INVESTIGATING THE CURRENT AND POTENTIAL DISTRIBUTION OF LIGHTNING ON A BUILDING TO DETERMINE ADEQUATE PROTECTIVE MEASURES

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Dissertation submitted in fulfilment of the requirements for the degree

Master of Engineering in Electrical Engineering

in the

Department of Electrical, Electronic and Computer Engineering

Faculty of Engineering, Built Environment and Information Technology

at the

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Bloemfontein

August 2022

DECLARATION

I, Jacques Johan Keyser (Student number: __________), hereby declare that this research project, which has been submitted to the Central University of Technology, Free State, for the degree of Master of Engineering in Electrical Engineering, is my own independent work, complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Student Signature

Date: 2022-08-04

ACKNOWLEDGEMENTS

I would like to begin by expressing my humble gratitude and admiration to my primary supervisor, Prof. A.J. Swart, for all of his guidance and encouragement, as well as for providing me with the opportunity to learn and develop academically by providing me with the necessary technical suggestions throughout my research pursuit. I would also like to express my gratitude to my co-supervisor, Prof. P.E. Hertzog, for his insightful comments, observations and engagement throughout the review process.

I would also like to express my sincere appreciation to DEHN AFRICA for providing me with financial support for this study and allowing me to use the specialised software that made this study possible.

Finally, I would like to express my profound gratitude to my partner, Cherise, for her unwavering support and encouragement throughout my years of study and the process of researching and writing this dissertation. This achievement would not have been possible without your assistance.

ABSTRACT

Lightning is one of the most powerful and spectacular natural phenomena that mankind has ever encountered. Approximately 3 billion lightning flashes occur around the world every year. In South Africa, lightning is responsible for millions of deaths, which is significantly more than the global average. In particular, Bloemfontein is classified as having a high susceptibility to direct lightning strikes, making it a focal point for imposing lightning education and protection measures, owing to the city's rapid population growth.

The challenge exists when people are not educated in lightning protection measures and is considered last when constructing new structures, thus leaving a blank space when it comes to budgeting. There is a widespread misconception that people are immune to the effects of lightning because they are protected by structures and believe that lightning will never come into direct contact with them or have any impact on their daily life. This research's first objective is to identify appropriate buildings that would clearly distinguish the type of impact that lightning would have on a building, considering various structural and environmental factors. The second objective is to propose a lightning protection system (LPS) for each building based on the outcomes of the lightning risk analysis. The third objective is to conduct a lightning analysis on the pre-defined buildings to outline the types of buildings that are highly susceptible to lightning side effects. The fourth objective is to evaluate the proposed LPS in terms of mitigation to demonstrate the economic impact that lightning would have on a building and focus on the various ways it could interact with people, causing injuries and fatalities. To address each objective of the study, simulations were performed with appropriate computer-based software.

A lightning risk analysis was performed using the DEHNsupport Toolbox software to determine the occurrence of lightning strikes, the source of damage and identify the lightning-related risk components for buildings that will be occupied by people. This analysis was performed in accordance with the methods outlined in the lightning standard SANS 62305. The analysis focused on three specific buildings: Boet Troskie Hall, the Free State Provincial Government and Loch Logan Park. After establishing the lightning sources and risk components, a proposed LPS was implemented on the buildings using architectural software, SketchUp, which was the subject of the lightning simulation study. The lightning study was carried out with an earthing and lightning simulation software, XGSLab, focusing on the

frequency and time domains and considering a first negative lightning impulse of 50 kA to visualise the engineering aspects of the current and potential distribution across the LPS.

It was concluded that each building considered for the analysis showed differing results. First, the ground potential rise (GPR) is highly dependent on the earthing resistance by altering the number of conductive materials buried in the soil surface and the magnitude of impulse injected into the LPS. Secondly, the quantity and length of a down-conductor had a significant impact on the current distribution and potential difference simulated at selective points over the LPS. The separation distance that needs to be maintained to prevent dangerous sparking of any metallic elements, resulting in unsafe conditions for people, electrical and electronic equipment, depends on the length of the down-conductors. Thirdly, the current distribution measured over each down-conductor in the LPS for each building did not exhibit any significant variation from the current injection point and the conductors further away. However, as demonstrated on three buildings, adjusting the length and quantity of the down-conductor produced varying results.

Communities should acknowledge the impact of lightning strikes and the extent of damage that could be inflicted on a structure and the consequences that can result from a lightning event. This implementation of an adequate, compliant LPS should be paid attention to by adhering to the appropriate standards. It is recommended not to be designed or implemented with a lack of knowledge, as the effects of lightning may outweigh the benefits, considering the expense of the system.

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ABBREVIATIONS

μs	Unit of time (micro-seconds)
2D	Two-dimensional space
3D	Three-dimensional space
CDEGS	Current Distribution, Electromagnetic Fields, Grounding, and Soil Structure Analysis
CUT	Central University of Technology
DEHNsupport	Planning software for lightning protection systems
ESE	Early Streamer Emission
GPR	Ground potential rise
HV	High voltage
kA	Current (kilo-Ampere)
kHz	Frequency (kilo-Hertz)
LEMP	Lightning electromagnetic pulse
LPL	Lightning protection level
LPS	Lightning protection system
LV	Low voltage
m	Metre
m^2	Square metre
MJ/m^2	Radiant exposure (Mega-Joule per square metre)
MV/m	Field strength (Mega-Volt per metre)
N_G	Ground flash density
PEEC	Partial element equivalent circuit method

RMS	Root mean squared
SANS	South African National Standards
SAWS	South African Weather Service
SPD	Surge protection device
XGSLab	Lightning and Earthing Software
Ω	Omega (symbol for Ohm)
Ω.m	Electric resistivity (Ohm-metre)

CHAPTER 1: INTRODUCTION

1.1 Background

Every year, lightning results in an average of around 2 000 deaths worldwide [1]. Due to a lack of lightning education in less developed countries, there are fewer safe workplaces, schools, and homes [2]. As a result of lightning dangers awareness and education, lightning-related fatalities have decreased in developed countries [3]. Direct lightning strikes represent only 3 to 5 percent of deaths, whereas ground potential rise (GPR) accounts for 50 to 55 percent because of the difference in voltage between the person's feet that causes a current to circulate through the body [4].

In South Africa, lightning accounts for an average between 1.5 and 8.8 million deaths, which is about four times higher than the global average [5]. According to the South African Weather Service (SAWS) report, Bloemfontein has a lightning ground flash density of 7.4 flashes per square kilometre per year, which falls within the category of severe to extreme lightning risk [6]. Buildings in this region are at a risk of catastrophic damage. These damages may result in: injuries to human beings, fire, explosions, mechanical and chemical reactions, and failure of electrical and electronic systems [7].

In South Africa, during the summer, moisture is fed from the eastern oceans around the South Indian Anticyclone area into the central and northern parts of the country [8], with this moisture being part of the three major mechanisms in thunderstorm development, along with instability and a triggering mechanism [9]. The analysis of the lightning distribution of ground flash density over South Africa shows that most of the lightning occurs in spring and summer and the regions with the lowest median peak current in South Africa correspond to the areas with the highest flash density in the eastern part of the country. The median peak currents of positive lightning are generally 2–5 kA higher than those of negative lightning [10] and in Bloemfontein, the median peak lightning cloud-to-ground current tends to be around 1–15 kA [6].

