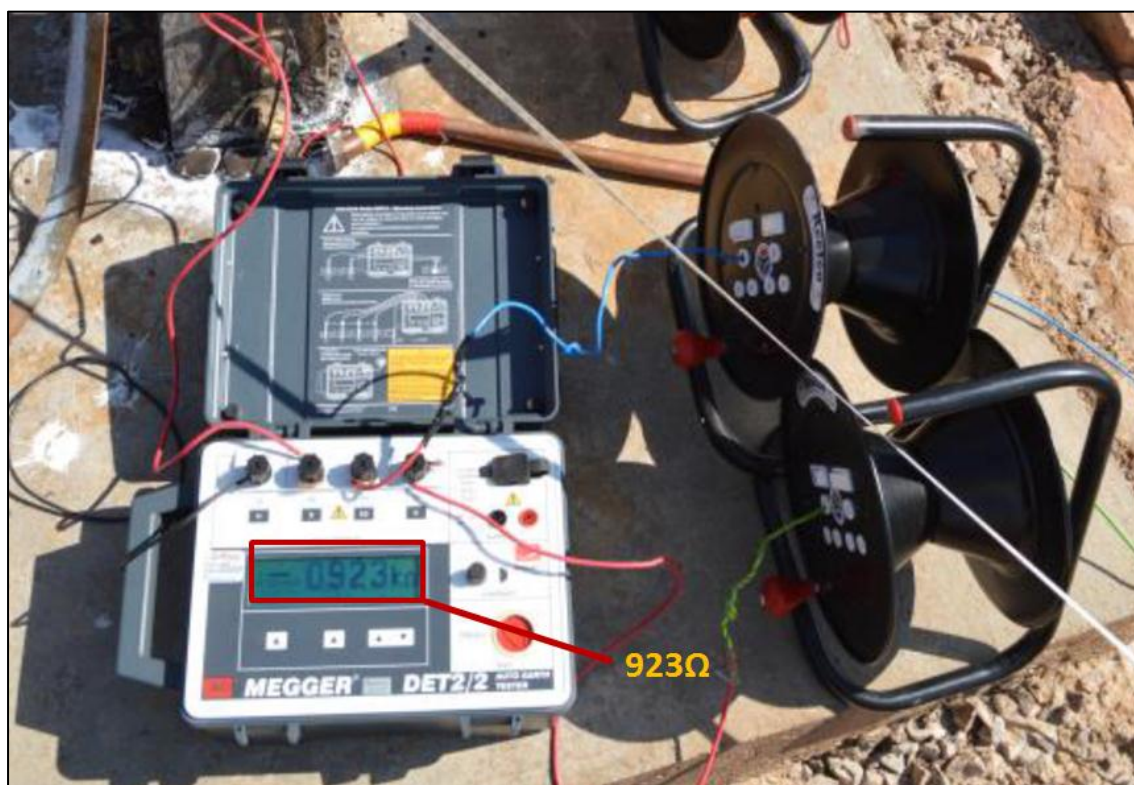


Figure 82: Earth resistance tester instrument used for LF measurement displaying a typical reading for this section of line⁴⁶.

⁴⁶ Adapted from Pretorius (2014a)

Subsequently in August 2014, the LF measurement of the tower footing resistance at tower 69 was repeated, and additional measurements were performed at towers 70, 71 and 72 (Pretorius 2014b). *Table 7* presents the measured resistances.

Table 7: Measured tower footing resistances for towers 69, 70, 71 and 72 (Pretorius 2014b).

Tower Number	Measured Tower Footing Resistance [Ω]
69	1065
70	843
71	839
72	No obtainable reading

Note: No reading was obtained for tower 72 due to the resistance being out of range

The design for Cahora-Bassa (CB) lines was performed in the early 1970's and the details are not available. Furthermore, values for the nominal tower footing resistances for the 533 kV HVDC towers are not published in the Eskom standard for the "Earthing of Transmission Line Towers" which is compiled around HVAC. The tower footing resistance values are related to the Lightning Impulse Withstand Level (LIWL) for the line insulation. The other significant factors that influence this relationship are the required fault rate, tower surge impedance and coupling between phase and shield wire conductors. Therefore, in order to get an indication of a suitable value for the CB line consistent with the practice for HVAC lines, the insulation levels can be compared between the HVDC and HVAC line values and used to estimate the tower resistance value. *Table 8* encapsulates the lightning impulse withstand levels and tower footing resistance values for the various nominal system voltages applied by Eskom for HVAC transmission systems.

Table 8: Nominal tower footing resistance values for HVAC Lines according to the Eskom standard (TST41-3, 2006).

Nominal system voltage	Lightning Impulse Withstand Level	Nominal footing resistance
[kV]	[kV]	(Ω)
132 kV	650	20
220 kV	1050	30
275 kV	1175	30
400 kV	1550	40
765 kV	2100	50

The LIWL for the CB lines is 1800 kV. By linear interpolation between the LIWL for 400 kV of 1550 kV and for 765 kV of 2100 kV, the tower footing resistance value for CB would be 45.5 Ω .

The measured values for towers 69 to 71 are about 20 times higher than the estimated tower footing resistances of 45.5 Ω .

As the tower footing resistances are very high on this section, the probability of back-flashover due to strokes terminating on the shield wire would be high, even for relatively low amplitude strokes, and this is the main factor that could account for the unusually high fault rate on this section of Line 1 between towers 68 and 76.

7.8.2 Local Geological Conditions

From observation of the surface, the local conditions are consistent with extensive rock outcrops of quartzite as can be seen in *Figure 83*. Quartzite is known to have high resistivities in relation to most other types of rock, and in turn, up to three orders of magnitude higher than most soil types.



Figure 83: Typical local geological conditions near towers 69 – 74 (Pretorius 2014a).

Several of the towers have foundations in decomposed metamorphic rock as can be seen for tower 69 in *Figure 84*. The locations for towers 72 and 73, exhibit rocky conditions, which are similar to that of tower 69.



Figure 84: Soil conditions near tower 69 (Miya, 2014a).

The area surrounding towers 70 and 71 show evidence of cohesion-less sand with low organic content, mixed with some decomposed rock. Whilst in *Figure 85* of tower 74, sandy conditions without rock are apparent. Both these conditions are associated with high soil resistivities.



Figure 85: Soil conditions near tower 74 (Miya, 2014a).

Tower 77 in the foreground of *Figure 86* is located in sandy conditions similar to the conditions at tower 74. The N4 highway can be seen running between towers 77 in tower 78 in background of *Figure 86*.



Figure 86: Soil conditions near tower 77 (Miya, 2014b).

The geology of the area is mostly comprised of quartzite based metamorphic rock. Resistivities were determined by soil resistivity investigations using the “Wenner array”. It was ascertained that the resistivities ranged from about 17.4 k Ω .m to 64.7 k Ω .m (Pretorius 2014a). Furthermore, the high resistivities extend deeply into the soil structure as was determined by the soil resistivity surveys, and can also be seen from the cut out for the N4 highway about 1.2 km North-North-West from tower 69 (Pretorius 2014a) in *Figure 87*.

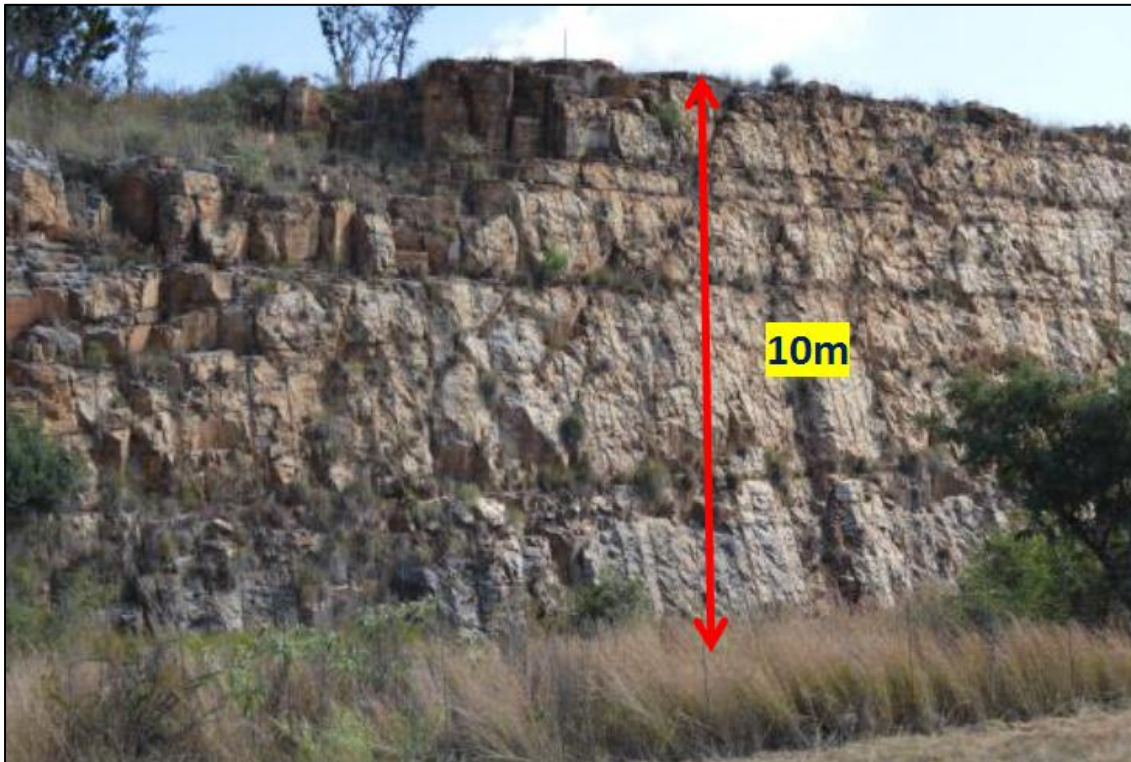


Figure 87: Typical local subsurface structure shown in N4 road cut-out⁴⁷.

7.8.3 Line Elevation above Surrounding Area

The section between towers 69 and 73 is elevated above the surrounding area as the line is constructed along a ridge formed by an exposed rocky outcrop (*Figure 88*). In addition, there are no tall trees or other objects that would screen the line. Whilst, towers 68 and 74 are less exposed and are situated in areas, which are associated with conditions of lower soil resistivity. An example of this can be seen in *Figure 85* of tower 74.

⁴⁷ Adapted from Pretorius (2014a)



Figure 88: The elevated position of tower 69 (Pretorius 2014a).

In conclusion, the section of Line 1 between towers 68 and 76 experiences an unusually high fault rate due to a combination of specific local geological and topographical reasons. Localised meteorological conditions affecting cloud formation are not considered a factor, as cloud formation is at several kilometres above ground level.

8. Conclusion and Further Work

The outcomes of the research are summarised and it is discussed as to whether the hypothesis has been adequately addressed by this work. Further steps built on these findings are identified in the recommendations for further work.

8.1 Conclusion

Comparison of the stroke peak current frequency between the two HVDC lines, for both positive and negative stroke polarities show that the lightning exposure for the two lines is very similar over the 8-year period of analysis.

The results from the lightning exposure investigation of the Cahora-Bassa HVDC lines indicate the fault rate due to lightning for the positive line to the negative line is about 10:1.

It appears that the polarity affects the lightning performance. This result concurs with international findings in several references, mainly in China but also in Canada.

In China, investigations indicate that faults due to shielding failure favour the positive pole by between 8:1 and 10:1. The literature suggests that the dominating lightning induced fault mode is shielding failure.

Faults for Cahora-Bassa have not been differentiated between shielding failure and back-flashover at this stage. The classification of the fault mode is required to make a closer comparison to the international performance data.

8.2 Further Work

The following proposed significant steps are required to develop a better understanding of the mechanisms and associated parameters involved in lightning protection and performance prediction of HVDC lines:

- a. *Model development* – A model to be developed for HVDC lines that will simulate the “attractive distances” for lightning, in relation to the stroke magnitude and polarity, as well as the voltage level and polarity of the pole conductor. This model would predict the maximum threshold penetration current that could result in shielding failure and thus a direct strike to the pole conductor. This model would allow faults to be differentiated between the shielding failure and back-flashover mechanisms.
- b. *Verification of the model* - The model predictions will be compared to the actual performance of the Cahora-Bassa lines in order to verify the validity of the model.
- c. *Experimental work* – Possibilities and validity of experimental work to further this understanding may be proposed.

8.2.1 Development of a Model

Traditional methods of lightning protection system design evolved around HVAC lines. These models neglect the conductor voltage in the lightning attachment process in two significant ways:

- a. The line voltage is negligibly small when compared to the tip potential of the descending leader (Risk 2012).
- b. On AC systems, the power frequency voltage has a mean value that approaches zero (Maruvada 2008) and therefore any voltage-induced effects appear to be largely negated.

Clearly, the second assumption is not applicable to HVDC. However, the first is also inaccurate in the HVDC case.

The line operational voltage should not be compared to the tip potential of the descending leader, but should be considered in relation to the space potential (electric field gradient) that is required for the initiation of an induced upward leader (Rizk 2012).

The effective conductor voltage (U_e) resulting in positive leader initiation is given by the following expression according to Rizk (2012):

$$U_e = V_{p-g} + E_g h + U_i \quad \text{Equation (5)}$$

Where

V_{p-g} is the pole to ground voltage

E_g = Ambient ground field due to cloud charge

h is the height of conductor above ground

U_i is the induced voltage at conductor position due to descending leader charge

A significant portion of the space potential required (around 30% for a positive 600 kV pole) may be provided by pole voltage (Rizk 2012). The effect of pole voltage is all but ignored in published models (Rizk 2012) except for an extension of the Rizk model in (Maruvada 2008) which was developed in order to evaluate HVDC lightning performance.

After review of the published models, with specific focus on those that incorporate conditions particular to HVDC, the apparent validity of the models will be assessed. This process will culminate in the adoption of a suitable model or possible development of a revised or extended version of an existing model.

8.2.2 Simulation for Model Verification

In order to differentiate between lightning induced faults that were due to shielding failure and back-flashover, the maximum penetration current must be determined.

The development of a model will be pursued in further work. It is planned that simulations will be performed using the model in order to investigate its validity by means of correlation with field performance.

8.2.3 Experimental Testing

Experimental testing depends on how effectively the lightning attachment process can be simulated. Full-scale tests are expensive and require very high impulse voltages. Therefore, for practical reasons such tests are often conducted with scale models.

The validity of such “scaled-down” tests is frequently stated to be questionable or even completely invalid (Golde 1941; Becerra & Cooray 2008) as the conditions for these discharges do not simulate lightning leaders.

Large air-gap laboratory tests are frequently used to simulate the conditions under which upward positive leaders are initiated, although these tests cannot fully replicate the conditions during natural lightning (Becerra & Cooray 2008).

It is challenging to initiate flashovers by means of the leader mechanism in laboratory conditions, even at impulse voltages in the megavolt range. There are possibilities related to using slower wave fronts (e.g. switching impulses) to initiate leader breakdown. However, the electric fields associated with switching impulses, do not adequately approximate the field produced by a negative downward leader. With switching, the electric field rate of change varies from fast to slow whereas with natural lightning the rate of change is reversed from slow to fast as shown in *Figure 89*.

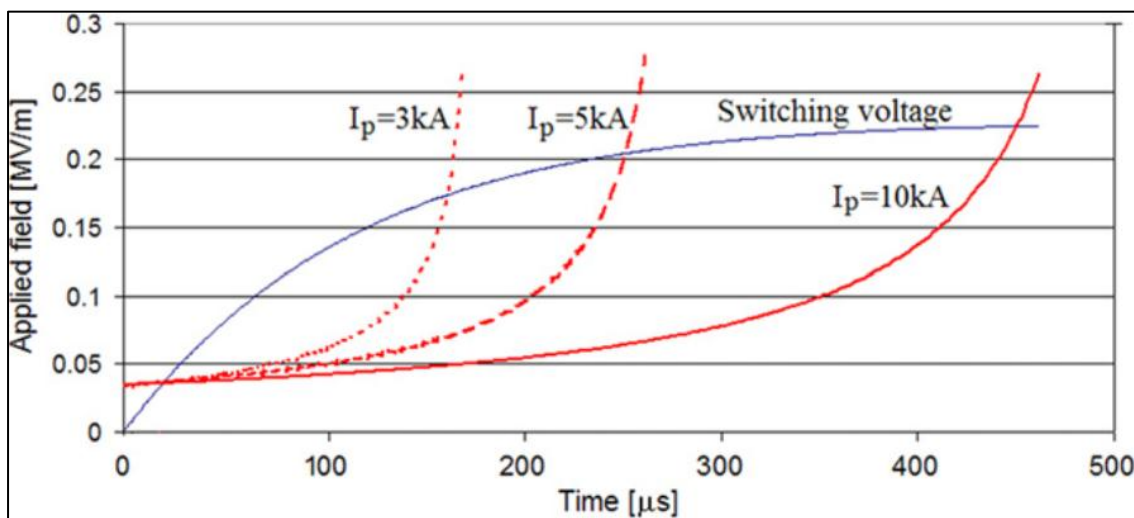


Figure 89: Simulated electric field for switching vs. various peak return lightning stroke currents associated with downward descending leaders (Becerra & Cooray 2008).

The execution of large-scale representative tests requires extensive resources that are not readily available. Therefore, no experimental work is proposed at this stage.

9. References

ABB (2016): [Online] <http://new.abb.com/systems/hvdc/references/cahora-bassa> [Accessed: 17 May 2016].

Bahrman, M.P. & Johnson, B.K. (2007) “*The ABCs of HVDC Transmission Technology*”, IEEE Power & Energy Magazine, March/April 2007, Vol. 5, No. 2.

Bardo, E. (2005) “*South African Weather Service Chooses Vaisala Thunderstorm Information System*”, Vaisala News.

Becerra, M. and Cooray, V. (2008) “Laboratory experiments cannot be utilized to justify the action of early streamer emission terminals”. *Journal of Physics D: Applied Physics*, March 2008.

Cigré (2016): [Online] <http://c4.cigre.org/WG-Area/WG-C4.26-Evaluation-of-Lightning-Shielding-Analysis-Methods-for-EHV-and-UHV-DC-and-AC-Transmission-lines>, [Accessed: 1 February 2016].

Chan-Ki, K., Vijay K.S., Gil-Soo, J., Seong-Joo, L., Seok-Jin, L., (2009), “HVDC Transmission: Power Conversion Applications in Power Systems”, Wiley-IEEE Press, ISBN: 978-0-470-82295-1.

Cooray, V., (2010), “Lightning Protection”, IET Power and Energy Series 58, The Institution of Engineering and Technology, Stevenage, Hertfordshire, United Kingdom, ISBN 978-1-84919-106-7.

Cummins, K.L., Krider, E.P., Malone, M.D. (1998a) “*The U.S. National Lightning Detection NetworkTM and Applications of Cloud-to-Ground Lightning Data by Electric Power Utilities*”, IEEE Transactions on Electromagnetic Compatibility, Vol. 40, No. 4, November 1998.

Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., and Pifer, A. E., (1998b) “A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network,” *Journal of Geophysical Research*, vol. 103, pp. 9035–9044, 1998.

Cummins, K.L., Murphy, M.J., Tuel, J.V. (2000) “*Lightning Detection Methods and Meteorological Applications*”, IV International Symposium on Military Meteorology Hydro-Meteorological Support of Allied Forces and PfP Members Tasks Realization, September 26 – 28, 2000, Malbork, Poland.

Eskom Power Series (2005), *“The Planning, Design and Construction of Overhead Power Lines”*, Crown Publications, Johannesburg.

Evert, R., (2011), *“Falls Analysis Part 2: Lightning Asset Exposure Analysis Procedure Revision 2”*, Eskom Research Report RES/RR/10/32901.

Gibjen, M., (2012), *“Lightning Climatology of Southern Africa with Special Focus on Lightning Risk Maps”*, 22nd International Lightning Detection Conference, 2 -3 April, Broomfield, Colorado, USA.

Golde R.H., (1941), *“The Validity of Lightning Tests and Scale Models”*, *Journal IEE*, vol. 88, Part II, no. 2, pp. 67-68, 1941.

Greyling, E., (2014), Personal communication with Eric Greyling, Eskom Apollo Lines and Servitudes Manager on the 20 November 2014.

Greyling, E., (2015), *“Apollo Lines – Servitude Report Database”* Eskom fault database spreadsheet for Cahora-Bassa HVDC transmission lines.

He, H., He, J., Zhang, D., Ding, L., Jiang, Z., Wang, C., Ye, H., (2009), *“Experimental Study on Lightning Shielding Performance of 500 kV HVDC Transmission Lines”*, IEEE, New York. ISBN 978-1-4244-2487-0

He, J., Zhang, X., Dong, L., Zeng, R., Liu, Z., (2009): *“Fractal model of lightning channel for simulating lightning strikes to transmission lines” Science in China Series E: Technological Sciences*, Nov. 2009, vol. 52, no. 11, ISBN 3135-3141.

Holtzhausen, J.P., Hendricks, H., Pieterse, P.J., (2007), *“Corona on the Cahora Bassa DC Line: Theory and Tests on a Scale Model”*, Proceedings of the 16th South African Universities Power Engineering Conference (SAUPEC), 25-26 January 2007.

Hubbard, R., (2016), Personal communication with Roy Hubbard, Eskom Senior Consultant responsible for Cahora-Bassa performance improvement portfolio on 15 Jan 2016.

Hunt, H.G.P., (2012), *“A Methodology for Matching Lightning Detection Network Data with Ground-truth Records”*, School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg.

IEEE Std 998 (2012), "Guide for Direct Lightning Stroke Shielding of Substations", Institute of Electrical and Electronics Engineers, New York. ISBN 10016-5997.

Kiessling, F., Nefzger, P., Nolasco, J.F., Kaintzyk, U., (2002): "*Overhead Power Lines, Planning, Design, Construction*", Springer-Verlag, Berlin, ISBN 3-540-00297-9.

Maruvada, P.S, (2008), "*EPRI HVDC Reference Book: Overhead Lines for HVDC Transmission, Electrical Performance of HVDC Transmission Lines*", Chapter 4, "Lightning Performance", EPRI, Palo Alto, California, 1016999.