1.2 Problem Statement

Using adequate protection measures implemented on building structures can lead to lightning risk being mitigated to a tolerable level. The problem is that there are many environmental and structural factors that can affect the likelihood of damage and loss occurring with or without protection measures and these factors influence the current and potential distribution on a building that needs to be quantified in order to identify mitigation techniques. Designing protective measures for buildings based on lightning simulation software also proves challenging as specialised knowledge in this field is required. The sub-problem to be studied is outlined as follows:

- The number of down-conductors required is specific to each building type, and specialised software is required to determine the required number.

- The separation distance must be calculated for each type of building based on its unique properties. The problem is that the lightning protection level (LPL) as determined by a lightning risk analysis is required for the separation distance calculation.

1.3 Purpose

This study aims to investigate the current and potential distribution of lightning on a building to determine adequate protective measures by considering environmental and structural factors. Three predefined buildings were used as examples of different construction materials and textures. The objectives of the study are outlined below:

- To conduct a lightning risk analysis of three specific buildings located in Bloemfontein;

- To propose an external lightning protection system (LPS) on the buildings using computer-based software;

- To simulate a direct lightning strike to the structure and observe the impact in terms of current and potential distribution using computer software; and

- To evaluate the proposed lightning protection system (LPS) in terms of lightning mitigation.

1.4 Methodology

A lightning protection risk analysis was the first step, which was extremely important for establishing the source of lightning damage. It should be developed for each structure that will be occupied by people, regardless of the insignificance of the structure [11]. The DEHNsupport Toolbox software was used to conduct the lightning analysis. As shown in Figure 1, the sources of lightning damage are classified into four types, namely: direct lightning strikes to the structure (S_1), indirect lightning strikes to the structure (S_2), direct lightning strikes to the incoming power lines (S_3) and indirect lightning strikes to the incoming power lines (S_4) [7].

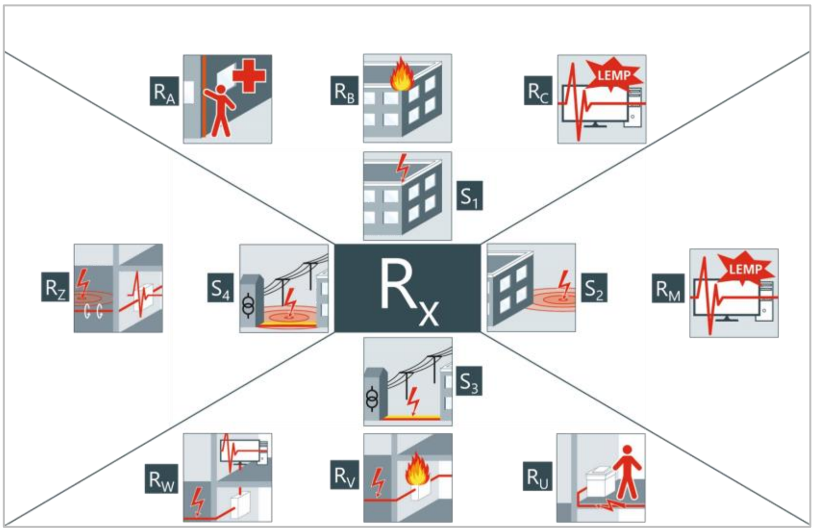

Figure 1: Summary of the risk components [12].

The second step was to propose a LPS using the software SketchUp, based on the calculated LPL determined by the risk analysis results. As illustrated in Table 1, a LPS consists of four levels and while it is preferable to implement a LPL, this may result in overdesign, which is why a risk analysis was recommended to address the economic losses and human life concerns.

Table 1: Lightning current parameters [13]

Lightning protection level (LPL)	Minimum peak value of lightning current	Maximum peak value of lightning current	Impulse waveshape
I	3 kA	100 kA	1/200 µs
II	5 kA	75 kA	1/200 µs
III	10 kA	50 kA	1/200 µs
IV	16 kA	50 kA	1/200 µs

The third step was to simulate and inject a 1/200 μs first negative impulse on the predefined air termination rods placed on the three buildings from the rolling sphere method findings and observe the impact that lightning can have on the resistance of the structure. The simulation was conducted with specialised earthing and lightning software (XGSLab) and the results were visually displayed. A conclusion was then drawn as to whether the current and voltage distribution within the external lightning protection network was sufficient to avoid any sparking of any metallic elements [13].

The last step was to evaluate the proposed LPS and to outline the effect that lightning had, considering the height and structural layout of each building. Figure 2 illustrates an overview of the methodology by means of a flow diagram.

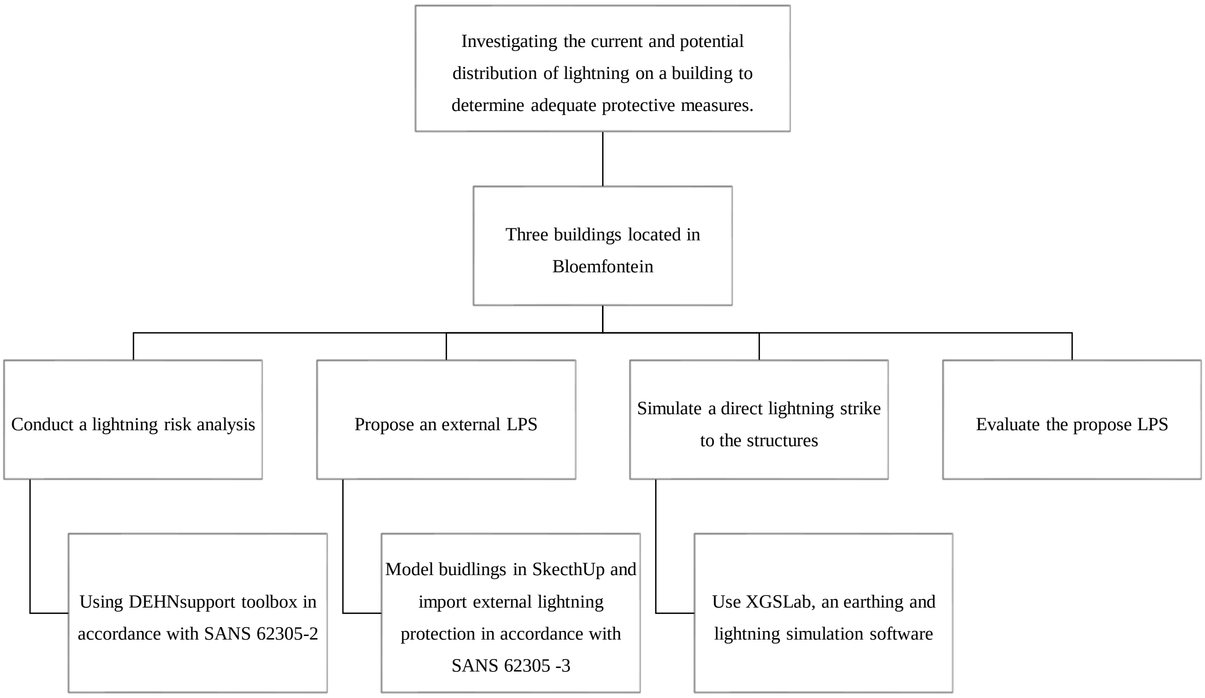

Figure 2: Study overview

1.5 Definition of terms

Lightning protection system (LPS):	Complete system to reduce physical damage to the structure due to lightning flashes. It consists of both external and internal lightning protection systems [14].
Rolling sphere method:	It is a method of lightning protection that uses an imaginary sphere with a radius in accordance with the level of lightning protection

	class. This is rolled over the surface of the structure to predict the point of lightning strikes [14].
Lightning protection level (LPL):	The number related to a set of lightning current parameters values relevant to the probability that the associated maximum and minimum design values will not be exceeded in naturally occurring lightning [15].