Miya, S., (2014a): "Apollo Grid Technical Incident Investigation Report, 26 October 2013, 20:43:26:995", Eskom Technical Incident Investigation Report, Unique identifier TAPRP PWPTII 26/11/13 @ 20h43: Line 1.

Miya, S., (2014b): "Apollo Grid Technical Incident Investigation Report, 26 October 2013, 20:55:38:205", Eskom Technical Incident Investigation Report, Unique identifier TAPRP PWPTII 26/10/13 @ 20h55: Line 1.

Nayel, M., Jie, Z., He, J., (2010), "*Analysis of Significant Parameters Affecting the Shielding Failure of HVDC-TL*", IEEE, New York. ISBN 978-1-4244-6395-4.

Pretorius, P.H., (2014a): "Tower Footing Resistance Analysis and Its Conceptual Improvement - Tower No 69 on Pole 1 of the Cahora Bassa Line - Part 1 - A Progress Report" Rev 0.0, Eskom Technical Memorandum.

Pretorius, P.H., (2014b) "Repeat Measurement of the Tower Footing Resistance of Tower No 69 and others on Pole 1 of the Cahora Bassa Line - Part 2 - A Progress Report", Rev 0.0, Eskom Technical Memorandum.

Rakov, V.A. & Uman, M.A., (2003), "*Lightning: Physics and effects*", Cambridge University Press, ISBN 0-521-58327-6.

Rizk, F.A.M., (2012): "*Lightning Exposure and Lightning Protection with Special Reference to High Altitudes, Review of State of the Art and Selection of Design Criteria*", Research report submitted to Trans Africa Projects in February 2012.

Siemens (2016): [Online] "HVDC – High Voltage Direct Current Transmission"
http://www.energy.siemens.com/rupool/hq/power-transmission/HVDC/HVDC-Classic/HVDC-Classic_Transmission_References_en.pdf [Accessed: 10 Jan 2016]

Shelemy, S.J., Swatek, D.R., (2001), "*Monte Carlo Simulation of Lightning Strikes to the Nelson River HVDC Transmission Lines*", International Conference on Power Systems Transients.

Smidt, E.R., (2003) "*Lightning Analysis in a High-voltage Transmission Environment*", Vaisala Tucson USA.

Smidt, E.R., Zaharescu, R., Richard, P., (2004) "*A Revolution in Lightning Detection Networks with Modular Technology for Focused Performance*" Vaisala, Tucson USA.

TST41-3, (2006), "Earthing of Transmission Line Towers", Rev. 0. Eskom Standard

Vaisala, (2012): "*Vaisala FALLS® Client Fault Analysis and Lightning Location System*". [Online] Vaisala. Available at: <http://www.vaisala.com/Vaisala%20Documents/Brochures%20and%20Datasheets/WEA-NWM-G-Falls-Client-datasheet-B210778EN-C-LoRes.pdf>, Vaisala, Tucson Arizona, USA.

Vaisala, (2013), "*User's Guide FALLS® Client for Windows*". [Online] Vaisala. Available at: http://www.vaisala.com/en/vaisalalists/Documents/FALLS_5.4_ClientUserGuide.pdf, [Accessed: 20 December 2015]. Vaisala, Tucson Arizona, USA.

Vestergaard, O., 2006: "*Description of DC Line Fault Locator (LFL)*", ABB Power Systems document no. 1JNL100109-384 Rev. 02.

You, M., Zhang, B.H., Cheng, L.Y., Bo, Z.Q., Klimek, A., (2010), "*Lightning Model for HVDC Transmission Lines*", IEEE, New York.

Appendix A: Tabular Summary of Lightning Correlation Results for All Faults

A.1 Introduction

Table A.2 condenses the correlation results for each fault recorded on the line protection between the 17th of September 2008 and the 31st of August 2014.

A.2 Software used

The following two “FALLS” software tools were used to perform the analysis. The results of the analysis are summarised in the *Table A.2* for all fault events:

- a) *Small Area Exposure (SAE)* – This tool is used to determine when lightning activity occurred within selected periods, and within the buffer region.
- b) *Reliability Analysis (RA)* – Reliability Analysis checks for correlations between fault incidents and lightning activity. Temporal correlations are made between the entered fault time and lightning stroke times. The temporal correlation is only performed for reported stroke positions that are spatially correlated with a buffer region around the line.

A.3 Results of SAE and RA analysis

The line polarity and fault correlation result are highlighted according to the *Table A.1* below:

Table A.1: Colour legend for tabular correlation results.

Legend			
Green – Fault Correlation	No Colour – No Fault Correlation	Red – Positive Line Polarity	Blue – Negative Line Polarity

Table A.2: Results of SAE and RA analysis for faults between 17 September 2008 and 31 August 2014.

Line	Fault Date	Fault time from protection system	Lightning correlation result and comments
1	19 09 2008	12:58:28:809	RA - No Lightning during this period No Spatially correlated lightning
1	21 09 2008	02:38:46:781	RA - No Lightning during this period No Spatially correlated lightning
1	21 09 2008	02:49:04:415	SAE: No lightning activity on these days. SAE shows lightning activity on 26th September only (15 Strikes)
1	21 09 2008	10:32:02:000	
1	23 09 2008	22:32:01:518	
1	24 09 2008	14:56:54:482	
1	27 09 2008	11:24:24:347	RA - No Lightning during this period No Spatially correlated lightning
1	27 09 2008	13:04:12:992	
1	27 09 2008	15:09:45:885	

1	01 10 2008	05:12:32:916	SAE: SAE analysis for 02 October 2008 shows negative Lightning between 19:28 and 19:52 and positive Lightning at 21:40. Otherwise, there was no lightning activity at the time of these faults. (These faults were likely due to pollution flashover due to fog etc.)
1	01 10 2008	05:16:23:476	
1	02 10 2008	03:52:26:479	
1	02 10 2008	04:09:16:401	
1	02 10 2008	04:16:10:669	
1	02 10 2008	04:41:49:443	
1	02 10 2008	04:48:25:440	
1	02 10 2008	05:20:09:571	
1	02 10 2008	05:37:02:388	
1	02 10 2008	05:42:03:206	
1	02 10 2008	05:44:08:291	
1	02 10 2008	04:41:49:000	
1	02 10 2008	04:48:25:000	
1	05 10 2008	06:52:33:000	SAE: No lightning activity
1	05 10 2008	06:52:33:000	SAE: No lightning activity
1	07 10 2008	04:28:56:000	SAE: Negative lightning between 20:00 and 24:00 (The faults were probably due to pollution flashover due to fog etc.)
1	07 10 2008	04:29:12:000	
1	07 10 2008	05:25:19:000	
1	07 10 2008	04:28:56:000	
1	07 10 2008	04:29:12:000	
1	07 10 2008	05:25:19:000	
1	09 11 2008	12:45:36:372 - 518	SAE: No Lightning on the 09 November 2008. Details of faults recorded: Recorded as 6 faults on Line 1 between 12:45:36:372 - 518
2	09 11 2008	12:45:36:555 - 881	SAE: No Lightning on the 09 November 2008. Details of faults recorded: Recorded as 12 faults on Line 2 between 12:45:36:555 - 881
2	09 11 2008	12:45:38:454 - 826	SAE: No Lightning on the 09 November 2008. Details of faults recorded: Recorded as 13 faults on Line 2 between 12:45:38:454 - 826
1	10 11 2008	10:51:00:962 - 10:51:01:619	SAE: No lightning on the 10 November 2008 Details of faults: Numerous faults on Line 1 between 10:51:00:962 - 01:619
2	10 11 2008	10:51:00:962 - 10:51:01:619	SAE: No lightning on the 10 November 2008 Details of faults: Numerous faults on Line 2 between 10:51:00:962 - 01:619

1	30 11 2008	01:43:35:936 and 945	SAE: No spatially correlated lightning RA: No Lightning at time of faults
1	30 11 2008	01:43:36:194 and 204	SAE: No spatially correlated lightning RA: No Lightning at time of faults
2	02 12 2008	02:02:01:000	SAE, RA: No Lightning
1	10 12 2008	03:52:49:000	SAE, RA: No Lightning
2	22 12 2008	10:42:51:000	SAE, RA: No Lightning
2	22 12 2008	10:42:51:000	SAE, RA: No Lightning
1	26 12 2008	04:17:55:934 and 945	SAE, RA: No Lightning
1	26 12 2008	04:17:56:206	SAE, RA No Lightning
2009			
1	19 01 2009	23:13:38:108	RA: Exact time correlation with -18 kA
1	19 01 2009	23:13:38:117	RA: No correlation
1	19 01 2009	23:13:38:193	RA: Exact time correlation with -9 kA
1	19 01 2009	23:13:38:202	RA: No correlation
1	19 01 2009	23:13:38:232	RA: Exact time correlation with -9 kA
1	19 01 2009	23:13:38:241	RA: No correlation
1	19 01 2009	23:13:38:395	RA: Exact time correlation with -11 kA
1	19 01 2009	23:13:38:404	RA: No correlation
1	19 01 2009	23:13:38:438	RA: Exact time correlation with -9 kA
1	19 01 2009	23:13:38:447	RA: No correlation
1	19 01 2009	23:13:38:493	RA: No correlation
1	19 01 2009	23:13:38:602	RA: No correlation
1	19 01 2009	23:13:41:151	RA: Exact time correlation with -7 kA
1	20 01 2009	00:50:42:744 and 754	RA: Exact time correlation with -17 kA at 00:50:42:744
1	20 01 2009	00:50:45:100 and 161	RA: No correlation
2	24 01 2009	19:30:22:183	RA: No correlation, SAE: Single negative stroke at 19h05
1	24 01 2009	19:33:22:437	RA: No lightning, SAE: No lightning during period 19:00 - 20h00
1	24 01 2009	19:34:22:217 and 225	RA: No lightning, SAE: No lightning during period 19:00 - 20h00
1	24 01 2009	19:37:30:860	RA: No lightning, SAE: No lightning during period 19:00 - 20h00
1	12 02 2009	09:01:04:734 - 995	SAE: No lightning during period 08:30 - 09h30 Three faults were recorded by protection system.
1	12 02 2009	09:01:05:422	SAE No Lightning during period 08:30 - 09h30
1	17 02 2009	20:28:40:024 - 147	Protection system recorded 7 Faults: 20:28:40:024, 033, 045, 093, 102, 138, 147 See RA for graphical correlation Correlation with the following strokes: 1. 20:28:40:024 with -26 kA 2. 20:28:40:138 with -17 kA
1	17 02 2009	20:47:53:956 - 967	Protection system recorded two faults. RA: Multiple lightning strokes between 20:47:05 and 20:48:43, but no correlation according to RA
1	17 02 2009	20:47:53:058 - 54:101	Four faults recorded: 20:47:53:058, 068, 092, and 20:47:54:101 RA: Multiple lightning strokes between 20:47:05 and 20:48:43, but no correlation according to RA

1	17 02 2009	20:51:11:237	RA: No correlation Closest correlation with a stroke at 20:51:17.543
1	17 02 2009	20:51:17:408 - 761	Five faults recorded: 408, 417, 543, 552, 761 Correlation at 2009-02-17 20:51:17.543 with -8 kA
1	21 02 2009	05:35:10:447 and 546	RA: No lightning activity
2	21 02 2009	11:46:34:000	RA: No spatially correlated lightning
1	12 03 2009	01:07:30:471-742	RA No Lightning Protection system recorded three faults recorded
2	20 03 2009	10:40:20:000	RA: No spatially correlated lightning
2	22 03 2009	10:22:30:296 and 305	RA: No spatially correlated lightning SAE: No lightning activity during this period
2	22 03 2009	10:55:17:444	SAE: No lightning during this period
2	22 03 2009	11:38:03:319 and 328	
2	22 03 2009	12:11:34:718 and 727	
2	24 03 2009	12:14:16:376 - 402	Protection system recorded four faults at 12:14:16:376, 385, 392, 402 SAE: No lightning during this period
2	24 03 2009	12:46:14:421 - 447	Protection system recorded three faults at 12:46:14:421, 430, 447 SAE: No lightning during this period
2	27 03 2009	13:44:22:858 - 887	Protection system recorded four faults at 13:44:22:858, 867, 877, 887 SAE: No lightning during this period
2	27 03 2009	13:44:23:102 - 123	Protection system recorded three faults at 13:44:23:102, 110, 123 SAE: No lightning during this period
2	27 03 2009	14:16:32:650 - 901	Eight faults recorded at the following times: 14:16:32:650, 669, 679, 690, 702, 711, 89, 901 - 901 SAE: No lightning during this period
2	27 03 2009	15:00:58:029 - 294	Seven faults recorded at the following times: 15:00:58:029, 039, 049, 060, 273, 282, 297 SAE: No lightning during this period
2	27 03 2009	15:32:42:202 - 465	Eight faults recorded at the following times: 15:32:42:202, 211, 221, 242, 444, 453, 465 SAE: No lightning during this period
1	05 06 2009	12:39:14:000	SAE: No lightning during June 2009 except for negative strokes on 18-06-2009
1	05 06 2009	12:40:11:000	
1	05 06 2009	02:01:36:000	
1	05 06 2009	02:01:00:000	
1	11 06 2009	01:47:38:000	SAE: No lightning except for on 18-06-2009
1	11 06 2009	01:43:00:000	
1	17 07 2009	06:02:00:000	SAE: No lightning activity during July 2009 First lightning activity on 01-08-2014
1	23 07 2009	09:19:11:000	
1	23 07 2009	09:47:00:000	
1	28 07 2009	12:38:56:000	
1	28 07 2009	01:47:06:000	
1	28 07 2009	12:38:00:000	
1	28 07 2009	01:47:00:000	

1	05 08 2009	02:25:25:000	SAE: No lightning activity during July 2009 Only lightning activity on 01-08-2014
1	05 08 2009	02:25:00:000	
1	10 08 2009	06:06:25:000	
1	10 08 2009	06:06:00:000	
1	29 08 2009	02:57:38:000	
1	30 08 2009	10:46:49:000	
1	30 08 2009	12:22:20:000	
1	30 08 2009	14:19:26:000	
1	30 08 2009	02:41:11:000	
2	30 08 2009	04:14:37:000	RA: No spatially correlated lightning SAE: No lightning activity during this period
2	30 08 2009	04:35:01:000	
2	30 08 2009	04:57:34:000	
2	30 08 2009	05:19:12:000	
1	01 09 2009	01:09:36:000	RA: No Lightning at 13:09:36 SAE: No lightning activity during this period
1	12 09 2009	01:49:06:000	SAE: No lightning activity during this period (Possibly pollution induced flashovers)
1	12 09 2009	02:31:04:000	
1	12 09 2009	03:39:29:000	
1	12 09 2009	01:49:00:000	
1	12 09 2009	02:31:00:000	
1	12 09 2009	03:30:00:000	
1	12 09 2009	03:31:00:000	
1	12 09 2009	03:39:00:000	
1	17 09 2009	12:27:50:769 and 778	SAE: No lightning activity between 2009-09-17 00:00:00 and 2009-09-19 00:00:00
1	17 09 2009	14:27:16:181	
1	18 09 2009	08:57:46:136 and 145	
1	18 09 2009	10:21:41:937 and 10:21:42:027	
1	18 09 2009	10:29:18:885 and 894	
1	18 09 2009	10:37:08:803 and 812	
1	18 09 2009	10:52:46:142 and 231	
1	18 09 2009	12:59:29:735 and 825	
1	18 09 2009	14:54:17:466 and 475	
1	18 09 2009	15:10:34:404 and 413	
1	18 09 2009	17:58:27:637 and 646	
1	18 09 2009	18:13:09:614 and 623	
1	23 09 2009	03:29:54:503 and 512	SAE No Lightning during this period (Faults possibly due to pollution)
1	23 09 2009	03:29:31:198 and 207	
1	23 09 2009	06:16:05:640	SAE No Lightning during this period (Faults possibly due to pollution)
1	23 09 2009	06:27:42:204	
1	23 09 2009	06:28:04:842 and 851	
1	23 09 2009	07:13:23:220	
1	23 09 2009	09:11:48:361	
1	23 09 2009	09:24:33:475 and 484	
1	23 09 2009	12:43:00:000	
1	23 09 2009	12:47:00:000	

1	24 09 2009	01:18:24:381	SAE: No lightning activity during this period
1	24 09 2009	01:54:15:406	
1	24 09 2009	01:18:00:000	
1	24 09 2009	01:54:00:000	
1	30 09 2009	01:10:06:544 - 553	SAE: No lightning activity during this period
1	12 10 2009	23:56:57:626 and 635	RA: No lightning correlation (See RA)
1	13 10 2009	12:36:05:222 and 231	RA: No lightning correlation
1	20 10 2009	06:23:38:829 and 838	SAE: No lightning activity during this period
1	20 10 2009	06:49:01:170	
2	04 11 2009	10:01:29:434 - 804	Recorded as four faults on Line 2 between 10:01:29:434 and 804 RA: No lightning correlation
2	06 11 2009	12:10:00:000	SAE: No lightning activity during this period
2	06 11 2009	12:40:20:245 - 514	Recorded as four faults on Line 2 between 12:40:20:245 and 514 SAE: No lightning activity during this period
1	10 11 2009	15:37:59:444 and 453	Recorded as two faults on Line 1 at 15:37:59:444 and 453 RA: No lightning activity
2	19 11 2009	04:27:00:142	RA: No spatially correlated lightning
1	19 11 2009	00:48:28:127 - 148	This fault actually occurred on Line 1 and not 2 as originally indicated. Indicated as three faults 128, 137, 148 RA: No correlation with lightning
1	19 11 2009	04:27:00:000	No Fault according to LFL RA: No spatially correlated lightning
2	01 12 2009	01:28:52:564 and 573	RA Best time correlation with 01:28:52:645 with a stroke of -11 kA at tower 771
2	05 12 2009	23:56:41:153 and 162	RA: No Correlation
1	13 12 2009	10:42:46:431	SAE: No spatially correlated lightning
1	13 12 2009	11:11:52:385	
1	13 12 2009	11:33:38:736	
1	13 12 2009	11:41:49:333	
2	13 12 2009	12:59:04:846	SAE: No spatially correlated lightning
2	13 12 2009	13:10:38:238	
2	13 12 2009	13:20:41:679	
2	18 12 2009	06:40:55:189	RA: No lightning, SAE: No lightning during this period
2010			
1	14 01 2010	18:59:58:344	Original fault time 18:59 RA Best time correlation with 19:00:19 (-6 kA) Poor spatial correlation
1	16 01 2010	01:16:39:590	RA: Correlated at 01:16:39.744 (-24 kA) with 200 m buffer Better time correlation with -16 kA (617 ms) and -15 kA (677 ms) with 1000 m buffer
1	20 01 2010	23:50:47:674	RA: No spatially correlated lightning
1	19 02 2010	05:34:42:295	RA: No correlated lightning SAE: No lightning activity

1	25 05 2010	05:58:57:517	SAE: No lightning at the time of these faults
1	26 05 2010	07:46:42:988	Some lightning activity on the following: 4, 1& 29 May
1	03 07 2010	03:18:04:911	SAE: No lightning activity at the time of these faults
1	03 07 2010	04:08:02:742	
1	03 07 2010	04:12:00:750	
1	03 07 2010	05:05:48:337	
1	03 07 2010	05:07:51:246	
1	03 07 2010	06:53:20:491	
1	03 07 2010	06:53:39:394	
1	10 07 2010	14:06:31:188	
1	19 07 2010	06:48:53:282	
1	03 08 2010	03:14:34:878	SAE: No spatially correlated lightning
1	12 08 2010	07:35:48:970	
1	15 08 2010	12:34:07:598	
1	19 08 2010	15:02:53:955	
1	19 08 2010	15:03:59:744	
1	19 08 2010	16:20:42:809	
1	21 08 2010	02:52:59:448	
1	21 08 2010	03:16:33:394	
1	21 08 2010	03:54:10:207	
1	21 08 2010	04:05:16:206	
1	21 08 2010	06:49:31:382 and 672	
1	25 08 2010	05:33:59:740	
1	26 08 2010	05:47:04:936	
1	27 08 2010	04:58:32:315	
1	27 08 2010	05:02:17:499	
1	28 08 2010	03:59:33:670	
1	28 08 2010	04:29:53:376	SAE: No lightning activity during this period
2	29 08 2010	12:21:16:827	RA: No lightning correlation
1	01 09 2010	15:27:34:906	SAE: No lightning activity during this period
1	01 09 2010	15:30:18:803	
1	02 09 2010	12:18:09:535	
1	02 09 2010	15:00:58:495	SAE: No lightning at the time of these faults No lightning in Sept 2010 except for 10Sept & 27Sept
1	02 09 2010	15:01:22:617	
1	02 09 2010	15:05:41:983	
1	03 09 2010	14:37:12:762	
1	04 09 2010	04:29:26:329	
1	04 09 2010	05:21:02:353	
1	04 09 2010	05:21:28:685	
1	04 09 2010	06:04:11:760	
1	05 09 2010	04:45:30:550	
1	05 09 2010	05:02:32:996	
1	05 09 2010	05:03:07:704	
1	06 09 2010	06:29:02:124	
1	08 09 2010	02:34:16:387	
1	08 09 2010	03:35:22:455	
1	12 09 2010	06:35:02:829	
1	12 09 2010	08:00:20:354	
1	13 09 2010	15:34:57:295	SAE: No lightning at the time of these faults No lightning in September 2010 except for on 10Sept and 27Sept
1	14 09 2010	15:56:28:534	

Appendix B: Graphical Reliability Analysis of Fault Correlations

B.1 Introduction

This appendix presents the details of the fault correlation process and elaborates in a graphical format on the classification of each of the faults that were considered “probable” to have been caused by a lightning stroke. The strokes that are considered “probable” are selected based on criteria that are defined in B.3. This appendix is compiled from the output from the “Reliability Analysis” (RA) tool in “FALLS” software program.