1.6 Importance of the research

In order to mitigate the risk of lightning strikes, a risk analysis was performed to determine the source of damage that the structure may encounter, the probability of being struck directly and the losses associated with the risk shown in Figure 1, that can be expected during such an event. The losses are defined as the loss of human life and the loss of economic value. The loss of service to the public and cultural heritage was not considered for this study.

The research results will provide an in-depth study of the experience of a lightning event on the following three buildings: (1) The Loch Logan Park building, which is the tallest residential building, with many residents at home at night; (2) the Free State Provincial Government building, which is the tallest office complex with many employees during the day; and (3) the Boet Troskie Hall at Central University of Technology (CUT), due to the amount of human life present inside the structure, especially during graduation ceremonies.

Human life can be affected by an electric shock and physical structure damage due to a direct strike to the building and incoming power lines. Based on the findings, it is recommended to implement an external LPS in conjunction with internal surge protection devices (SPDs).

1.7 Delimitations

The mechanical forces of lightning that act upon the structure and external lightning protection components were not considered for this study.

1.8 Overview of the report

Chapter 1 entails an introduction to the study, which is divided into four outcomes, namely: the lightning risk analysis; proposed external lightning protection; lightning simulation; and the evaluation of the LPS. The study's background is discussed and the problem statement is defined by emphasising the purpose and importance of the study. The methodology is broken down into steps and the definitions of the terms are provided. The delimitations are described, however, they are not taken into account for the study.

Chapter 2 contains a literature review in which the background and effects of lightning are introduced by examining the various types of lightning formation and damage. The various types of lightning systems are discussed and contrasted with the necessity of an adequate LPS.

The methodology for this research is initiated in Chapter 3, with a lightning risk analysis, modelling of the proposed external LPS and an approach to the lightning simulation. The lightning risk analysis procedure is described and once a tolerable level of risk was established, this procedure enabled the selection of risk-mitigation measures to mitigate the risk below the tolerable level. The modelling of an external LPS to intercept the lightning current and forge a direct path for the current to dissipate into the earth termination system was also carried out. Lastly, the methodology for the lightning simulation is described, with an emphasis on the methods that were used during the study.

The results obtained from the risk analysis and lightning simulation are presented and analysed in Chapter 4. This chapter discusses the occurrence of lightning in scientific terms, followed by the likelihood of lightning strikes.

Chapter 5 entails an evaluation of the proposed LPS, outlining the conclusions and recommendations. The system is reviewed to determine the effect of lightning in the context of previous lightning studies.

1.9 Summary

The introduction and purpose of lightning protection measures have been given. The methodology has been reviewed, as well as the delimitations of the project. Definitions of important terms and the importance of the research were presented together with an overview of the entire report. The following chapter will consider a literature review in which the background and effects of lightning are introduced through an examination of the various types of lightning formation, damage, and the necessity for a LPS.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In Chapter 1, the introduction and purpose of lightning protection measures were introduced and a review was done on the methodology and the delimitations of the project were outlined. The important terms and importance of the study were presented with a complete overview of the project.

In this chapter, the history and necessity of a LPS is illustrated by investigating previous studies conducted and the findings of each one to explain similar or different approaches. The history and effects of lightning are examined, as well as the various types of lightning formation, damage and the need for a LPS.

2.2 Historical Lightning Protection Research

In 1500 BC, lightning protection started with ancient civilisations [16]. The Etruscans were possibly the first to recognise that metal tips had the ability to attract or connect to lightning, while they were busy observing nature. This was taken into account, and priests in Egypt constructed high structures with copper laminated tips, which could be considered the first lightning rod. Because the faithful believed in gods, the corona or discharges that came from these tips during thunderstorms terrified them. In the fifteenth century, sailors and navigators saw this corona on top of the boat mast and thought it was a protective shield from Saint Elmo [11].

Benjamin Franklin discovered atmospheric electricity in 1752 and used the famous kite experiment to design the first lightning conductor or rod. He installed a metallic rod on top of his house, believing that when connected to a rod drilled into the ground, it would neutralise a lightning discharge. This is the origin of the lightning rod. A year after Franklin, Jacques de Romas, a magistrate of Nerac in France, repeated the Franklin kite experiment as shown in Figure 3, but he used a 240 m long kite string that was surrounded by a conducting material to increase the kite string's electrical conduction. He developed 20 cm sparks from the string by the additional conductive material and increased the kite strings up to a point where he got 3 m long arcs in the open air, generating from the string [16].