B.2 Information Presented in the Graphical Analysis

Each fault that has been correlated with lightning activity is described in a separate graphical analysis. The analysis presents the following information that is shown in figure B.1:

- A. *Graphical RA output* – The graphical output depicts the correlated lightning stroke confidence ellipses and the line with its buffer zone. The graphical output allows the spatial correlation of various lightning strokes with the line to be examined.
- B. *Tabular RA output* – This RA output lists the various correlated lightning strokes with a certain time tolerance around the inputted fault time. The most probable stroke time is highlighted.
- C. *Fault number* – The number of the fault is highlighted on the tabular output
- D. *Fault time* – The fault time from the protection system is highlighted so that it can be compared to the stroke that is most closely correlated.
- E. *Stroke time* – The reported stroke time is highlighted for the most probable stroke to facilitate comparison with the fault time
- F. *Comments* – Comments are made about the temporal and spatial correlations as well as any other significant details pertaining to the fault such as the stroke amplitude of the probable stroke. The comments are explained in more detail in the next section.

B.3 Comments in Graphical Analysis

The following comments are made for each graphical analysis presented.

- *Temporal correlation* – The temporal correlation is classified according to the criteria in *Table B.1*.
- *Spatial correlation* – The spatial correlation is classified according to the criteria in *Table B.2*.
- *Stroke amplitude and polarity* – The mean value for peak current amplitude for lightning exposure along the Cahora Bassa lines is 16 kA. Strokes that are significantly above this value, say 50% more (24 kA) are considered “High”. About half of this mean value i.e. single digit amplitudes are considered “Low”.

Some of the analyses have peculiarities that have been emphasised in the comments, such as:

- *Negative line polarity* – The vast majority of strokes affect the positive polarity line, therefore faults affecting the negative pole are highlighted.
- *Low number of detecting LDN sensors* – A low number of detecting sensors increases the uncertainty in the reported position of the stroke.

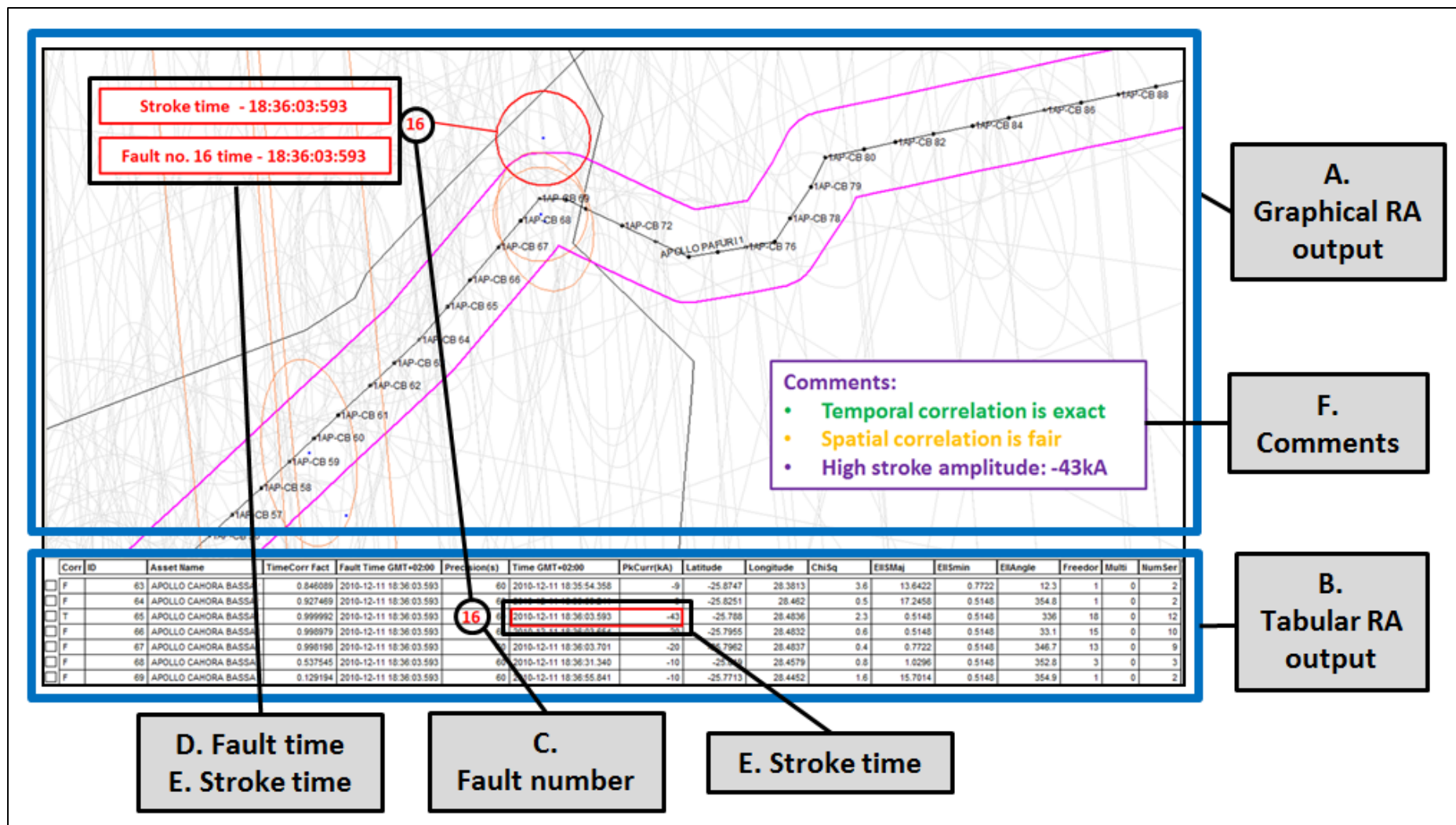


Figure B.1: Key to the information presented in the "Graphical Analysis" of the fault correlation.

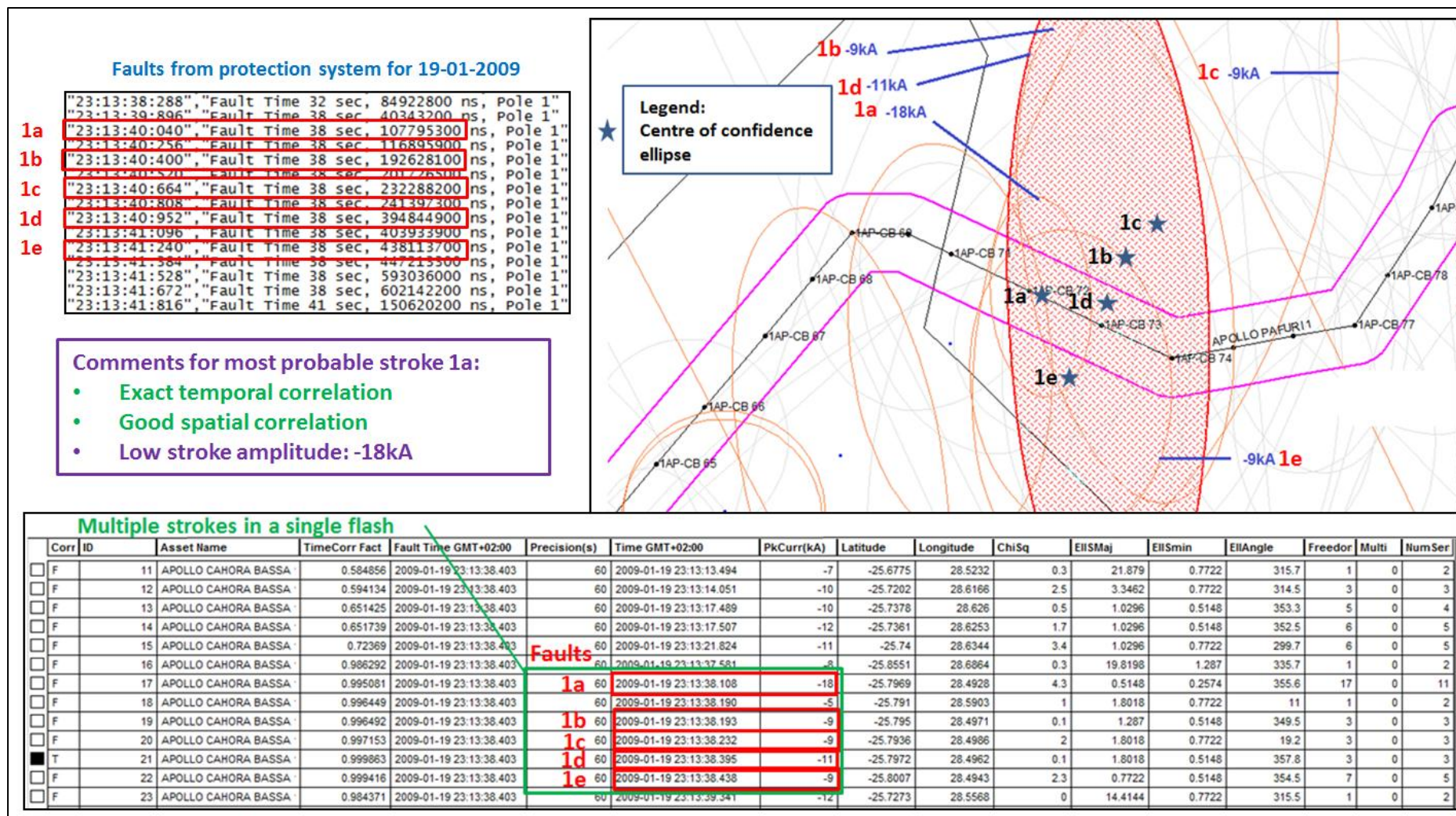


Figure B.2: Fault number 1a – 1f for 19 January 2009.

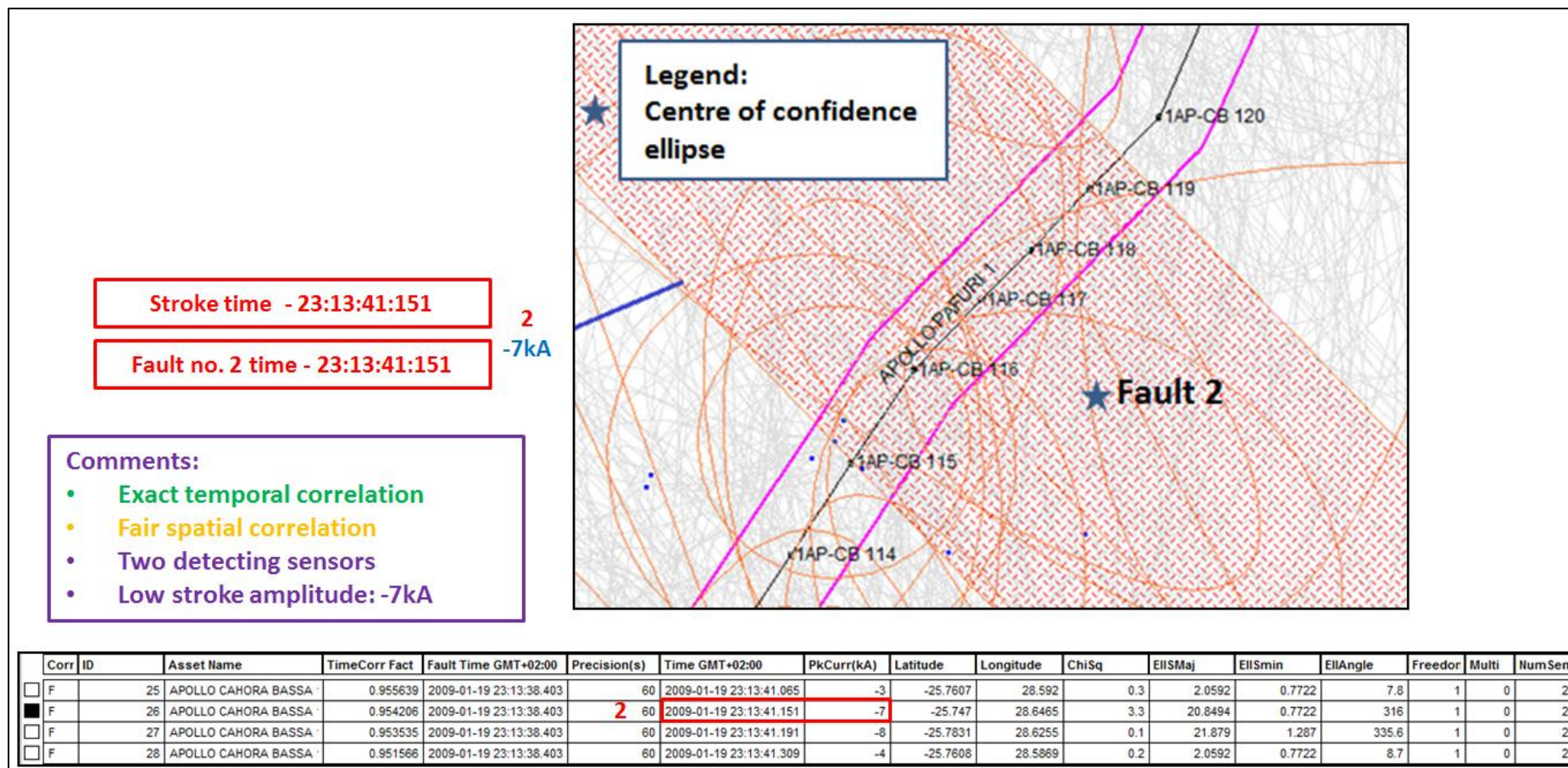


Figure B.3: Fault number 2 for 19 January 2009.

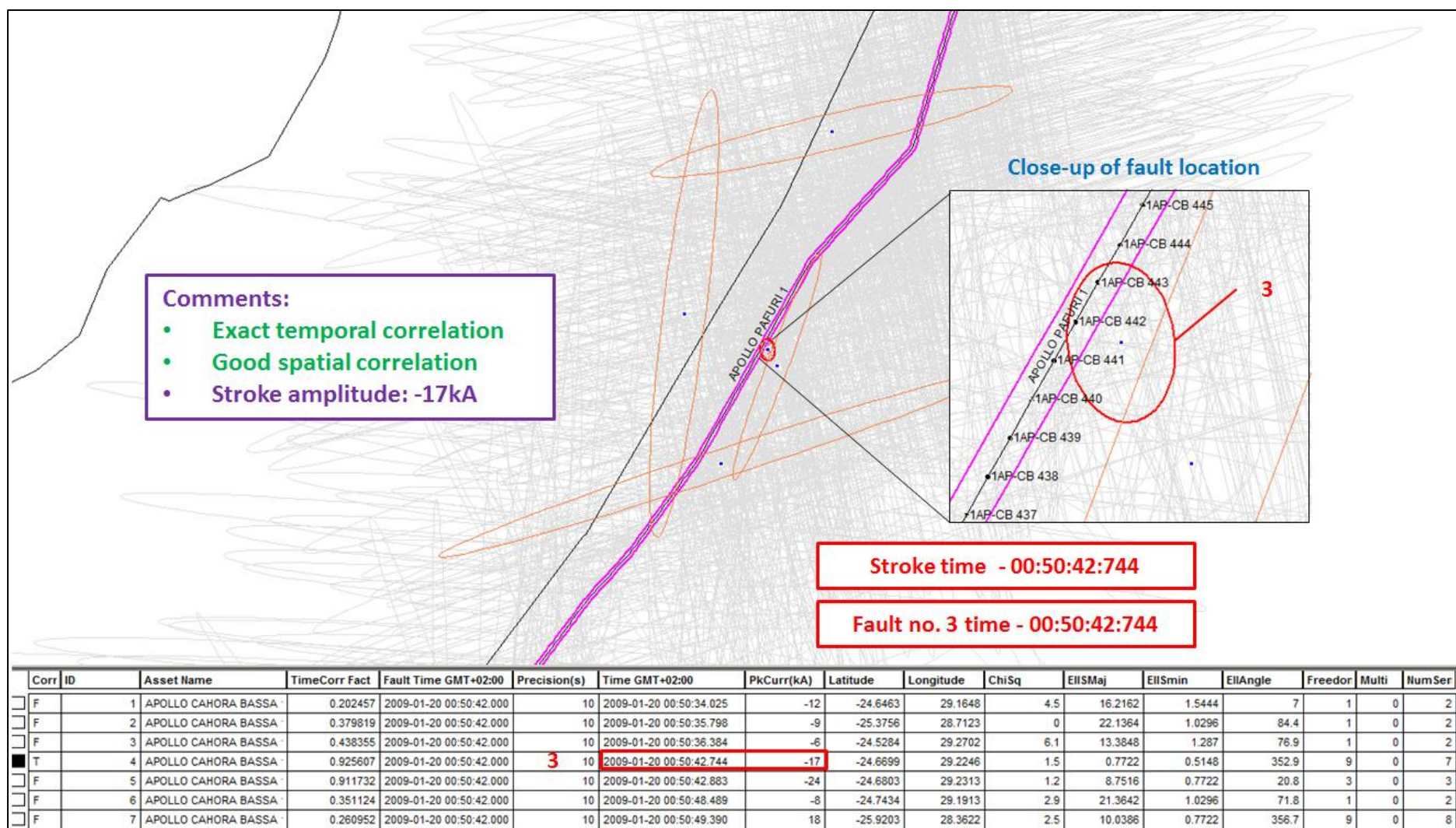


Figure B.4: Fault number 3 for 20 January 2009.

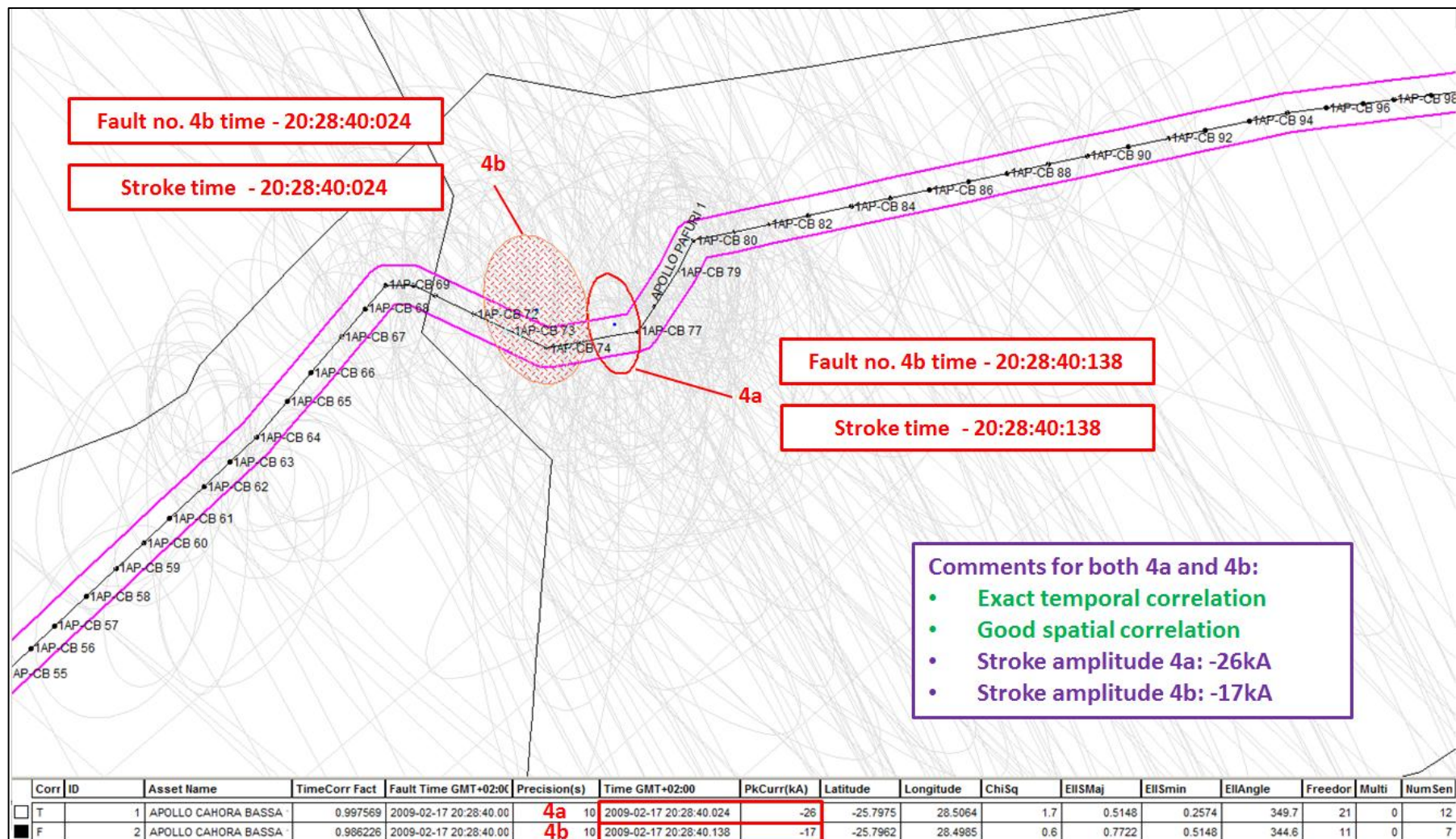


Figure B.5: Fault number 4a and 4b for 17 February 2009.