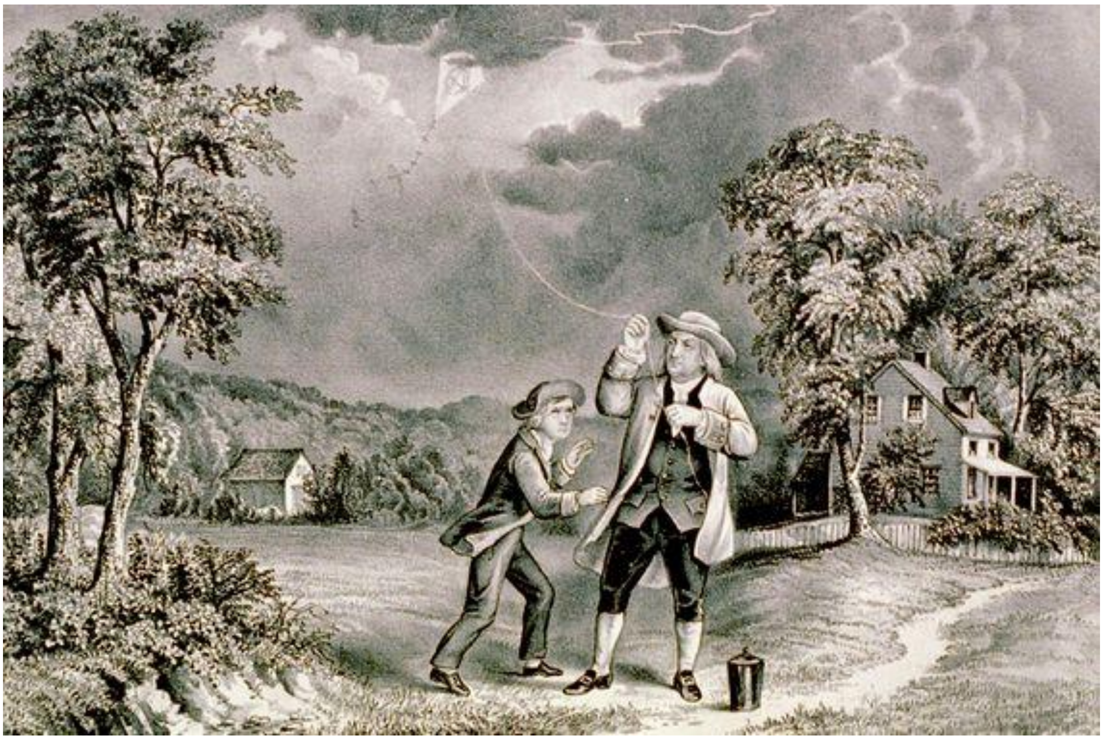

Figure 3: Franklin's experiment with a kite [17]

Karl Berger was a Swiss scientist who spent his entire life studying electrical discharges caused by lightning. The data he collected and the lightning parameters he devised are still in use today. Researchers from all over the world are currently recording and analysing flashes at their experimental workstations and making use of satellites to collect lightning data all over the world. The use of rockets to artificially trigger lightning was proposed by Gianni Battista Beccaria in 1753, and it is still used today for research [16].

2.3 Modern Lightning Protection Research

When lightning strikes a building, the resultant current and voltage transients can have a variety of harmful repercussions. The current flowing in a building's columns and beams generates electromagnetic fields, which couple with the components of electrical and electronic systems, causing material damage, equipment malfunction, and information alteration. When lightning strikes a building or close to it, the local earth potential rises to a dangerously high level. As a result, all equipment within the building is subjected to the same high earth potential. Other nearby buildings, even those next doors, will have a significantly lower potential [18].

For nearly 20 years, new generation devices have been on the market. Early streamer emission terminals (ESE) are outfitted with unique equipment that should cause the upward streamer to be emitted a little earlier than traditional rods. The purported protective zone and the physical mechanism of ESE terminals were never proven and were not recognised by scientific authorities [19] [20]. In addition, the producers of these systems have failed to provide any independent studies that may demonstrate that their devices have been field tested. Despite the fact that they have been doing laboratory and field studies all around the world for nearly three decades, this remains a mystery and has led to many buildings being damaged by direct lightning strikes, causing life-threatening concerns [21].

In contrast, ESE terminals have the same properties as conventional Franklin rods. The breakdown impulse voltage of configurations having a grounded active terminal is identical to the breakdown impulse voltage of configurations containing a grounded Franklin rod. This demonstrates that the protective zones of active terminals and Franklin terminals are the same at laboratory distances [22]. No experimental data exists to support the claim that an ESE air terminal can shield a wider area of space than a standard rod that is arranged in a similar manner and grounded and is the same height [23]. A typical ESE device is depicted in Figure 4 and can vary in shape and size depending on the manufacturer.

Figure 4: Typical ESE Device [24]

2.4 Results of Lightning Strikes

Lightning is one of the most powerful and spectacular natural phenomena that mankind has ever encountered. There are approximately 3 billion lightning flashes occurring around the world every year. Lightning strikes the ground from time to time, causing injuries and in extreme cases, death [25]. There are different ways in which lightning can interact with humans by means of: a direct lightning strike, side flashes, step and touch voltages, subsequent strikes, connecting leads and shock waves [26]. Figure 5 depicts a house that was struck by direct lightning, causing catastrophic structural damage and a failure of electrical and electronic systems. Fortunately, no one was inside the house at the time [27].

Figure 5: Direct lightning strike damage to house [27]

Direct lightning strikes represent only 3 to 5 percent of deaths, whereas GPR accounts for 50 to 55 percent because of the difference in voltage between the person's feet, causing a current to circulate through the body [4]. Compared to ground currents, direct lightning strikes only account for a small proportion of deaths, as shown in Figure 6.

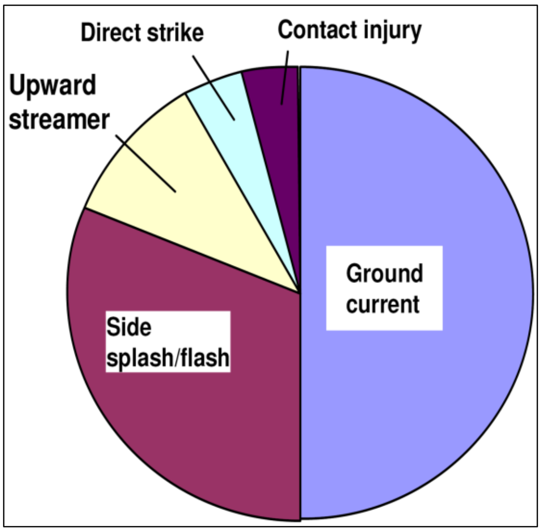

Figure 6: Distribution of lightning injury mechanisms [28]

Figure 7 depicts a case in which cattle were killed by a direct lightning strike to the metal feeder that resulted in a GPR and the creation of a potential difference between the ground and any other point of the cattle touching the ground. Touch potentials were present, which caused a current to flow through the cattle from the contact point to the ground, causing their death.

Figure 7: Cattle killed by a lightning strike that hit the metal feeder [29]

Step potentials are caused by a lightning strike to the ground, which causes a rise in ground potential. It is located between a person's feet, which causes an impulse to circulate through the body due to a potential grading effect. Figure 8 depicts the death of deer caused by a lightning strike to the ground, which created a step potential between the feet. Due to the impact of heat dissipation, the current path through or close to the eyes of the deer that was bleeding from the eyes may have crushed capillaries. As the deer keeps its face in contact with or close to the ground, the current may enter through the legs and exit through the face [30].

Figure 8: The death of deer in the incident caused by an indirect lightning strike [30]

2.5 Lightning Strike Research

A lightning study was conducted on two regional hospitals in Belgium that were struck by lightning over the course of a month. The first hospital, which had 236 beds, suffered a direct lightning strike to the building, resulting in a power peak and temporary failure of the standard power supply. There was no direct impact on the hardware observed and the issue was resolved by restarting the computer servers. The second hospital, which had 436 beds, had a lightning strike on the premises and experienced problems due to electromagnetic fields. The main failures were communication and electronic systems. Days after the strikes, problems with product line engineering software as well as network connections controlling the technical support system occurred. Up to 50 percent of direct lightning currents can be spread over different conductive elements in the building, even with a lightning rod and that led to this induction experienced by lightning [31]. The 50 percent lightning current split over metallic materials in the presence of a LPS has been questioned before, as there is no standing research substantiating this statement. This can only be justified by conducting a lightning simulation with advanced earthing and lightning software.