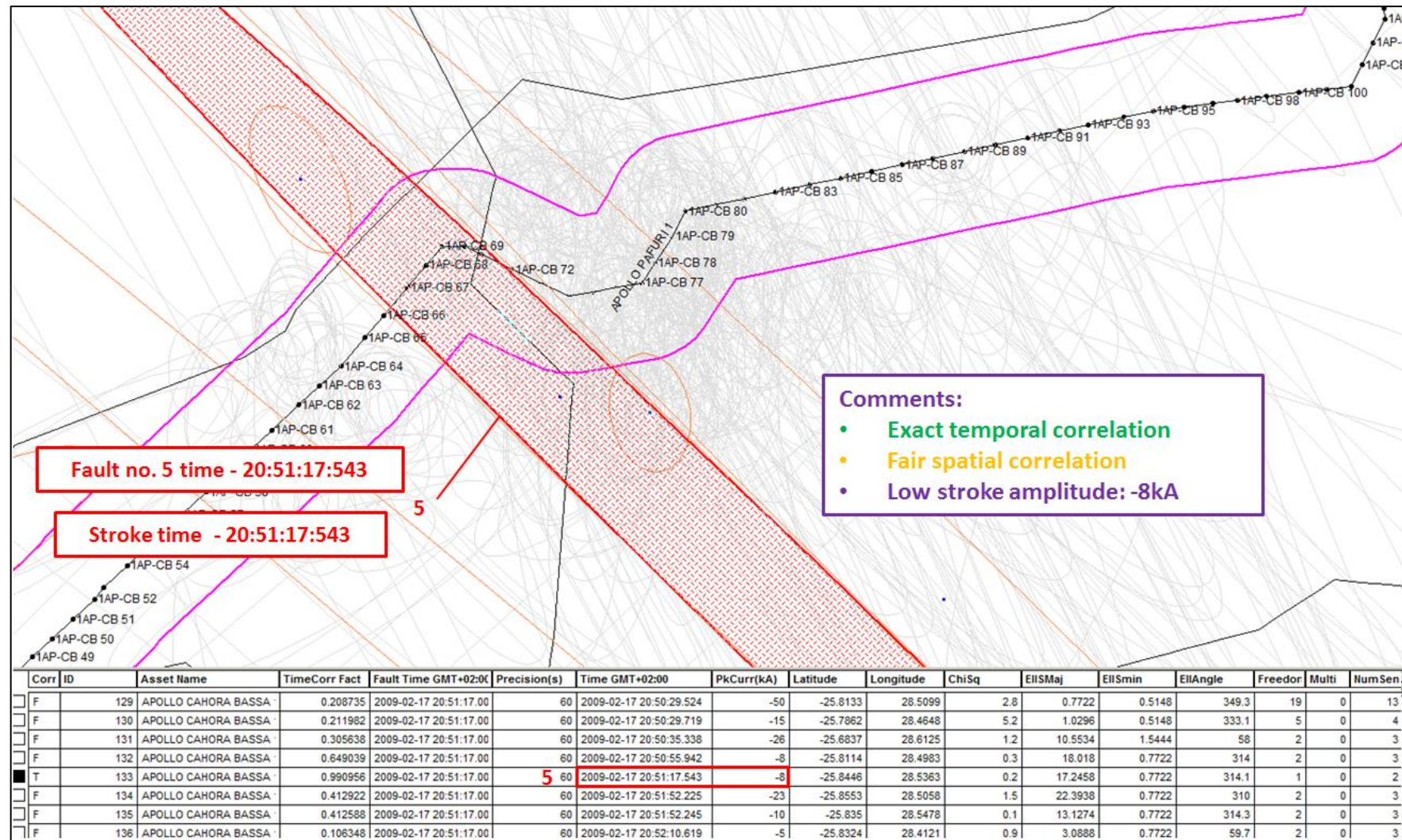


Figure B.6: Fault number 5 for 17 February 2009.

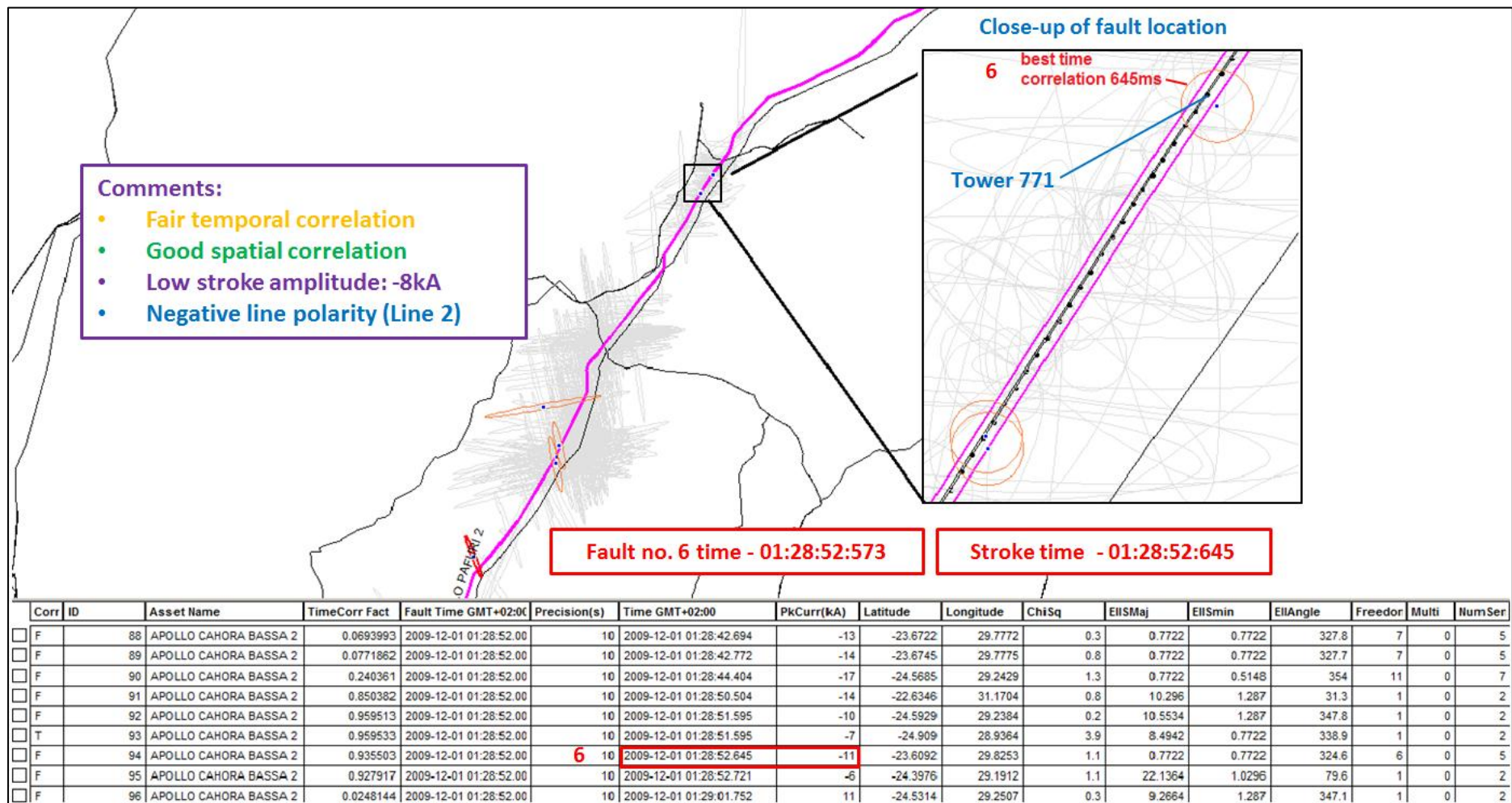


Figure B.7: Fault number 6 for 1 December 2009.

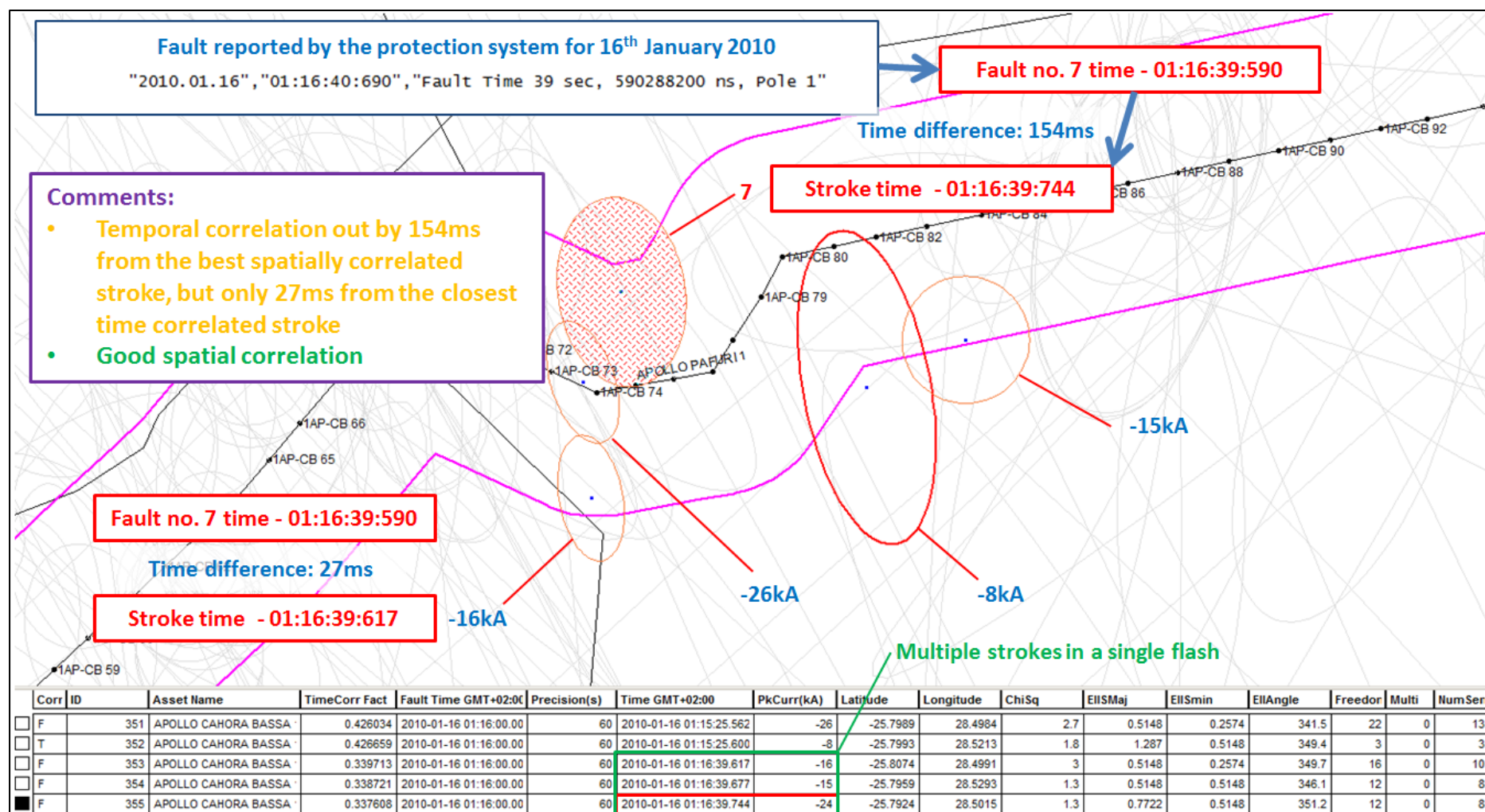


Figure B.8: Fault number 7 for 17 February 2009

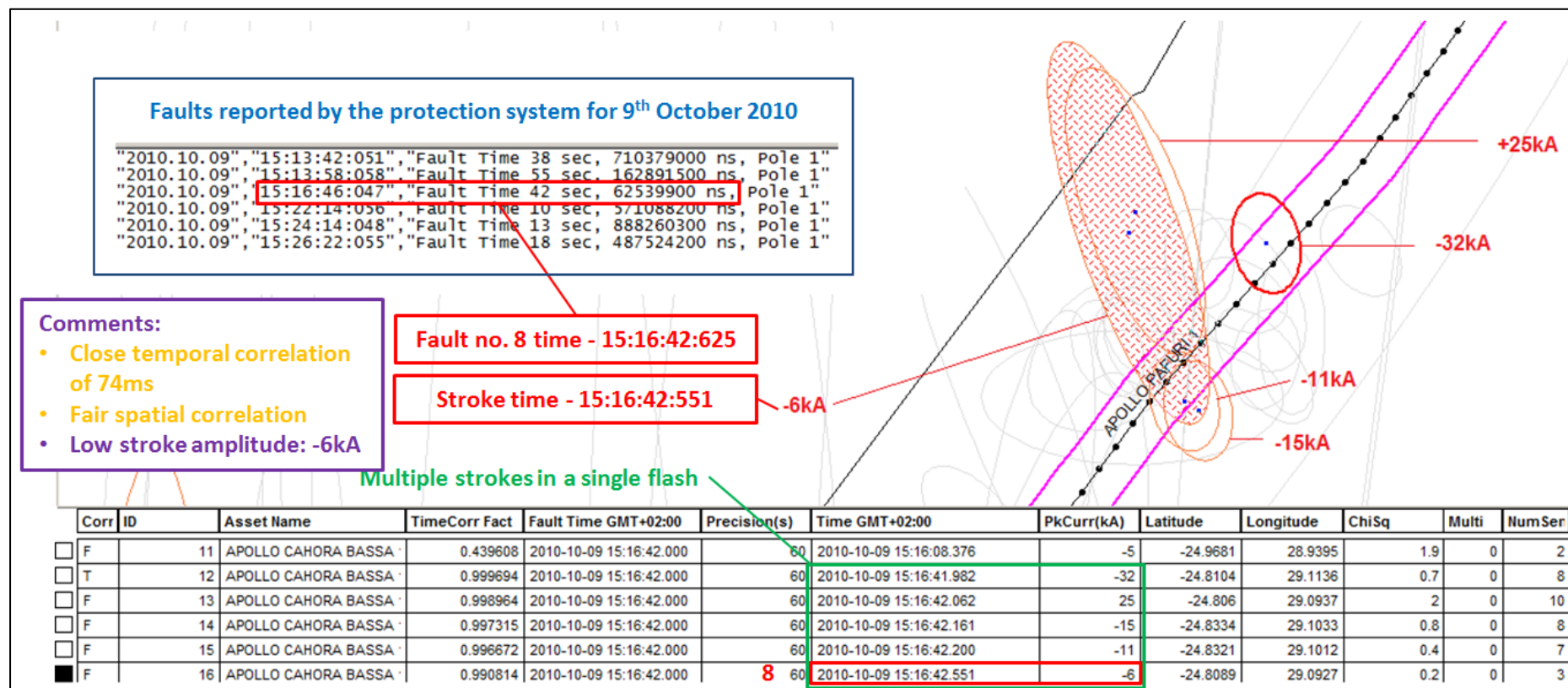


Figure B.9: Fault number 8 for 9th October 2010.

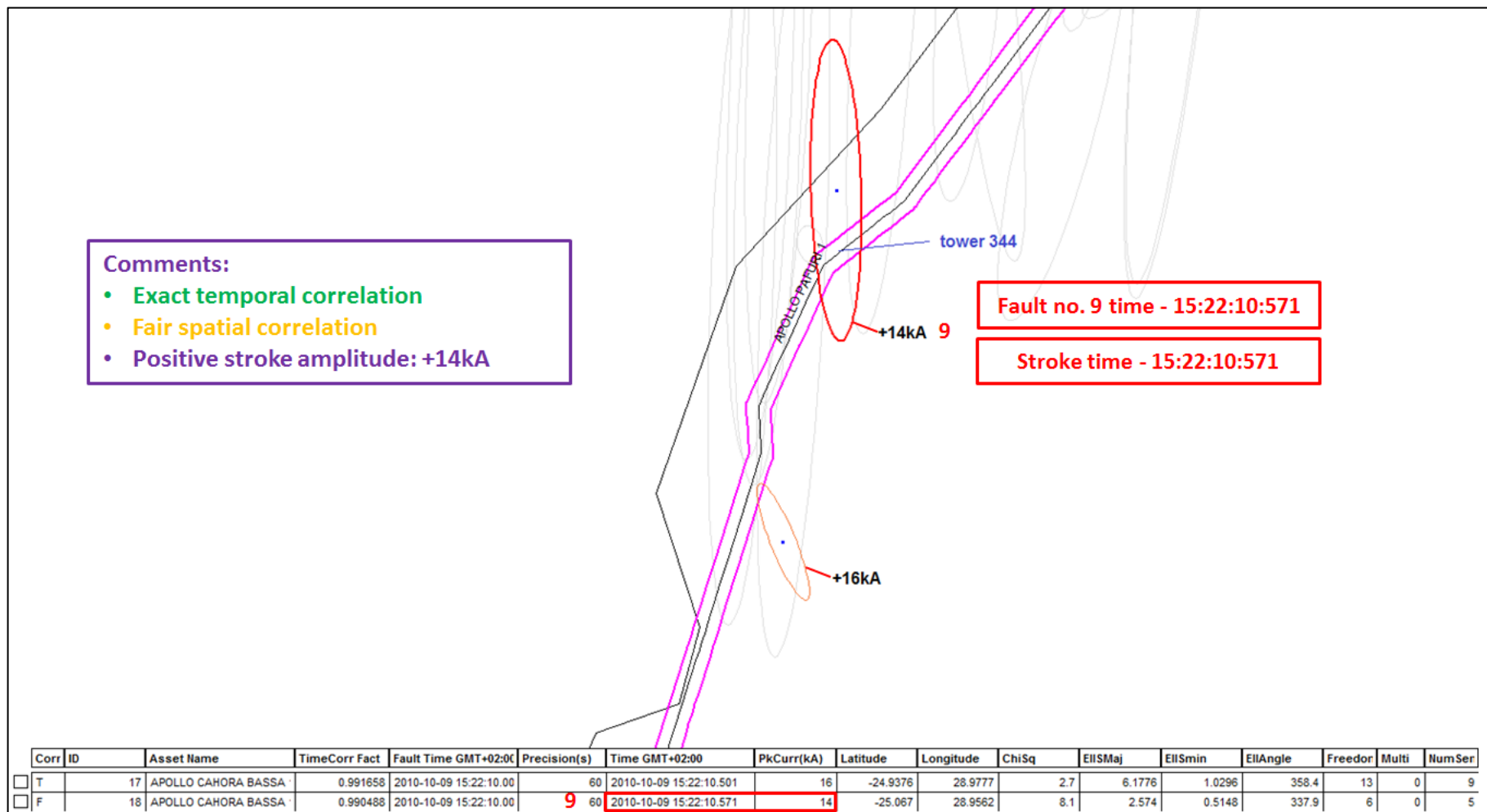


Figure B.10: Fault number 9 for 9 October 2010.

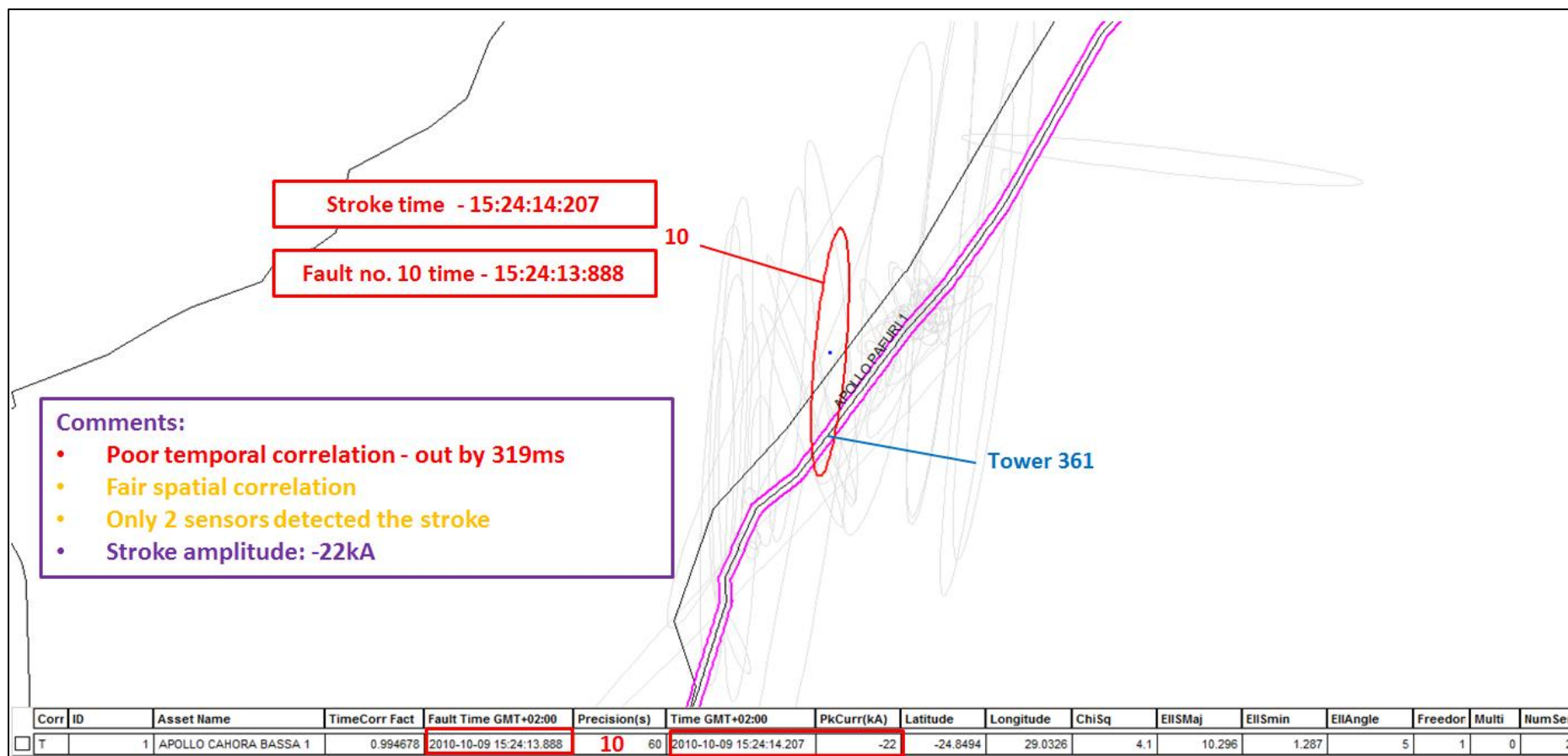


Figure B.11: Fault number 10 for 9 October 2010.

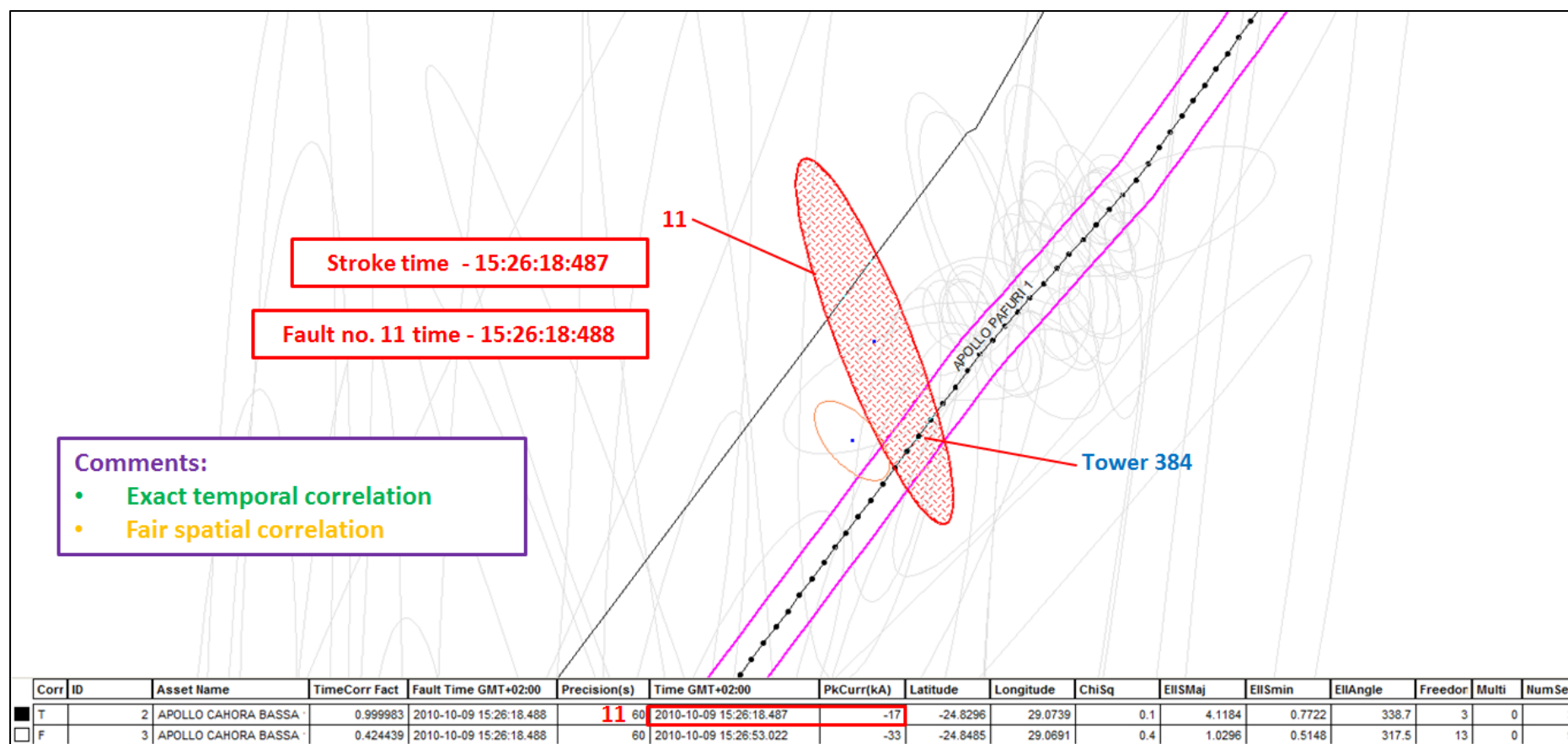


Figure B.12: Fault number 11 for 9 October 2010.

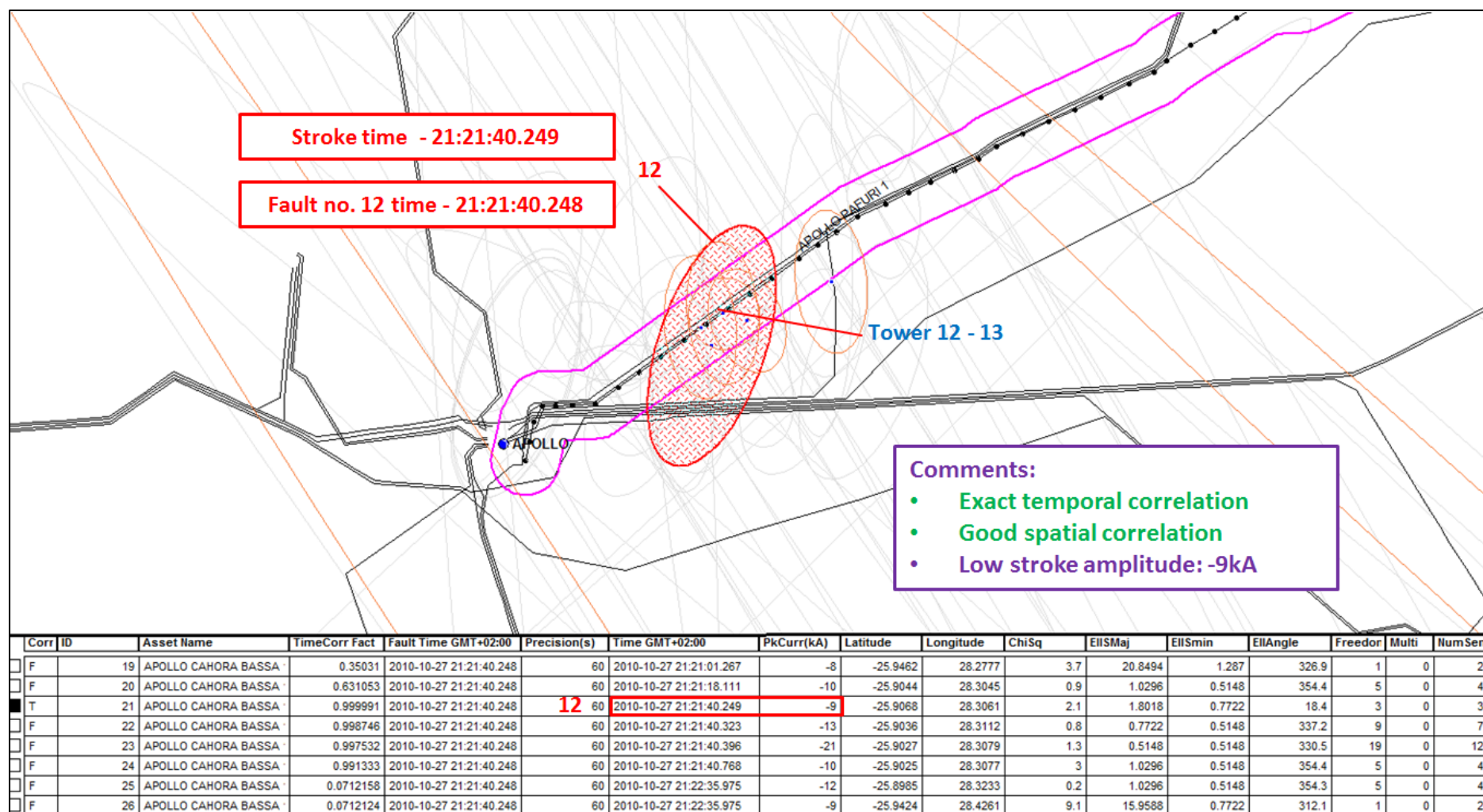


Figure B.13: Fault number 12 for 27 October 2010.

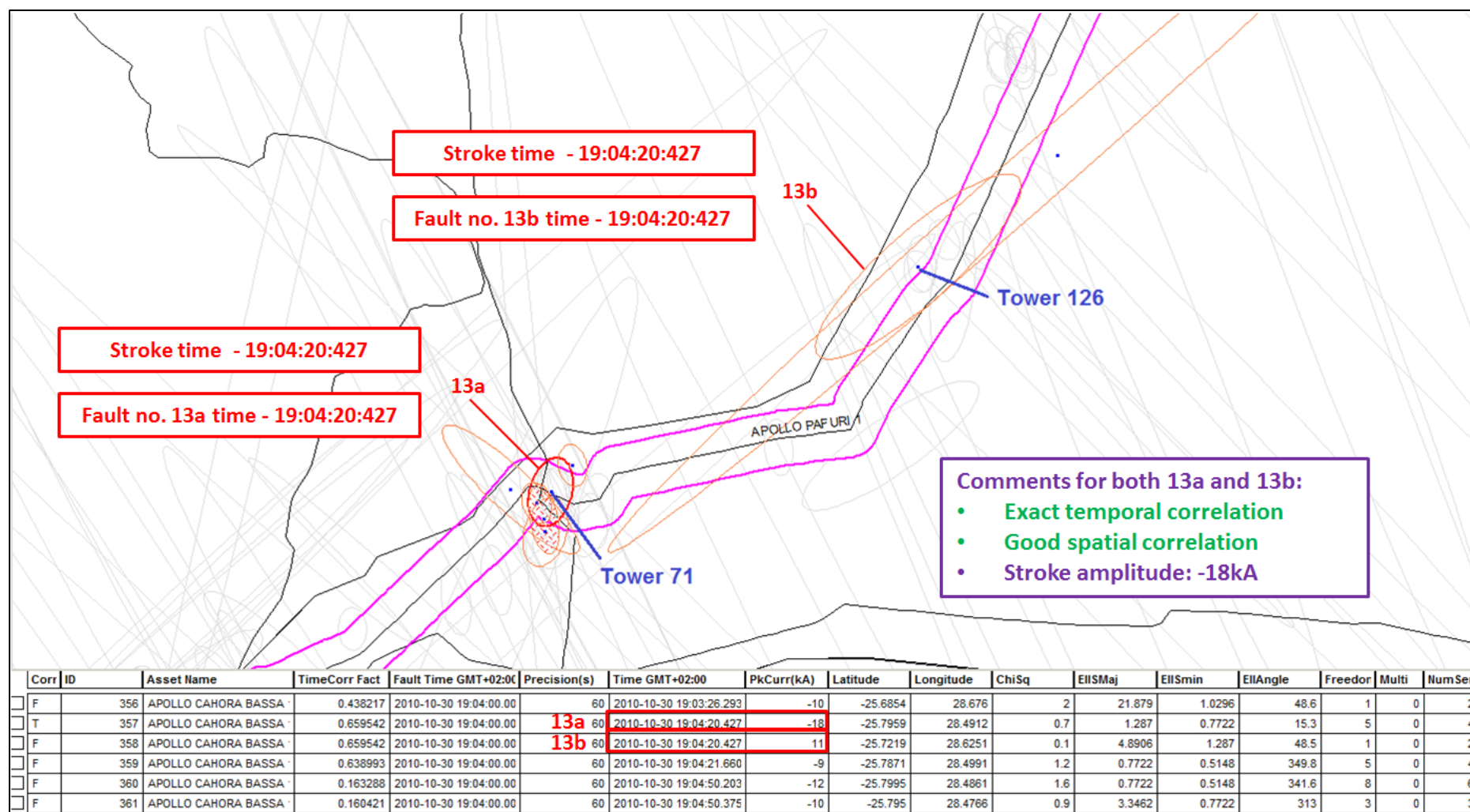


Figure B.14: Fault number 13a and 13b for 30 October 2010.

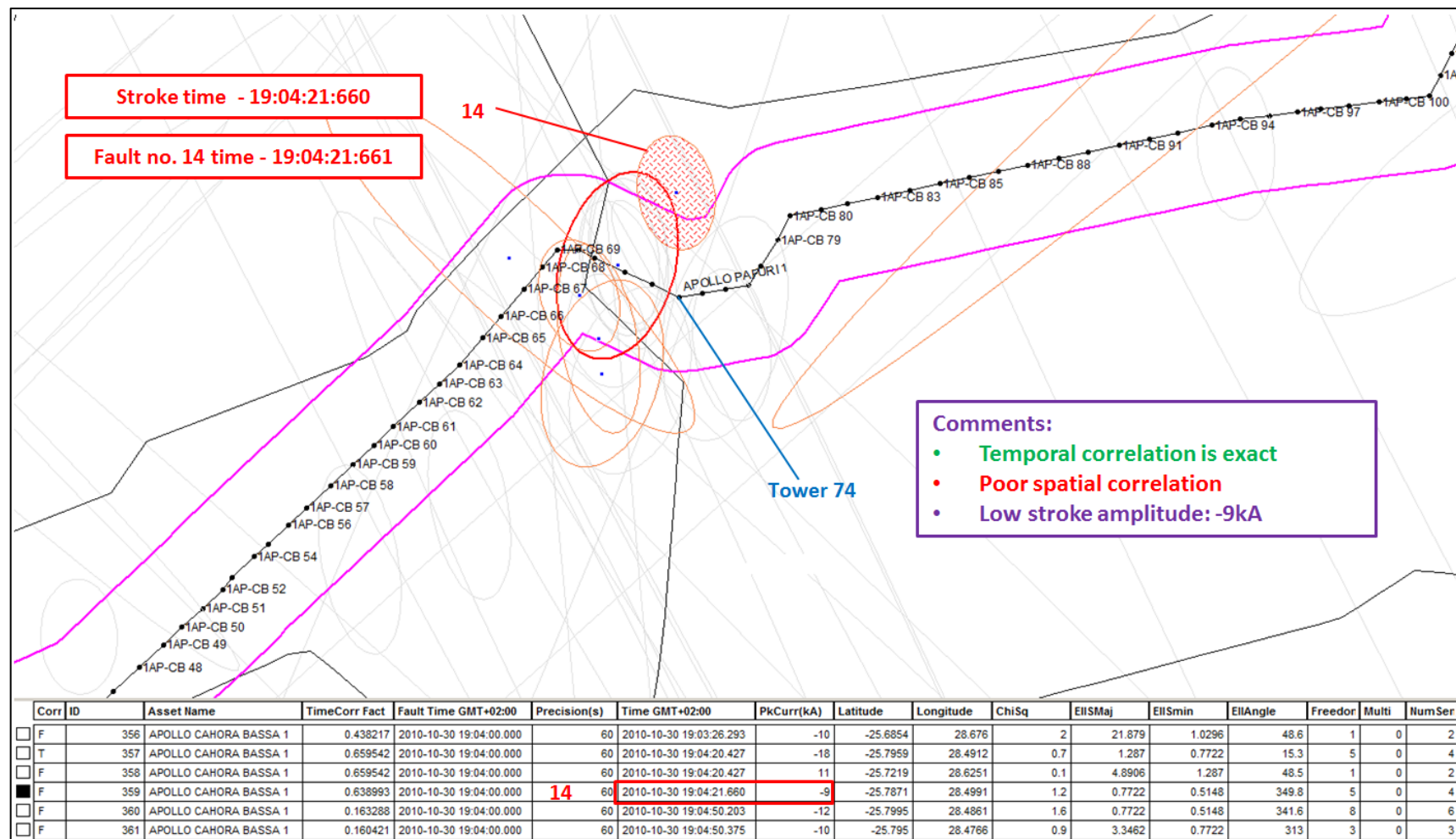


Figure B.15: Fault number 14 for 30 October 2010.

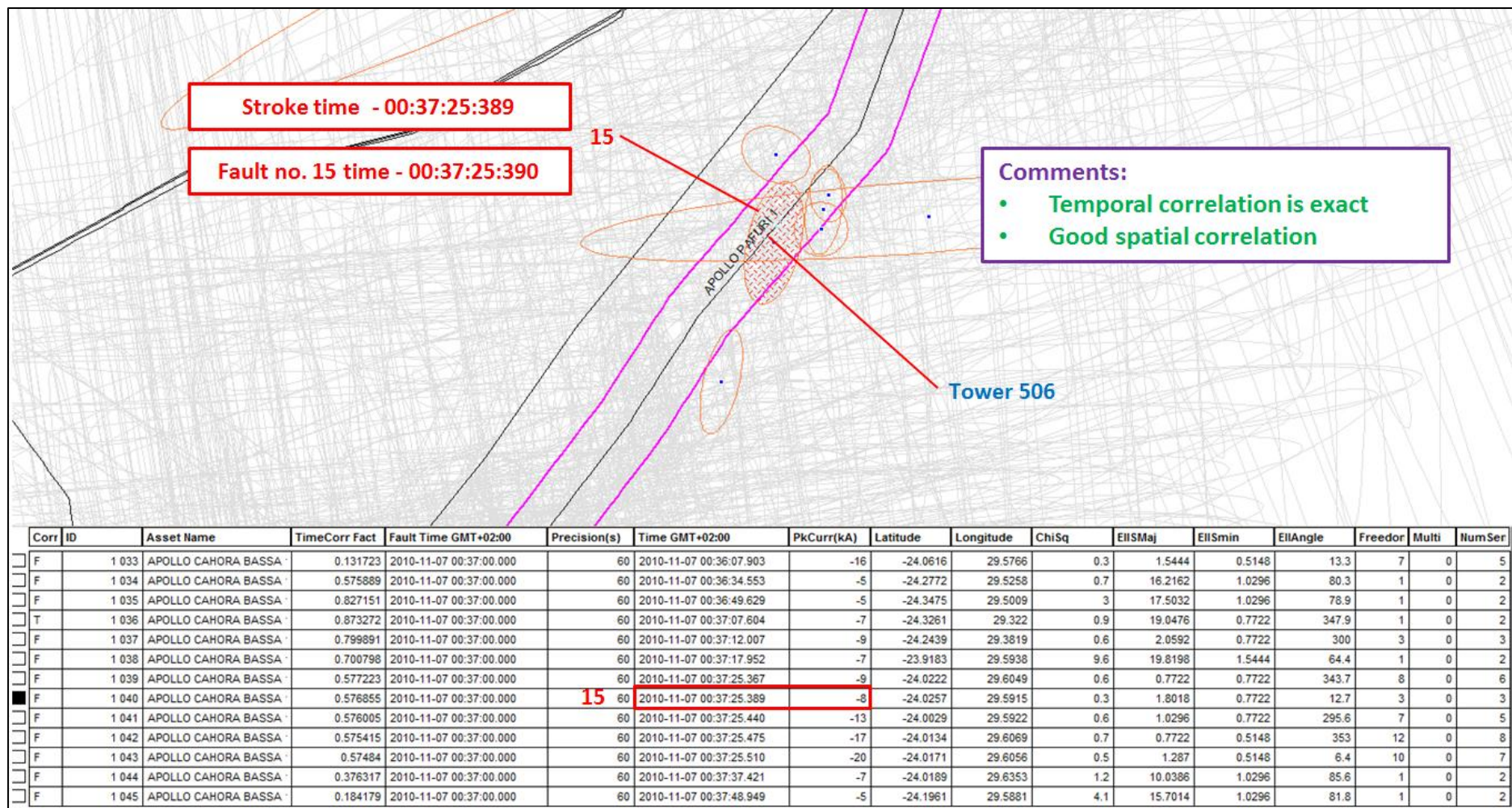


Figure B.16: Fault number 15 for 30 October 2010.

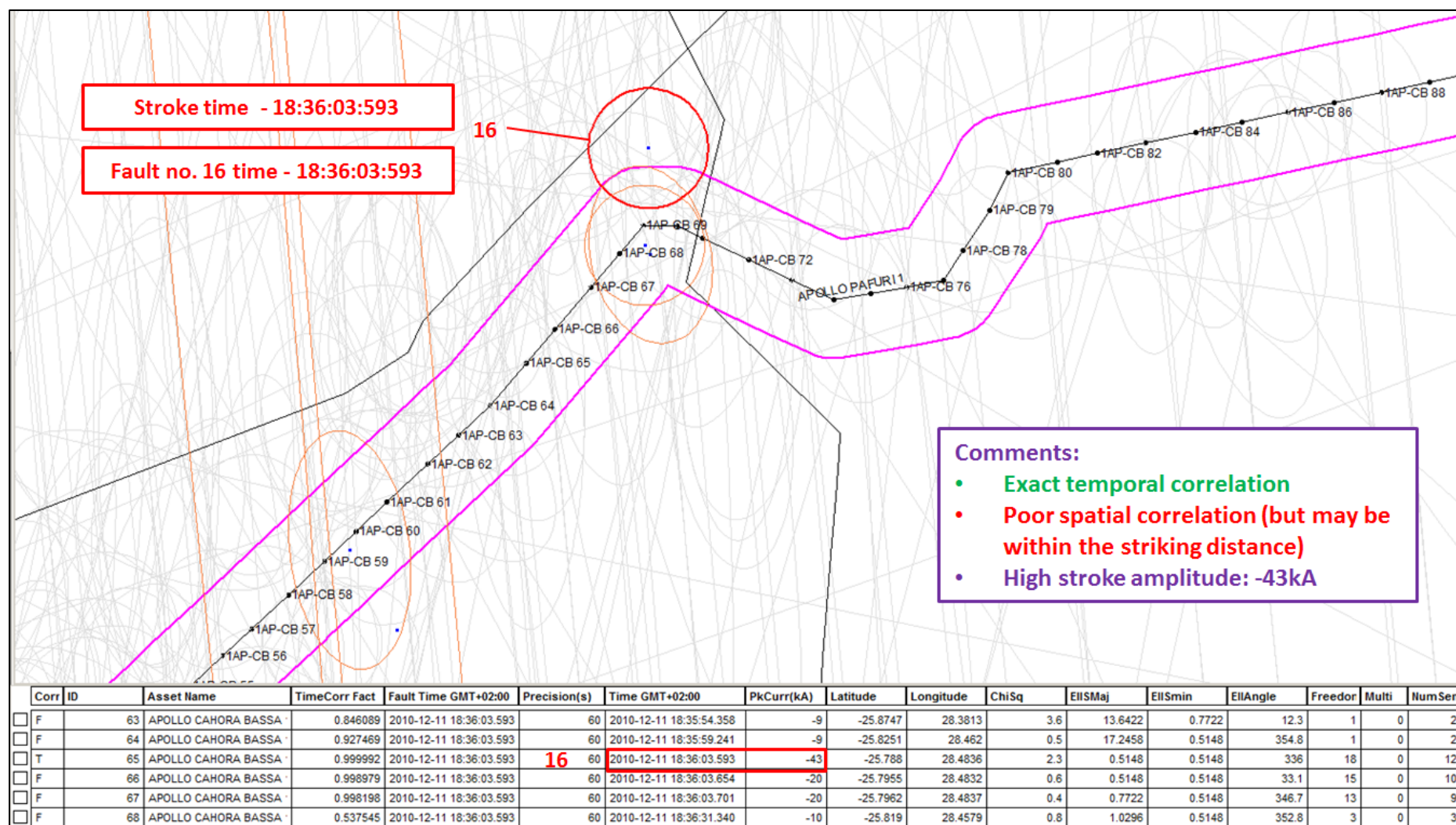


Figure B.17: Fault number 16 for 11 December 2010.