Another study showed that the magnetic field strength through a structure due to a direct lightning strike is greatly affected by changes in the soil resistivity [32]. This study shows that soil resistivity greatly affects the magnetic field strength through tall structures. The results show that the lowest resistivity value produces a higher magnetic field peak.

A third study showed that when using a standalone structure, it is emphasised to keep a 20 cm safety distance between any human body and the LPS components to avoid dangerous touch potentials and the possibility of arching [33]. The study was simulated by Ansys HFSS, a 3D electromagnetic (EM) simulation software, to show the separation distance through the LPS using three different materials. It is observed from the study that copper had the least separation distance to be kept from any conductive parts. The study was done with a lightning waveform that had a 20 kA negative first stroke with a font duration of 5.5 µs and a stroke duration of 75 µs. When considering a first negative impulse with a frontal rise duration of 1 µs and a stroke duration of 200 µs, the lowest level of protection measures is a class of LPS III or IV with a peak current of 50 kA. For analysis purposes, a frontal duration of 1.82 µs with a stroke duration of 285 µs must be used for a first negative impulse current shape [15].

This study seeks to verify these results by using three unique buildings located in the Free State province of South Africa by simulating the current split over an external LPS and in addition, this would also verify the lightning current split percentage over metallic materials. The safety separation distance between a human and the LPS components was calculated in accordance with SANS 62305 requirements and the results will then be verified by using lightning and earthing simulation software.

2.6 Different Types of Lightning Protection Systems

2.6.1 Protection Angle Method

In 1823, Gay-Lussac stated that a lightning rod effectively protects against a lightning strike in a circular space around it with a radius twice the rod's height [34]. Lodge later revised the definition of the zone of protection [35], which Golde reproduced and discussed [36]. The vertical conductor's angle of protection is defined as the cone's apex angle. The cone of protection concept, as shown in Figure 9, could be used to locate lightning conductors on a building. It should be noted that the greater the separation between adjacent lightning conductors located on the structure, the smaller the angle of protection assumed in the analysis.

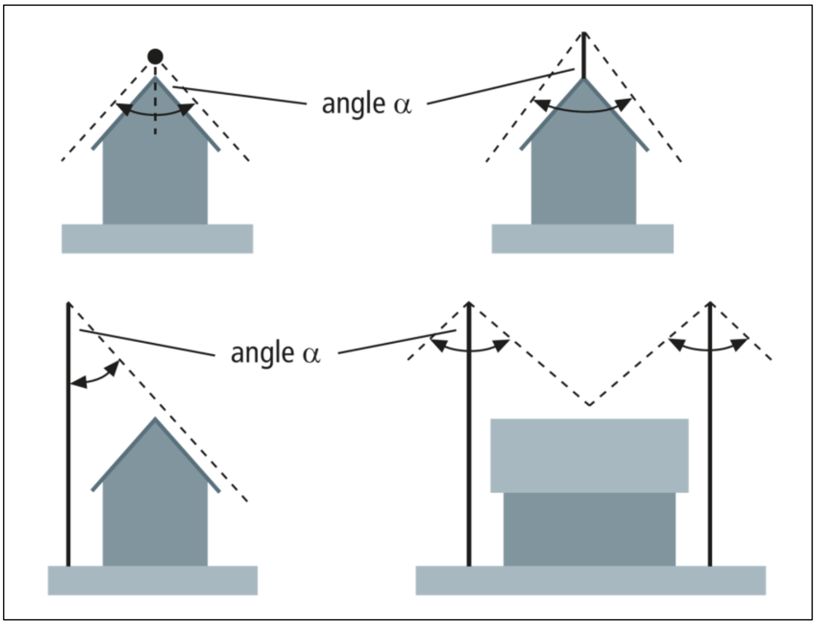

Figure 9: Volume protected by an air-termination conductor [12]

The protective angle method expresses a lightning rod as a protected area around it, with the tangent equalling the ratio of the horizontal extension of the protection to the lightning rod's height. This method has a limitation in that it can only be used to calculate simple structures.

Figure 10 depicts the protective angle air-termination system for LPSs' ranging from class I to class IV. The height is measured from the top of the air-termination rod to the earth-termination system and the angle remains constant for heights of less than 2 m.

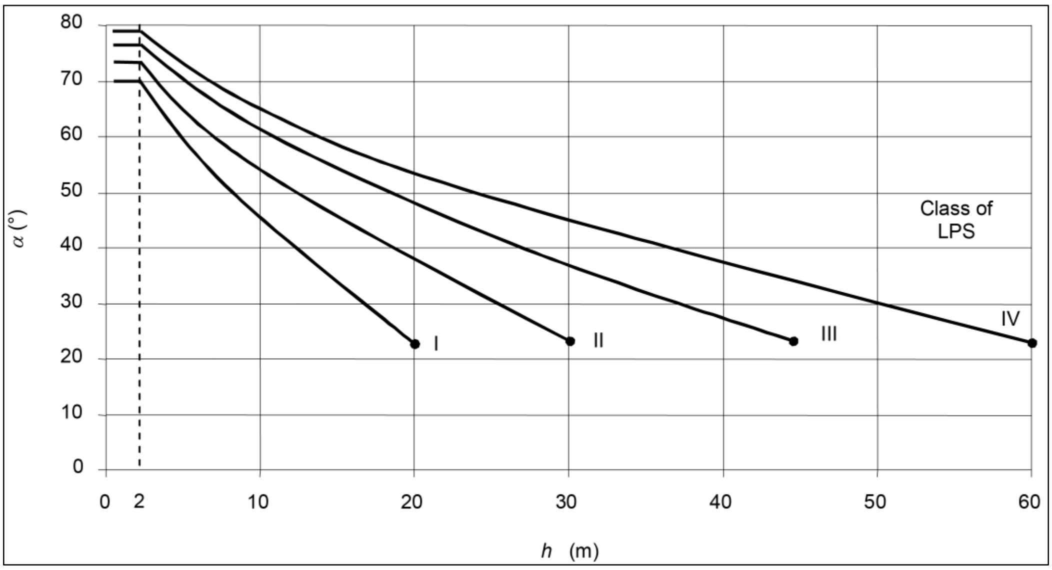

Figure 10: Protective angle air-termination system [37]

2.6.2 Rolling Sphere Method

The rolling sphere method was first introduced in the Hungarian Lightning Protection Standard in 1962 [38]. As shown in Figure 11, the rolling sphere method entails imagining a sphere with a radius equal to the final striking distance that is proportional to the peak current value of the strike rolling on the volumes of the structures to be protected against direct lightning strikes.