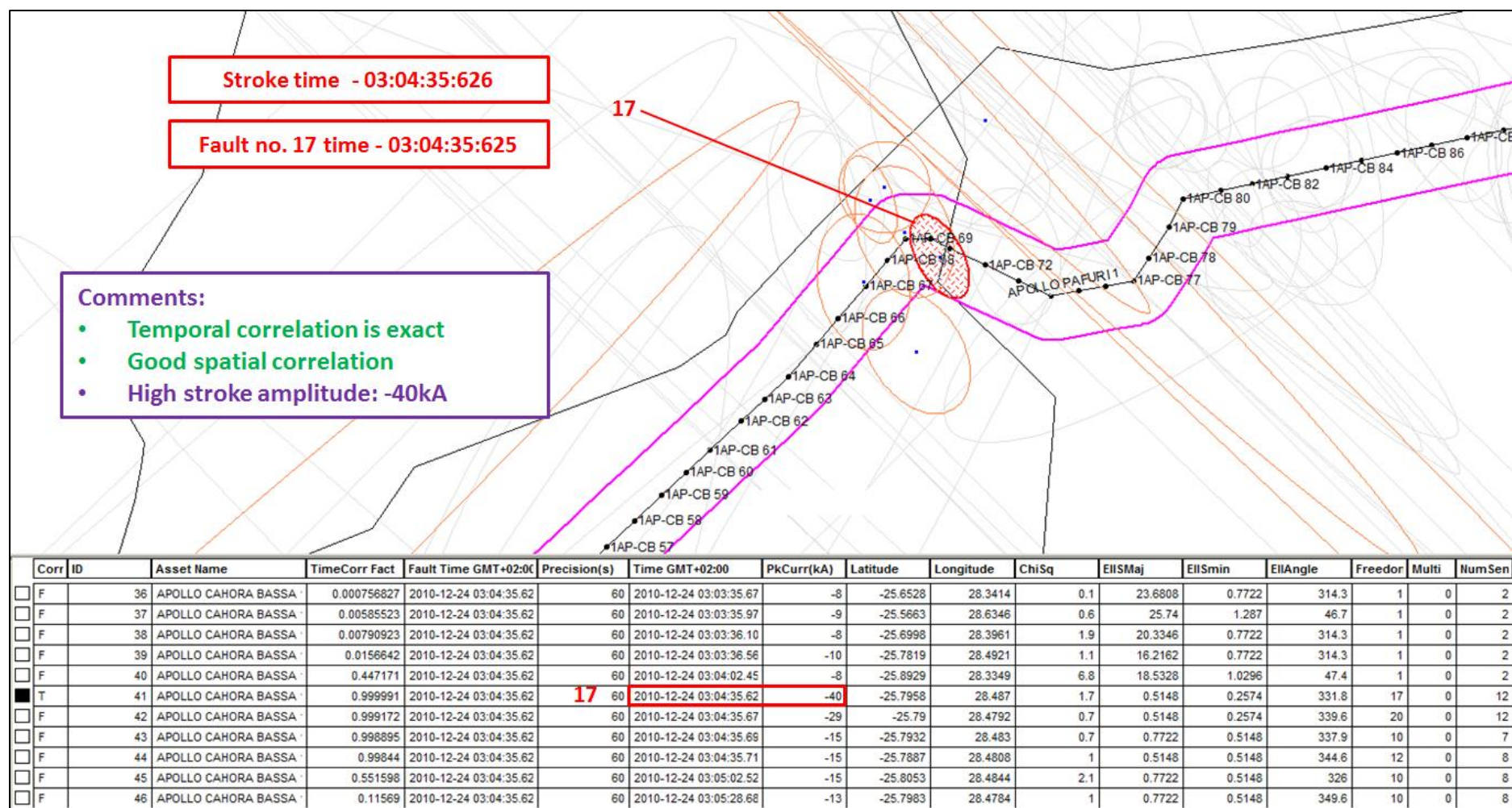


Figure B.18: Fault number 17 for 24 December 2010.

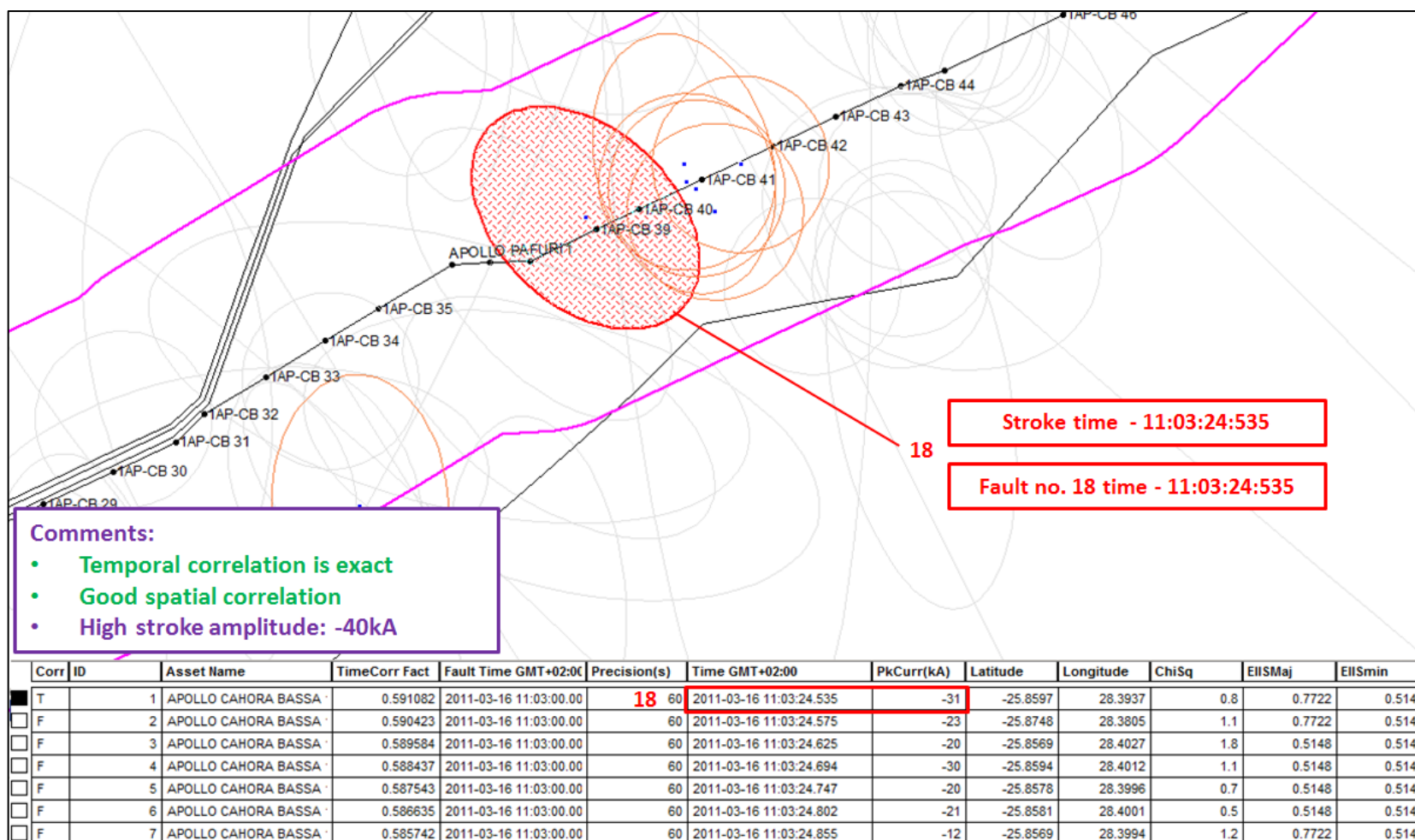


Figure B.19: Fault number 18 for 16 March 2011.

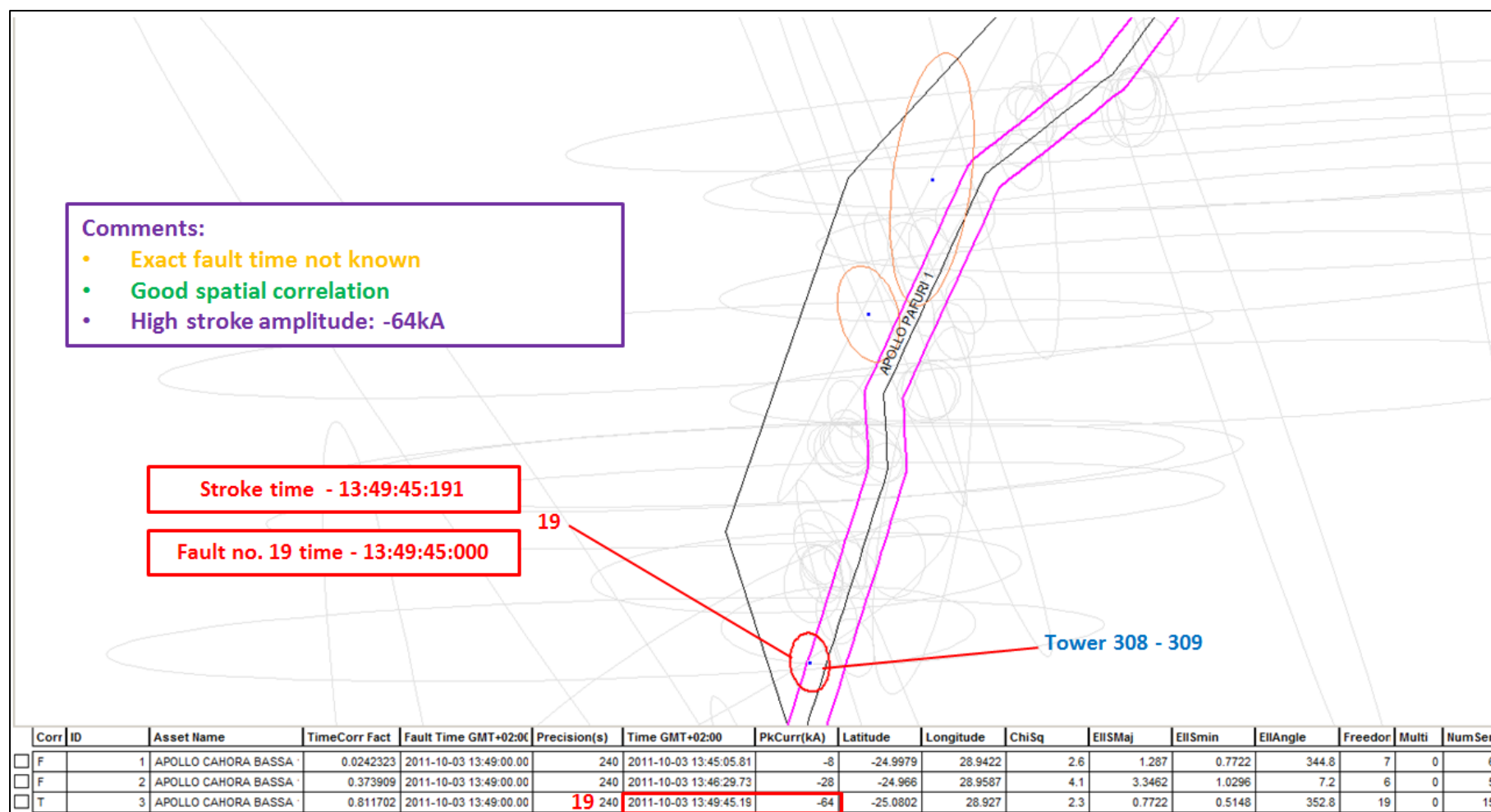


Figure B.20: Fault number 19 for 3 October 2011.

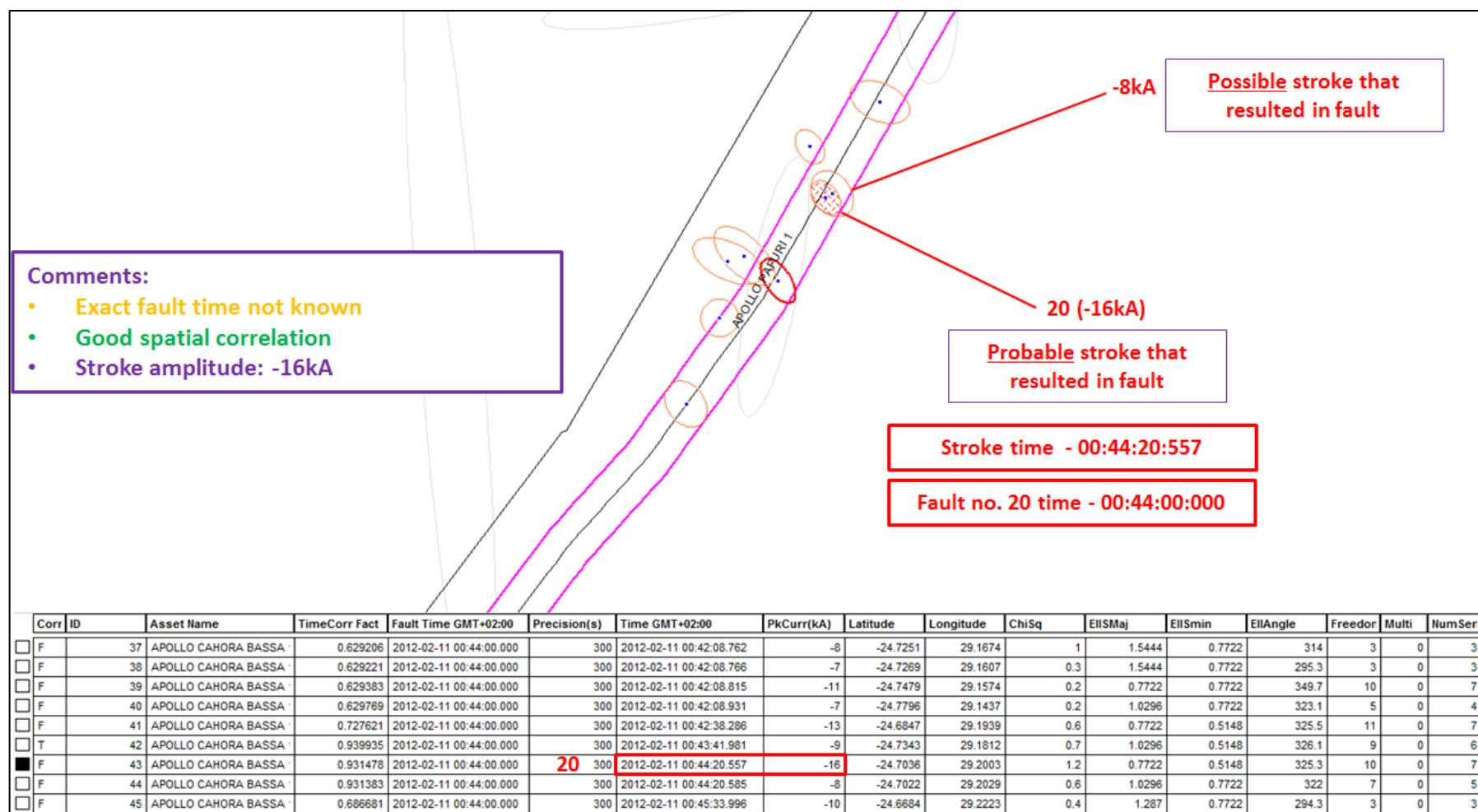


Figure B.21: Fault number 20 for 11 February 2012.

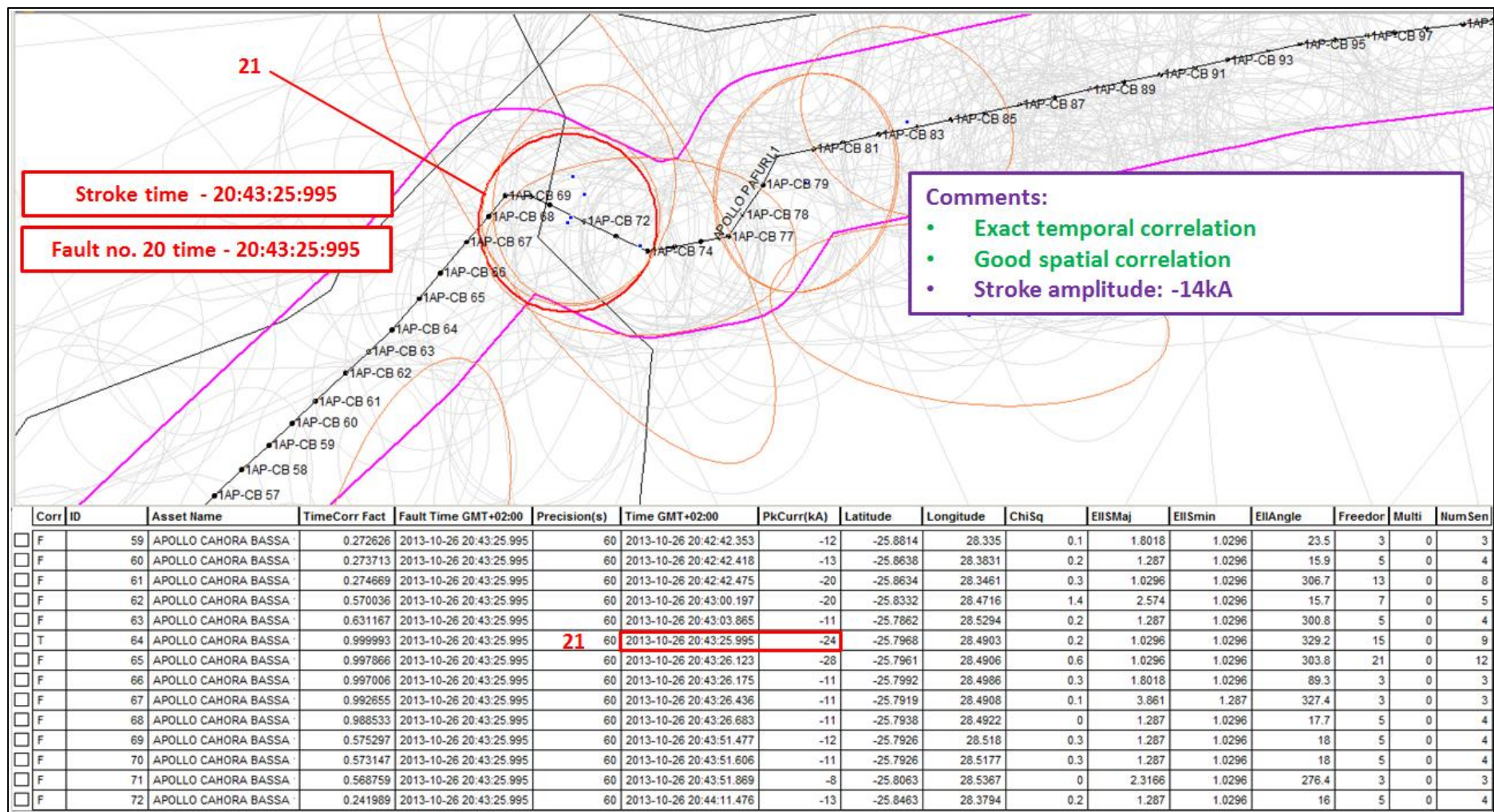


Figure B.22: Fault number 21 for 26 October 2013.

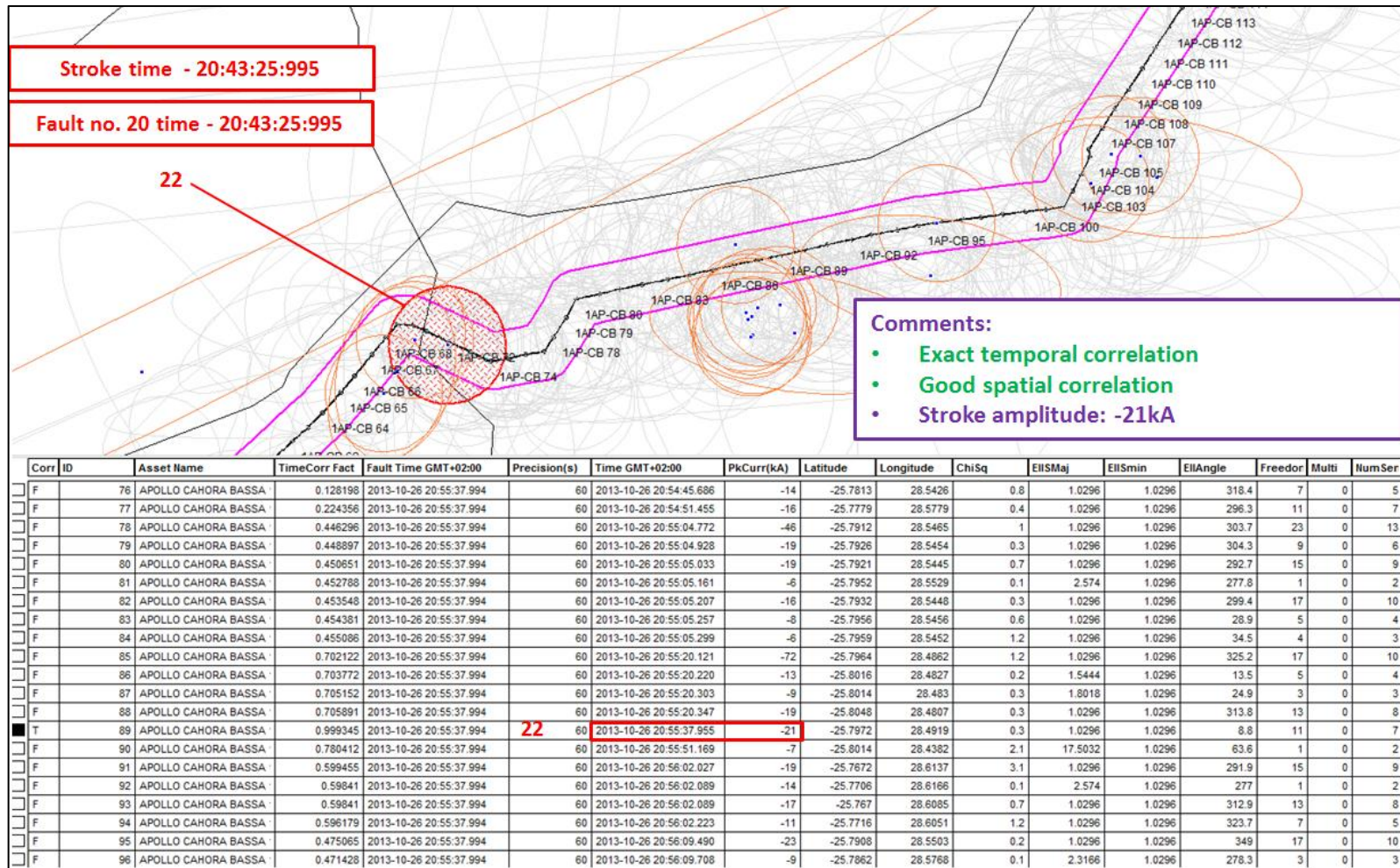


Figure B.23: Fault number 22 for 26 October 2013.