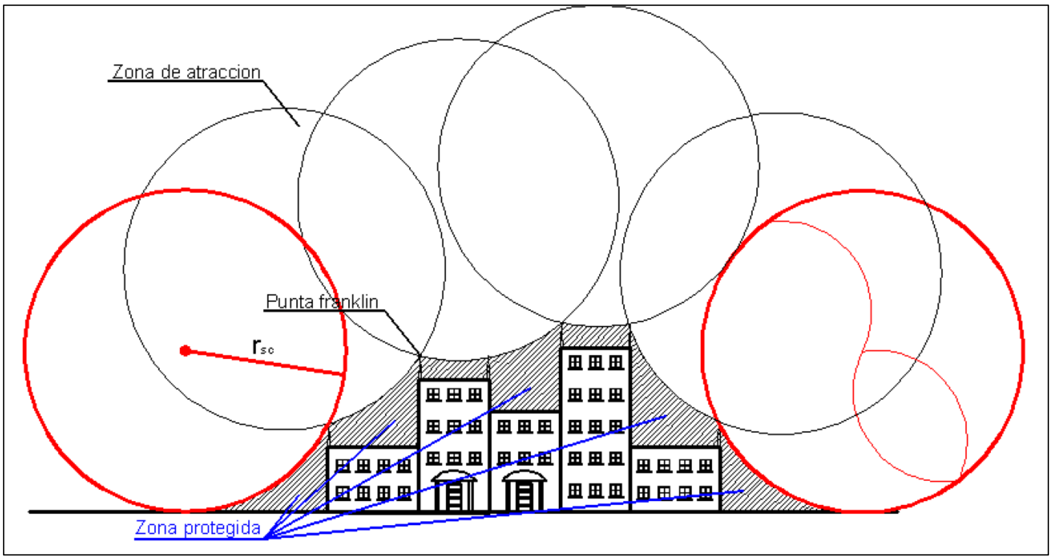

Figure 11: Rolling sphere method visualisation [39]

The rolling sphere method is based on the Electro-geometric Model, which is a technique for determining the lightning safety distance between lightning strikes and the air-termination rod [40]. In Table 2, the rolling sphere radii for an air-termination system are shown from a class of LPS I to IV, with the class of LPS I being the most effective LPL.

Table 2: Rolling sphere radii air-termination system [14]

Class of LPS	Rolling Sphere Radius (m)
I	20
II	30
III	45
IV	60

The main advantage of the rolling sphere method, according to its proponents, is its ease of use. This is true for simple structures, but for more complex structures, it is nearly impossible to apply by hand, necessitating sophisticated 3D numerical modelling software [41].

2.6.3 Mesh Method

In 1838, Maxwell proposed that a LPS increases the likelihood of a building being struck by lightning, and that encasing a building in a Faraday cage is the best way to protect it from lightning strikes [42]. As shown in Figure 12, the Faraday cage concept, also known as the mesh method, is the best way to protect a building from lightning strikes.

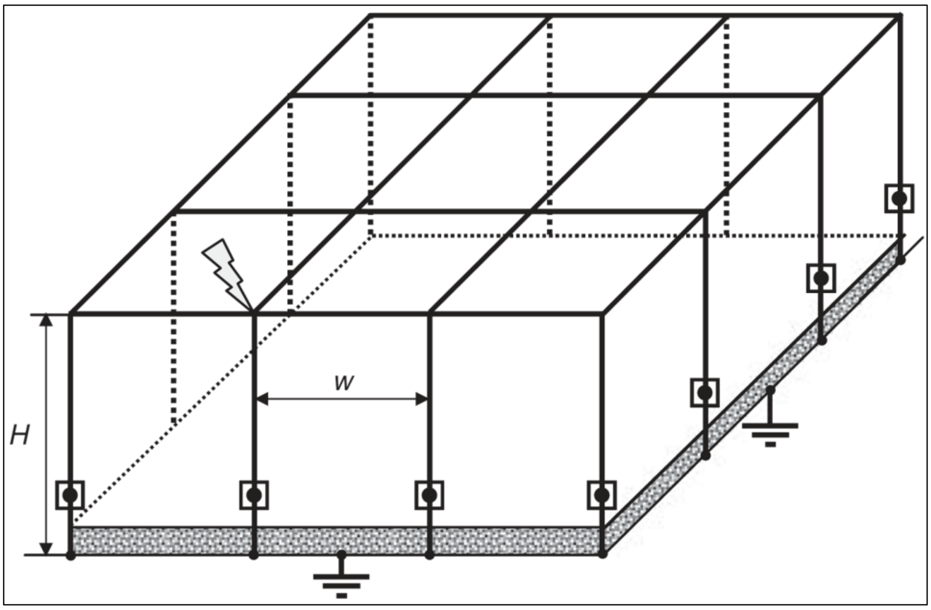

Figure 12: Meshed air-termination system [37]

In Table 3, the meshed air-termination size is shown from class I to IV LPSs' ranging from 5 x 5m to 20 x 20m. Figure 12 depicts the mesh size implementation, where the symbol 'w' represents the distance between each conductor that would be used for the air-termination system in accordance with the respective LPL.

Table 3: Mesh size [14]

Class of LPS	Mesh Size (m)
I	5 x 5
II	10 x 10
III	15 x 15
IV	20 x 20

2.7 Lightning Risk Analysis

A risk analysis is an essential component of the LPS for each structure that will be occupied by people. It serves as a foundation for decisions about the level of protection required and the risk associated with the structure. It also provides a solution for whether to protect a building from lightning.

A risk analysis was performed on an HV/LV substation and a temporary security cabin, according to a study conducted in South Africa. Because of the well-designed earthing system that connects all metal parts to provide equipotential bonding, the HV/LV substation did not require any additional lightning protection measures. The security cabin, on the other hand, required additional lightning protection in the form of surge protection devices (SPDs). As a result, even if the structure is a temporary installation or plays a minor role, a proper risk analysis must be performed [11].

According to another South Asian study, fewer than half of the vendors have hired professionals capable of conducting a risk analysis and as a result, an assumption was made that could lead to unnecessary or even hazardous selections [43]. Therefore, it is highly recommended to conduct a risk analysis where possible. In Chapter 3 of the study, an overview and methodology of the lightning risk analysis were conducted, where three predefined buildings were chosen due to their unique shapes and the different hours that each building would be occupied by people in a year in the event of a lightning strike.

2.8 Lightning Protection System Design

The results of a lightning risk analysis can be used to design an adequate LPS in accordance with the three methods discussed in Section 2.5. Because of the complexity of the shapes of the structures constructed, the rolling sphere method is the most commonly used method in practice today. The protective angle is appropriate for simple structures because it is designed to be the most time-efficient and does not require specialised drawing software. Because of the complex shapes of the three predefined buildings selected, the rolling sphere method would be the most appropriate method for this study.

After determining the air termination rod placement, down conductors should be implemented to create a path for the current to flow and the quantity is determined by the class of LPL selected. Figure 13 illustrates the current split throughout the system, showing the importance of an adequate LPS. Reducing the number of down conductors will significantly increase the electromagnetic forces that are acting on the conductors, as there would be insufficient conductive paths for the current to distribute.