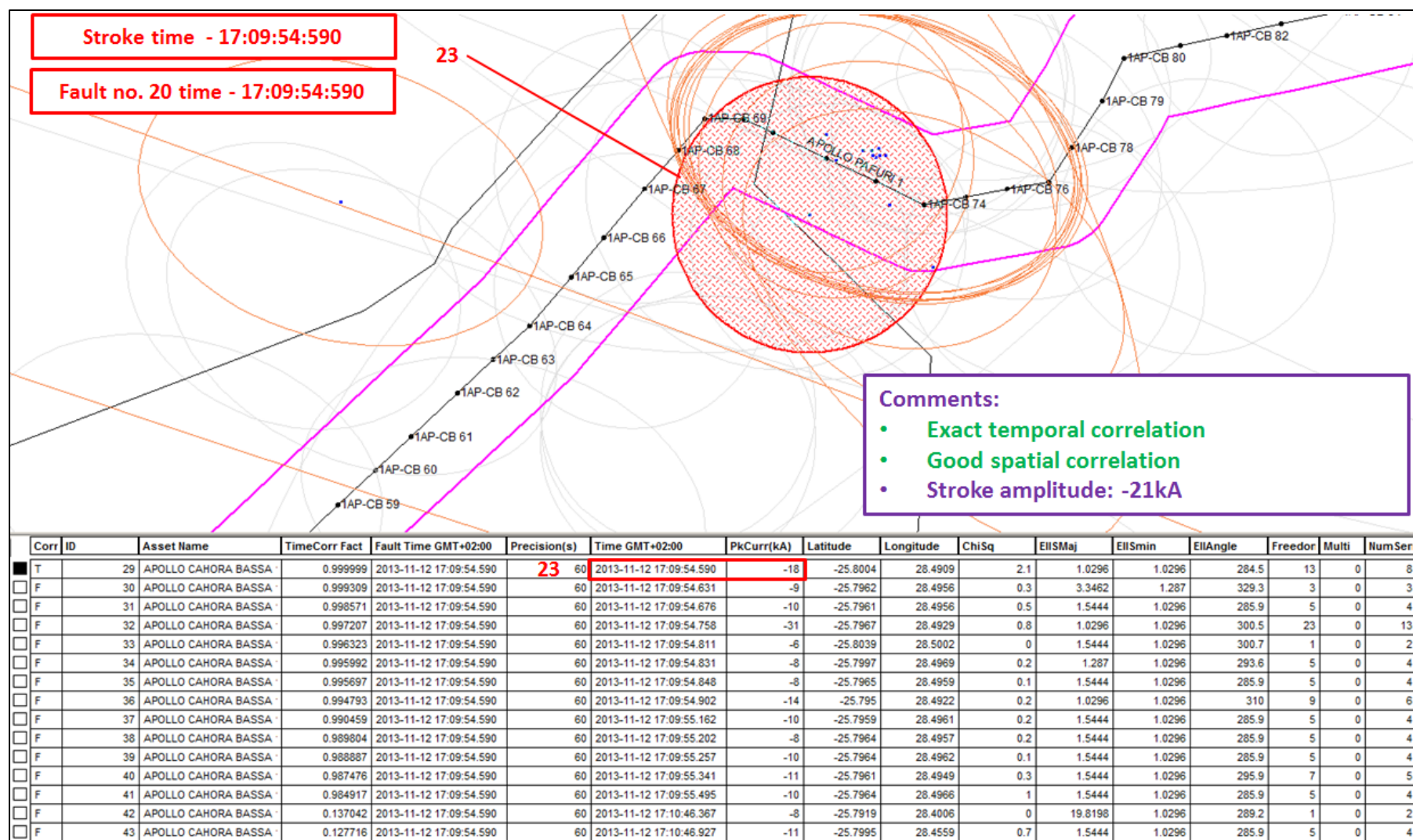


Figure B.24: Fault number 23 for 12 November 2013.

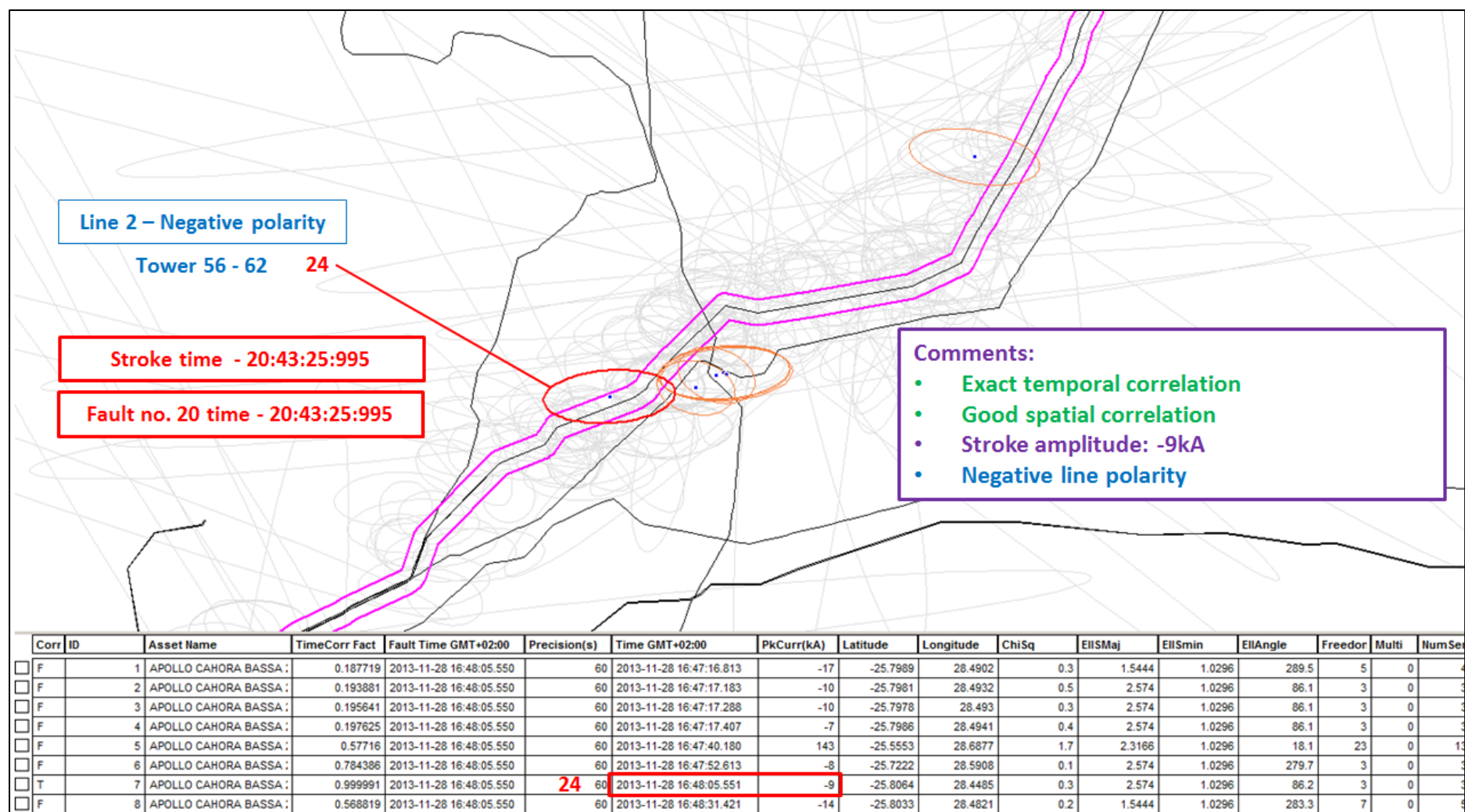


Figure B.25: Fault number 24 for 26 October 2013.

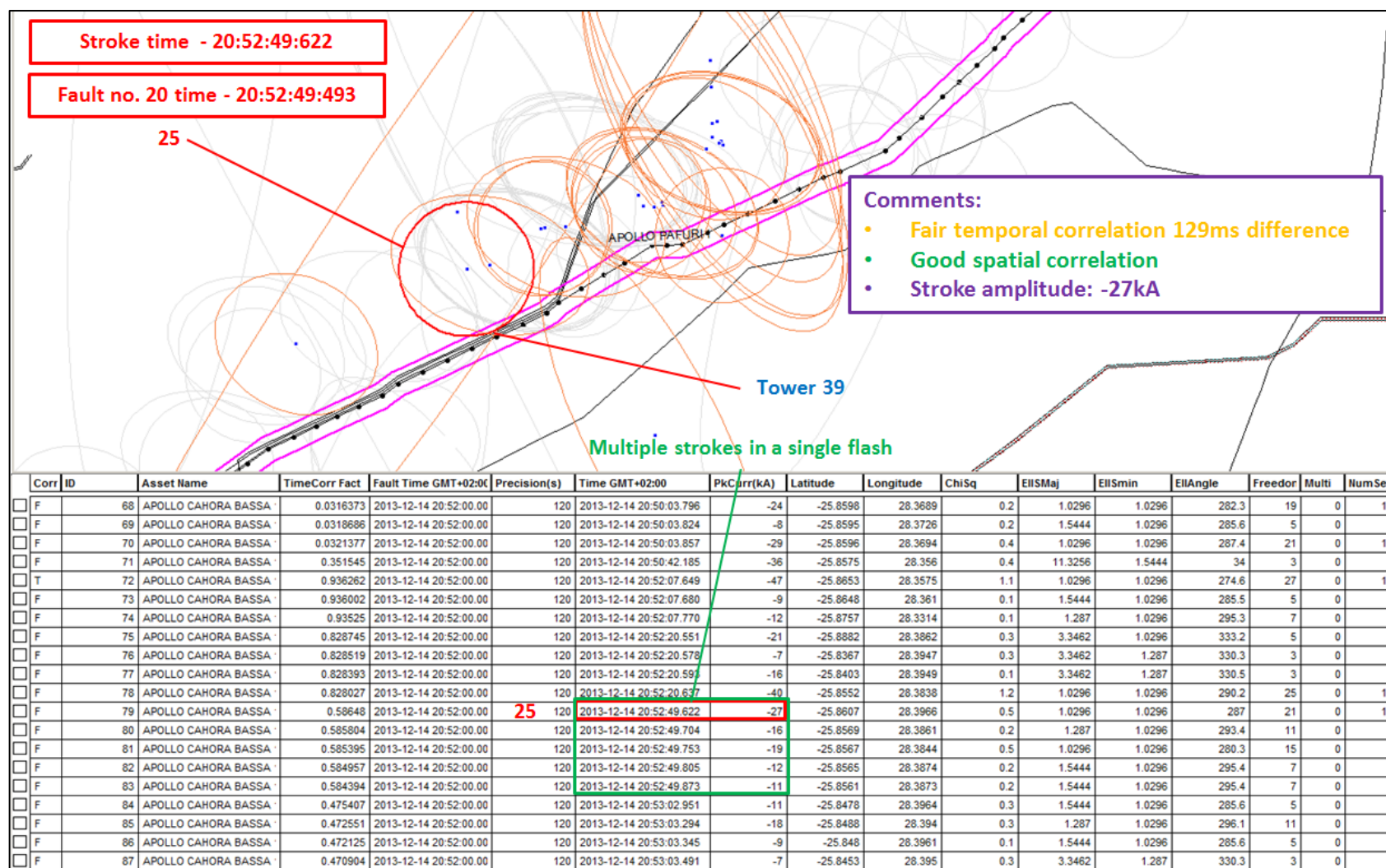


Figure B.26: Fault number 25 for 14 December 2013.

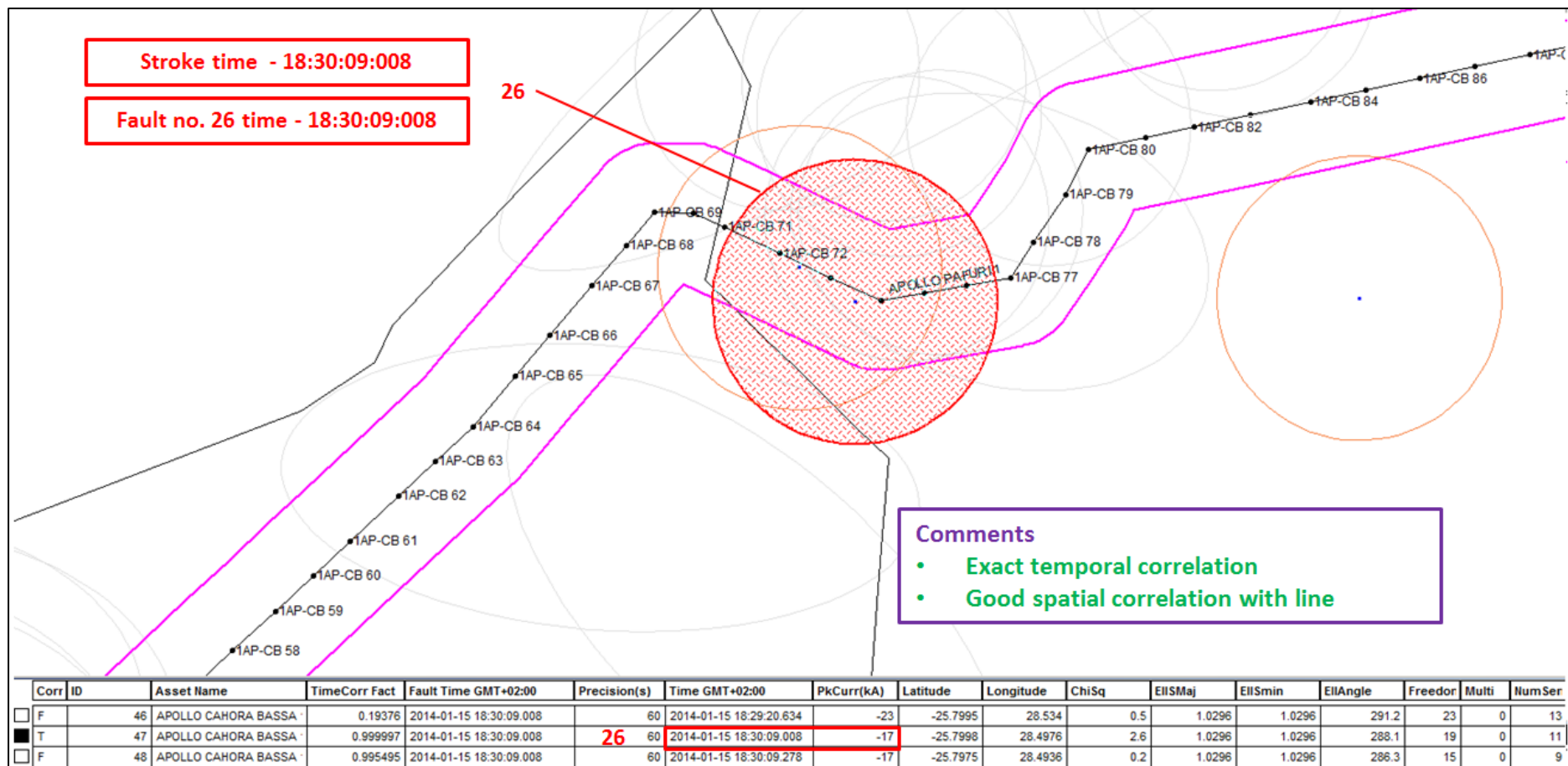


Figure B.27: Fault number 26 for 15 January 2014.

Appendix C: Comparison in the Lightning Performance between the Poles of the Cahora-Bassa ± 533 kV HVDC Lines – Presented at ISH 2015

This appendix contains a paper that was accepted and presented for publication by the *19th International Symposium on High Voltage Engineering*, in Pilsen, Czech Republic, 23 – 28 August 2015.

COMPARISON IN THE LIGHTNING PERFORMANCE BETWEEN THE POLES OF THE CAHORA-BASSA ± 533 kV HVDC LINES

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Abstract: This paper compares the lightning performance between the positive and negative poles of the 517 km South African portion of the 1414 km HVDC scheme between “Songo” hydro power station in Mozambique, and “Apollo” converter station north of Johannesburg, South Africa. This scheme is unique in that the positive and negative poles are constructed as two independent lines, separated by several kilometres. The separation between the lines is sufficient to distinguish between strokes to either line with high accuracy, whilst the lines are assumed to experience similar average weather conditions, and thus exposure to lightning. The available fault data for 7 years was analysed in order to compare the relative performance of the two poles in respect of lightning related faults.

1. INTRODUCTION

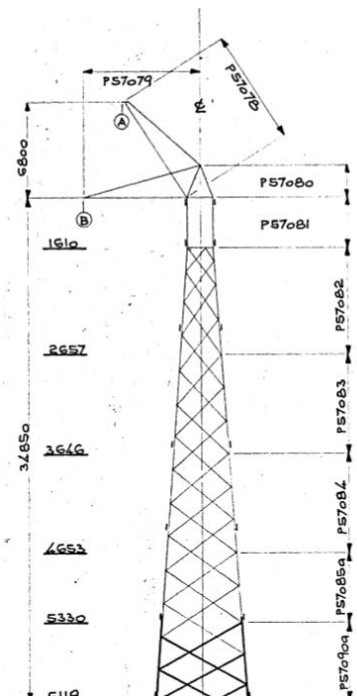
High performance is demanded from High Voltage Direct Current (HVDC) schemes due to the large energy transfer capacities compared to typical Alternating Current (AC) lines of comparable insulation levels. Although the incidence of faults due to lightning may be low, HVDC lines are relatively long and the impact of faults is therefore emphasised.

This paper compares the lightning performance between the positive and negative poles of the 500 km South African portion of the 1414 km HVDC scheme between “Songo” hydro power station in Mozambique, and “Apollo” Converter Station (CS) north of Johannesburg, South Africa.



Figure 1: Cahora-Bassa HVDC Scheme

This scheme is unique in that the positive and negative poles are constructed as two independent lines on mono-polar structures (Figure 2), separated by several kilometres. Internationally, all other HVDC schemes are constructed on bipolar structures, except for the Inga-Shaba scheme in the Democratic Republic of the Congo of which the mono-polar structures separated by a mere 60 m.



configuration is best suited to Line 1 being positive. Line 2 is operated at reduced voltage with only three bridges in series for a nominal sending voltage of 400 kV. The negative pole is operated at reduced voltage due to relatively poor signal to noise ratio affecting the performance of the power line carries telecommunications. Furthermore, the negative pole results in higher nuisance induced DC currents at ground level due to the higher negative ion mobility.

From July to August 2014, the polarities of the two lines were reversed from their normal mode. Pole 1 was run as negative due to an operational problem at Songo CS. This has not affected the lightning performance statistics as it was during the dry season and there was no lightning activity during this period.

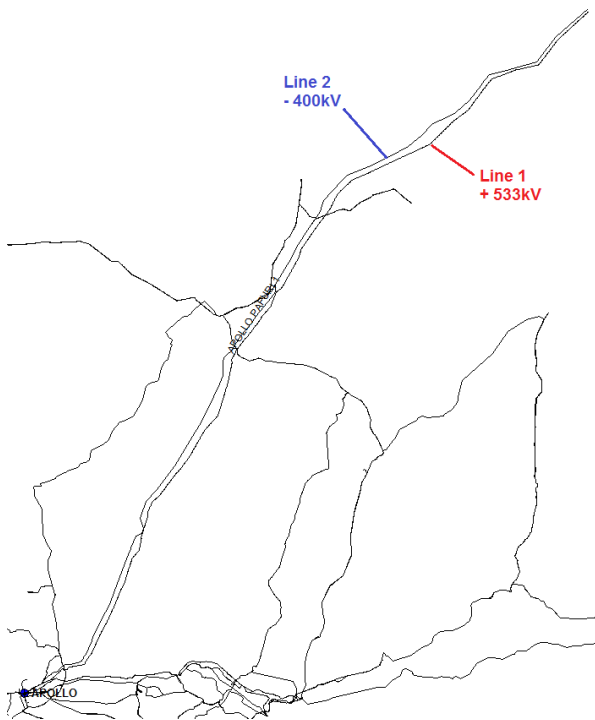


Figure 3: Mono-polar HVDC Lines between Apollo CS and Pafuri Border running a distance of 517 km

The separation between the lines is sufficient to distinguish between strokes to either line with high accuracy, whilst the lines are assumed to experience similar average weather conditions, and thus exposure to lightning.

The investigation only considers the 500 km portion of the line from the Mozambique border to Apollo CS which is maintained and operated by Eskom, as there is no performance data available at present, for the Mozambique section operated by “Hydro Cahora-Bassa”. The available fault data for the last 7 years, was analysed in order to compare the relative performance of the two poles in respect of lightning related faults.

2. BACKGROUND

In the design for lightning performance for AC lines, the sinusoidal variation in the potential of the conductor means that it is generally assumed that there is no net influence on faults due to lightning, in relation to the polarity of the downward stepped leader. Therefore, the line potential has been neglected in the design of overhead lines from a lightning protection perspective.

In the case of HVDC however, the constant potential and polarity of the line are expected to have a significant effect on the incidence of lightning induced faults [1].

There are two types of fault that can occur on an HVDC line due to lightning:

- a) Shielding failure – In the case of shielding failure, the downward leader bypasses the overhead shield wire, and strikes the pole conductor. If the magnitude of the lightning current leads to a conductor potential exceeding the line insulation, there is a significant probability that there will be a flashover across the line insulation from the conductor to the structure. Below a certain threshold stroke current (“critical” or “coordination” current), strikes will not result in insulation failure. For overhead lines (neglecting the conductor voltage), the permissible stroke current threshold must be coordinated with the insulation level as follows [2]:

$$I_s = \frac{LIWL}{Z_0/2} \quad (1)$$

Where:

I_s is the allowable stroke current in kiloamperes

$LIWL$ is the lightning impulse withstand level in kilovolts

Z_0 is the surge impedance of the conductor in ohms

The coordination current I_{c+} for the positive pole and I_{c-} for the negative pole will be offset by the pole voltage as follows:

$$I_{c+} = \frac{LIWL + V_{p-g}}{Z_0/2} \quad (2)$$

$$I_{c-} = \frac{LIWL - V_{p-g}}{Z_0/2} \quad (3)$$

Where: V_{p-g} is the pole to ground voltage

- b) Back-flashover – In the case of back-flash, lightning terminates on the structure, or shield wire. The lightning current causes the potential of the structure to increase in relation to the surge

impedances. If the potential on the structure exceeds the line insulation level, a flashover may occur across the line insulation from the tower to the pole conductor.

There are three situations where the polarity of the conductor will influence the interaction of lightning with a HVDC transmission line.

- a) The negative pole will be more vulnerable to flashover due to direct negative stroke, due to the supposition of the voltage developed due to the impulse current onto the negative DC offset of the line operational voltage. The potential for flashover is reduced if the conductor voltage is positive, and the voltage developed due to the stroke is negative. This means that the negative pole line insulation will flashover at a lower current threshold, compared to the positive pole.
- b) The positive pole will be more vulnerable to stroke penetration under negative stroke, due to the conditions for an induced leader from the pole conductor being more readily met, thereby increasing the effective attractive radius of the positive pole conductor [3][2]. According to [4], the contribution of the pole voltage calculated according to the electro-geometric model increases the shielding failure rate by 4,84 times for a positive pole voltage of 500 kV compared to when the line voltage is neglected in consideration of negative downward leader. The effect of negative pole voltage is not stated in [4].

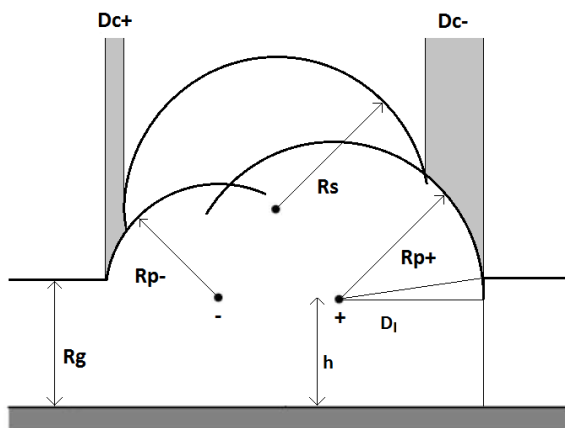


Figure 4: Attractive radii for the poles under approaching negative downward leader

- c) The positive pole will be more vulnerable to back-flashover under negative stroke since the positive DC bias increases the stress across line insulation under negative impulse.

Since the majority of downward strokes are of negative polarity (80 – 90% of all flashes [5]) the lightning

performance of the two poles of an HVDC line are predicted to show a marked disparity.

The above theoretical aspects are to be investigated in terms of the performance of the poles of the Cahora-Bassa line.

3. COMPARISON OF LIGHTNING PERFORMANCE OF TWO POLES

In order to compare the performance of the two poles, it is necessary to verify that the lightning exposure of the two mono-polar lines is similar, despite the lines following different routes. The Fault Analysis and Lightning Location System (FALLS) program is used to analyse the lightning performance. The FALLS function “Small Area Exposure” (SAE) analysis was used to determine the lightning statistics for the two lines, over a period of 8 years from 1 March 2006 to 1 March 2014 for which FALLS data is available. This analysis technique provides trends of lightning exposure over assets, and displays the exposure in terms of the amount and intensity of lightning exposure, discriminated by polarity and amplitude within user-defined buffers around assets [6]. These statistics are used to compare the lightning exposure for the two lines, in order to determine if the lines are exposed to similar average lightning activity. In order to compare the influence of the pole voltage on the incidence of lightning faults, the overall exposure between the positive and negative poles must be very similar.

This is demonstrated by the cumulative lightning exposure for both positive and negative strokes within a 1 km buffer region around each of the two lines. The lightning exposure is shown in the graphical representation of the SAE Analysis in Figure 5 and 6, Each “dot” represents a lightning stroke.

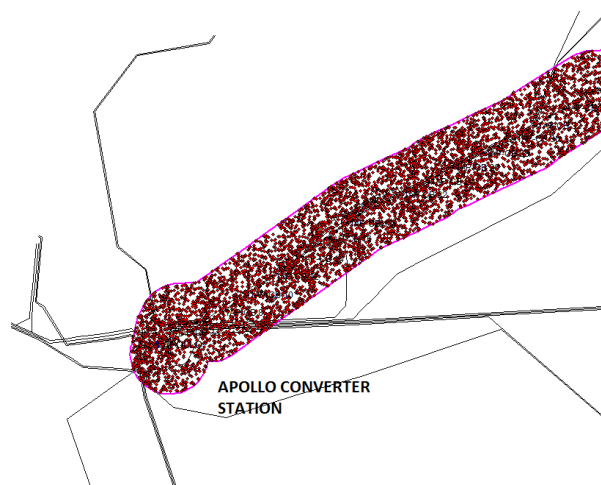


Figure 5: SAE Analysis for CB Line 1 near Apollo CS.

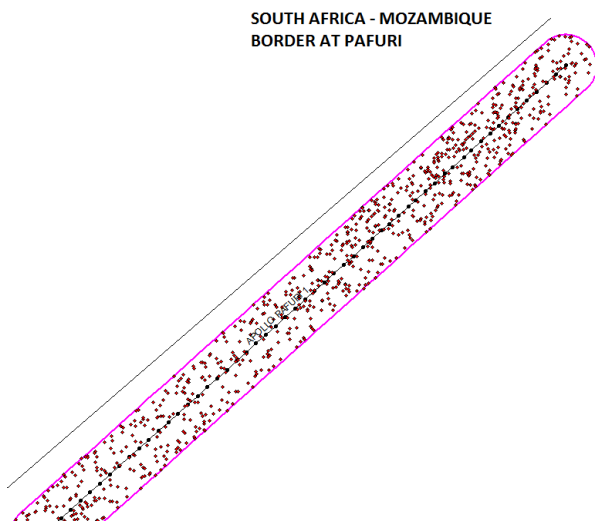


Figure 6: SAE Analysis for CB Line 1 near Pafuri Border.

It can be seen from Figure 5 and 6 that the lightning flash density is significantly higher towards Apollo CS compared to the Mozambique border.

Comparison of the stroke peak current frequency between the two lines for both positive and negative polarities is shown in Figures 7 to 10. It can be seen that the lightning exposure for the two lines is very similar over the 7 year period of simulation.

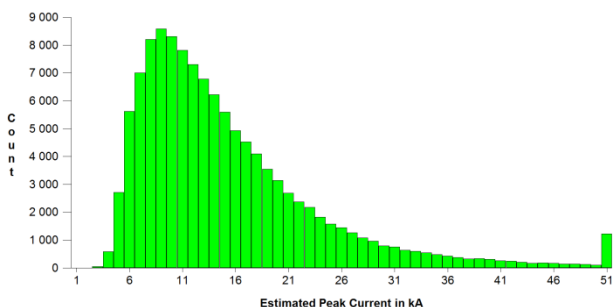


Figure 7: Line 1 Stroke Peak Current frequency (Negative Polarity)

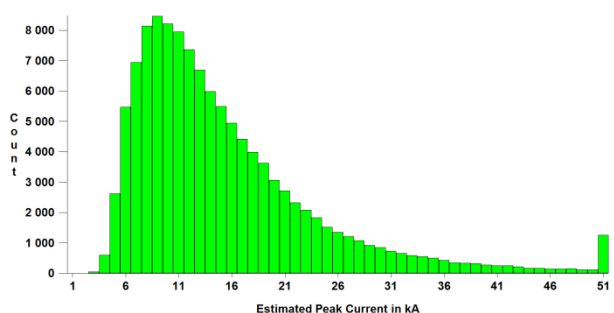


Figure 8: Line 2 Stroke Peak Current frequency (Negative Polarity)

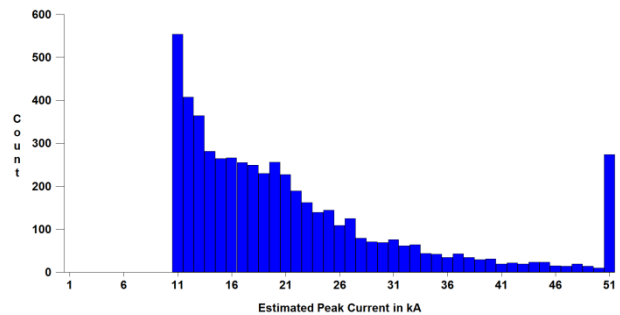


Figure 9: Line 1 Stroke Peak Current frequency (Positive Polarity)

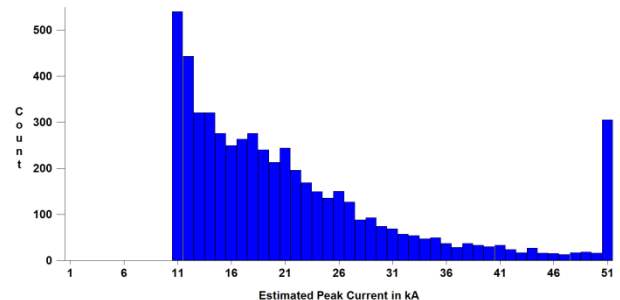


Figure 10: Line 2 Stroke Peak Current frequency (Positive Polarity)

Note that for positive polarity strokes below 10 kA are disregarded from the statistics due to potential misdiagnosis between cloud to ground and cloud to cloud strokes. The Small Area Exposure analysis carried out for the period from 2006 to 2014, indicates approximately 98% of lightning exposure on the lines is of negative polarity

4. FACTORS INFLUENCING PERFORMANCE DISPARITY BETWEEN THE TWO POLES

The lines follow different routes to reduce the risk of common mode failure due to extreme weather or sabotage. Since the lines follow different routes separated by several kilometres, there are instances where the structures of the two lines are located in different geological conditions which could influence the structure footing resistance and the consequent back-flash performance. Additionally, there are instances where the relative elevation of the line to the surrounding area exposes the line to a higher probability of being struck. Also the nature of the surrounding terrain, such as tall trees etc., may result in the exposure of the line to lightning being affected. These two factors have not been considered at this stage.

In future, the geology and topography will be further investigated. This is an extensive task as it involves more than 500 km of transmission line. There are some localised areas that show uncharacteristic very high fault incidence due to lightning activity which have

been investigated in [7]. These areas may experience high fault incidence due to passing over elevated areas, particularly with high footing resistances due to rocky outcrops.

In these areas special earthing design is necessary to ensure that tower voltages are coordinated below insulation levels to minimise the potential for line faults due to the back-flashover mechanism. In rocky areas it may be preferable for the implementation of low surge impedance remote electrodes, or surge arresters to prevent back-flashovers.

5. FAULT CORRELATION METHOD

During periods where no lightning activity is anticipated (e.g. dry season), SAE analysis was used to confirm that there was no unexpected lightning activity. Therefore, it was not necessary to further investigate individual faults during these periods in order to determine lightning correlation.

The FALLS function, “Reliability Analysis” (RA) is the tool used to correlate faults with lightning [6]. Correlation is performed between the entered fault time and the lightning stroke times from the lightning database. The strokes are also spatially correlated within a user defined buffer region around the line.

Fault times originate from the line protection scheme. An example of the fault time downloaded from the protection scheme is show in Figure 12. Protection fault time stamps are available from the 17 September 2008 when the new protection scheme was commissioned. FALLS lightning data is available until the 31 August 2014. Therefore lightning fault correlations were conducted over approximately 7 years.

Apollo-26-10-2013 Pole 1.txt - Notepad

File Edit Format View Help

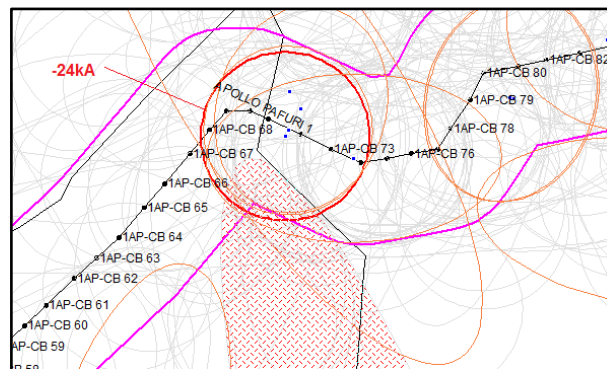
"2013.10.26","20:43:28:258","Fault Time 25 sec, 995240000 ns, Pole 1"

"2013.10.26","20:55:40:256","Fault Time 37 sec, 954685700 ns, Pole 1"

Figure 11: Sample download of line faults from protection scheme

The first fault in Figure 11 has a time of 20:43:25:995. This time was entered into FALLS program in order to determine if there was any spatially correlated lightning strikes coincident with that time.

An example of the output from the fault correlation is shown in Figure 12. The stroke highlighted in yellow exhibits precise temporal correlation. The spatial correlation is depicted graphically by the bold red circle.



Fault Time GMT+02:00	Precision(s)	Time GMT+02:00	PkCurr(kA)
2013-10-26 20:43:25.995	60	2013-10-26 20:42:42.353	-12
2013-10-26 20:43:25.995	60	2013-10-26 20:42:42.418	-13
2013-10-26 20:43:25.995	60	2013-10-26 20:42:42.475	-20
2013-10-26 20:43:25.995	60	2013-10-26 20:43:00.197	-20
2013-10-26 20:43:25.995	60	2013-10-26 20:43:03.865	-11
2013-10-26 20:43:25.995	60	2013-10-26 20:43:25.995	-24
2013-10-26 20:43:25.995	60	2013-10-26 20:43:26.123	-28
2013-10-26 20:43:25.995	60	2013-10-26 20:43:26.175	-11
2013-10-26 20:43:25.995	60	2013-10-26 20:43:26.436	-11
2013-10-26 20:43:25.995	60	2013-10-26 20:43:26.683	-11
2013-10-26 20:43:25.995	60	2013-10-26 20:43:51.477	-12
2013-10-26 20:43:25.995	60	2013-10-26 20:43:51.606	-11

Figure 12: Example of correlation at 20:43:25:995 with a stroke of -24 kA

Of those faults that correspond with lightning, the majority correlate precisely within a tolerance of a millisecond. Some of the fault times are different from the closest stroke time by of the order of 100 ms. This may be due to inaccuracies in the fault time stamp or the FALLS lightning time. However these faults are assumed to be due to lightning as they are spatially correlated with the line, and are very closely correlated in time.

6. RESULTS AND DISCUSSION

The results of the fault correlation for the 517 km HVDC Lines between Apollo CS and the Pafuri Border with Mozambique for the period between the 17 September 2008 and 31 August 2014, are shown in the table below.

Table 1: Summary of fault correlation on the Cahora-Bassa HVDC Lines

	Line Polarity	Date	Fault Time	Stroke Time & Correlation	Stroke Current & Polarity
27.	1 (+)	19 01 2009	23:13:38:108	23:13:38:108	-18 kA
		19 01 2009	23:13:38:193	23:13:38:193	-9 kA
		19 01 2009	23:13:38:232	23:13:38:232	-9 kA
		19 01 2009	23:13:38:395	23:13:38:395	-11 kA
		19 01 2009	23:13:38:438	23:13:38:438	-9 kA
		19 01 2009	23:13:41:151	23:13:41:151	-7 kA
28.	1 (+)	20 01 2009	00:50:42:744	00:50:42:744	-17 kA
29.	1 (+)	17 02 2009	20:28:40:024	20:28:40:024	-26 kA
30.	1 (+)	17 02 2009	20:28:40:138	20:28:40:138	-17 kA
31.	1 (+)	17 02 2009	20:51:17:543	20:51:17:543	-8 kA
32.	2 (-)	01 12 2009	01:28:52:564 & 573	01:28:52:645	-11 kA
33.	1 (+)	16 01 2010	01:16:39:590	01:16:39:744	-24 kA
34.	1 (+)	09 10 2010	15:16:42:625	15:16:41:982	-32 kA
				15:16:42:062	-25 kA
				15:16:42:161	-15 kA
				15:16:42:200	-11 kA
				15:16:42:551	-6 kA

	Line Polarity	Date	Fault Time	Stroke Time & Correlation	Stroke Current & Polarity
35.	1 (+)	09 10 2010	15:22:10:571	15:22:10:571	-34 kA
36.	1 (+)	09 10 2010	15:24:13:888	15:24:14:207	-22 kA
37.	1 (+)	09 10 2010	15:26:18:488	15:26:18:487	-17 kA
38.	1 (+)	27 10 2010	21:21:40:248	21:21:40:249 21:21:40:323 21:21:40:396 21:21:40:768	-9 kA -13 kA -21 kA -10 kA
39.	1 (+)	30 10 2010	19:04:20:427	19:04:20:427 19:04:20:427	-18 kA -11 kA
40.	1 (+)	30 10 2010	19:04:21:661	19:04:21:660	-9 kA
41.	1 (+)	07 11 2010	00:37:25:390	00:37:25:389	-8 kA
42.	1 (+)	11 12 2010	18:36:03:593	18:36:03:593	-43 kA
43.	1 (+)	24 12 2010	03:04:35:625	03:04:35:626	-40 kA
44.	1 (+)	16 03 2010	11:03:24:535	11:03:24:535	-31 kA
45.	1 (+)	03 10 2010	13:49	13:49:45:191	-64 kA
46.	1 (+)	26 10 2013	20:43:25:995	20:43:25:995	-24 kA
47.	1 (+)	26 10 2013	20:55:37:955	20:55:37:955	-21 kA
48.	1 (+)	12 11 2013	17:09:54:590	17:09:54:590	-18 kA
49.	2 (-)	28 11 2013	16:48:05:550	16:48:05:551	-9 kA
50.	1 (+)	14 12 2013	20:52:49:493	20:52:49:622	-27 kA
51.	1 (+)	15 01 2014	18:30:09:008	18:30:09:008	-17 kA

Legend:

RED indicates positive line and positive stroke polarities
BLUE indicates negative line and negative stroke polarities
Strokes in **GREEN** are perfect correlations
Strokes in **YELLOW** indicate close correlations
Strokes in **GREY** indicate multiple strokes that are not fault correlated

The following comments can be made about

- The total correlated lightning faults is 25 over a seven year period
- Of the total lightning correlated faults 23 (92%) are on the positive line (Line 1), and 2 (8%) are on the negative line (Line 2). The positive polarity appears to increase probability of strike by negative downward leader.
- Only two (8%) out of 25 correlated faults are due to positive strokes.
- Some faults are caused by unexpectedly low amplitudes. Further investigation is required; however preliminary assessment is that the faults are due to back flashover originating from exceptionally high footing resistances.
- Out of 25 line faults, 13 (52%) are on the positive line (Line 1) over a short section of comprised of 9 towers, where the line crosses a rocky outcrop about 30 km north of Apollo CS.

7. FUTURE WORK

In order to differentiate between lightning induced faults that are due to shielding failure and back-flashover, the maximum penetration current must be determined.

A preliminary shielding failure analysis for Cahora-Bassa towers was performed using the T Flash module of the Electric Power Research Institute (EPRI) software TL Workstation – Gen 2.

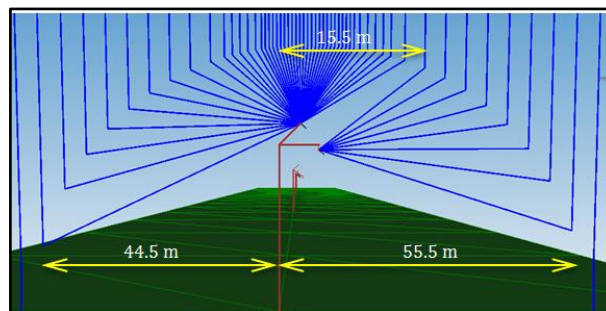


Figure 13: Preliminary simulation depicting shielding failure

The results of the simulation were inconclusive and the model will have to be refined in order to discriminate between shielding failure and back-flash.

REFERENCES

- [1] Electric Power Research Institute, "EPRI HVDC Reference Book: Overhead Lines for HVDC Transmission, Electrical Performance of HVDC Transmission Lines", Chapter 4, "Lightning Performance", EPRI, Palo Alto, CA, 2008
- [2] Institute of Electrical and Electronics Engineers, "IEEE Std 998-2012"
- [3] Rizk F.A.M., "Lightning Exposure and Lightning Protection with Special Reference to High Altitudes, Review of State of the Art and Selection of Design Criteria", Internal research report submitted to Trans Africa Projects in February 2012
- [4] Hengxin HE, Junjia HE, Dandan Zhang, Li DING, Zhenglong JIANG, Cheng WANG, Huisheng YE "Experimental Study on Lightning Shielding Performance of 500 kV HVDC Transmission Lines", IEEE 2009
- [5] Rakov V.A. and Uman M.A., "Lightning: Physics and Effects", Book, Cambridge University Press, 2003
- [6] Vaisala FALLS® Client Fault Analysis and Lightning Location System
- [7] Pretorius P.H., "Engineering Perspectives on Soil Properties Important to the Design and Performance of Earth Electrodes at Low and High Frequency", ISH 2015