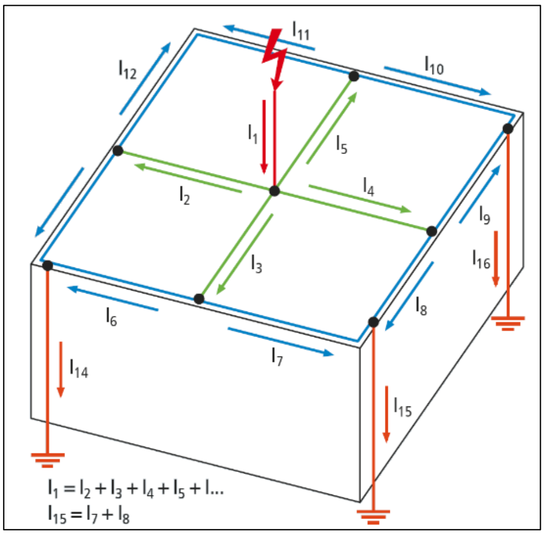

Figure 13: Kirchhoff's law applied to a basic structure [12]

The protection measures consist of an external LPS that will create a low resistance path for the lightning current to flow to the earth termination system and surge protection measures to provide protection against lightning electromagnetic pulses (LEMP) and lightning currents entering the building. Pluggable devices with electronic circuits should be rated with an impulse withstand voltage against an overvoltage of at least 1.5 kV [44]. This shows that equipment is always at risk of lightning strikes and, therefore, adequate protection measures are crucial.

2.9 Software

2.9.1 Lightning Risk Analysis

A lightning risk analysis can be conducted in accordance with SANS 62305-2 requirements, as this provides an overview on how to calculate the risk mathematically and implement protection measures to reduce the risk to a tolerable value. Based on the lightning protection standard, the software provides a simple solution that can be used to conduct lightning protection zones that are not clearly defined in the standard. Therefore, lightning risk analysis software was introduced to obtain consistency and simplicity.

For this study, the DEHNsupport toolbox was selected as it offers additional modules that can be used to evaluate the potential risk for structures. The DEHNsupport toolbox software was one of the first to be released in the market, and DEHN has over 111 years of experience in surge and lightning protection, making them a market leader [12].

There is a plethora of lightning risk management software on the market, including Lectrotech [45], ABB's Furse StrikeRisk [46] and others, that use the same principle to calculate lightning protection measures in accordance with SANS 62305. This software, however, requires additional licenses, which is why they were not used in this study.

2.9.2 Lightning Simulation

Due to availability, the software XGSLab, an electromagnetic simulation for power, grounding, and lightning protection systems, will be used for the lightning simulation. The XGSA_TD module of XGSLab that will be used is a multipurpose engineering software for the time domain analysis of conductor networks, including soil resistivity analysis and Fourier analysis, with a maximum bandwidth of about 100 MHz. This module can take into account transients with well-known equations such as Double Exponential, Pulse, or Heidler, which are transients used in electromagnetic compatibility studies [13].

CDEGS (Current Distribution, Electromagnetic Fields, Grounding, and Soil Structure Analysis) is a powerful set of integrated software tools designed to accurately analyse a variety of electromagnetic-related problems encountered in all industries involving electric networks [47]. Given the need, this software would necessitate a licence, which would be prohibitively expensive to pursue for this study.

2.10 Summary

The history and necessity of a lightning risk analysis were illustrated in this chapter by incorporating previous studies and their findings. The history and methodology of lightning protection design methods were introduced, distinguishing the various types of methods that could be used for this study and emphasising the importance of conducting a design.

The similarity and approach of this study to previous studies were validated by simulating the current split percentage over a LPS on three predefined buildings. In addition, the current and potential distribution of lightning will be simulated to determine the appropriate separation distance to maintain to prevent arcs between metallic paths.

In Chapter 3, a lightning risk analysis for each structure was performed to show the type of risk associated with the source of damage that can be expected based on theoretical calculations performed by the DEHNsupport toolbox software. The class of LPS obtained from the software will be used to design a 3D external LPS that will be used to conduct the lightning simulation.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

Chapter 2 was committed to presenting the literature review of the study. The history and methodology of lightning protection design methods were introduced, distinguishing the various types of methods used for this study, thereby emphasising the importance of implementing a LPS.

This chapter examines the methodology for a lightning risk analysis in conjunction with a lightning simulation. The purpose of this chapter is to outline the methodology that was followed in the study. Figure 14 depicts the remaining study process by providing an overview of each topic explored.

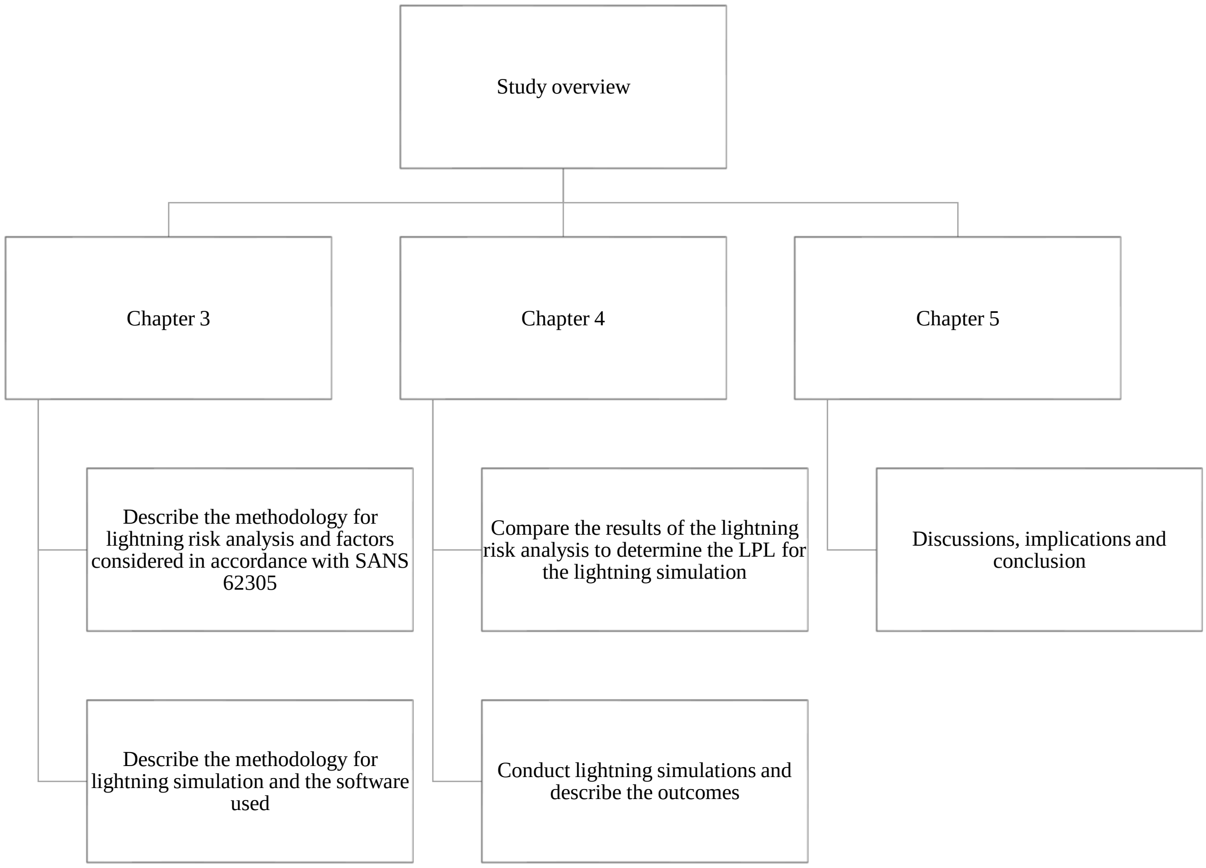

Figure 14: Study overview flow diagram

The methodology for conducting the lightning risk analysis is detailed in Section 3.2.1, while Section 3.2.2 details the factors used to calculate the LPL for each building used in the lightning simulation in accordance with SANS 62305 requirements. The lightning simulation methodology is described in Section 3.3.2, where the buildings are modelled to conduct the lightning simulation.

3.2 Lightning Risk Analysis

The aim of a risk analysis is to reduce the risk to an acceptable level, R_T, by an economically sound selection of protection measures. A risk analysis was conducted for the areas identified in Figure 15 by the red boxes due to the motives mentioned in Chapter 1.6.

Figure 15: Areas identified for the lightning risk analysis

3.2.1 Overview

A lightning protection risk analysis would be the first step and is extremely important for establishing the source of lightning damage and should be developed for each structure that will be occupied by people, regardless of the insignificance of the structure [11].

The sources of lightning damage are classified into four types, namely: direct lightning strikes to a structure (S_1), indirect lightning strikes to a structure (S_2), direct lightning strike to the incoming power lines (S_3) and indirect lightning strikes to the incoming power lines (S_4) [7].

The types of losses describe the physical impact that would occur from lightning events where the most severe loss is the loss of human life (R_A and R_U), followed secondly by an outbreak of fire (R_B and R_V). The economic losses (R_C, R_M, R_W and R_Z) are mainly due to direct lightning strikes and indirect lightning strikes that accumulate into LEMP that can damage any electrical or electronic equipment [7].

The average lightning ground flash density can be estimated for a specific area by using Equation 1, where the lightning ground flash density results in 10% of the thunderstorm days obtained from an isokeraunic map [7].

$$N_G \approx 0{,}1 \times T_D \tag{1}$$

where:

N_G: Lightning ground flash density (flashes/km²/year)
T_D: Thunderstorm days per year

According to the SAWS data, Bloemfontein has a lightning ground flash density of 7.4 flashes per square kilometre per year, which falls within the category of severe to extreme lightning risk [6]. Buildings in this region are at risk, which could result in catastrophic damage. These damages can cause human injuries, fires, explosions, mechanical and chemical reactions and the failure of electrical and electronic systems [7].

The frequency of annual lightning activity coupled with the size of the site creates the possibility of the loss of human life and damage to the structures, which is considered an economic loss. The probabilities of damage and the relevant loss values are defined and evaluated in the risk analysis of the structures.

The frequency of direct lightning strikes per year to the structure can be calculated by using Equation 2, where the collection area and location factor of the structure can play an important role. The location factor is unique for each building, where it considers all the surrounding objects and buildings. A direct lightning strike considers the relative height of the building with respect to the surrounding objects or the ground within a distance of three times the height of the structure.

$$N_D = N_G \times A_D \times C_D \times 10^{-6} \quad (2)$$

where:

N_D: Direct lightning strikes to the structure
N_G: Lightning ground flash density (flashes/km²/year)
A_D: Collection area of the structure (m²)
C_D: Location factor of the structure

Equations 3 and 4 define the collection areas for a structure. As seen from Equation 2, the expected direct lightning strikes to the structure will be different for each structure and therefore, a risk analysis should be performed for each structure individually to obtain accurate results.

$$A_D = L.W + 6.H(L + W) + 9.\pi.H^2 \quad (3)$$

$$A_M = 2 \times 500 \times (L \times W) + \pi \times 500^2 \quad (4)$$

where L, W and H are expressed in metres.

Equation 5 can be used to calculate the indirect lightning strikes per year for each building. An indirect lightning strike extends to a distance of 500 m from the structure's perimeter [7].

$$N_M = N_G \times A_M \times 10^{-6} \quad (5)$$

where:

N_G: Lightning ground flash density (flashes/km²/year)
A_M: Collection area of flashes striking near the structure (m²)

Figure 16 shows the basic concept of the boundaries surrounding a structure and that a direct strike to the structure extends to three times the height of the structure. It is seen that the height of a structure can have a significant impact related to a direct lightning strike. When a service cable enters this zone, the entire distance should be considered up to the next connecting node. A node can either be classified as an HV/LV transformer or a power substation, where there is a point on the line from which onward surge propagation can be assumed to be neglected [7].

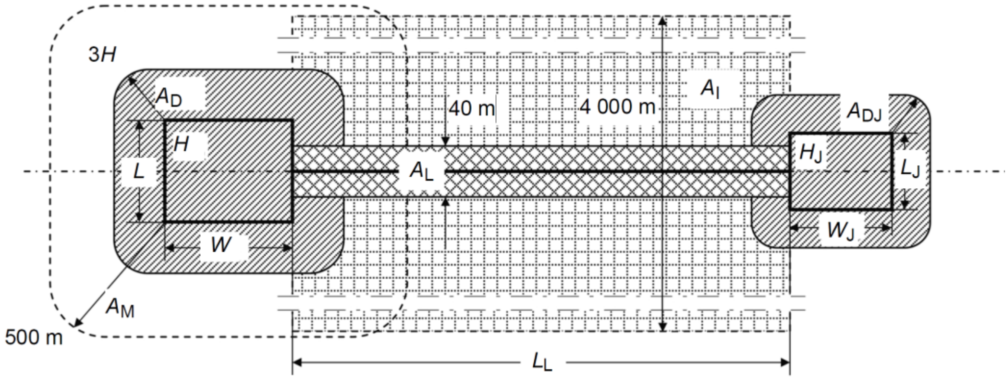

Figure 16: Collection areas identified [7]

When the distance from the structure is unknown, the lightning standard specifies assuming a distance of 1 000 m as this is the maximum distance that can impact a lightning risk analysis [7].

The frequency of annual lightning activity, combined with the size of the site, raises the possibility of loss of human life and structural damage, both of which are considered economic losses. In the risk analysis of the structures, the damage probabilities and relevant loss values are defined and evaluated. The following results were obtained by applying the above theory to the three predefined structures in the lightning risk analysis software.

3.2.2 Factors selected for the study

Table 4 depicts the relevant risks and values that can be tolerated, which were chosen based on the type and function of the structures, with only the risk of human life and economic value being relevant, as there is no risk of cultural heritage or public service. The tolerable risks, R_T, were established by determining the risks. If the calculated risk values of the structures exceed the permissible risk values, adequate risk mitigation actions must be taken.

Table 4: Applicable risks for the buildings

Risk	**Description**	**R_T (y^{-1})**	**Relevant Risks**
R_1	Risk of loss of human life	$1x10^{-5}$	☒
R_2	Risk of loss of service to the public	$1x10^{-3}$	☐
R_3	Risk of loss of cultural heritage	$1x10^{-4}$	☐
R_4	Risk of loss of economic value	$1x10^{-3}$	☒

The ground flash density (N_G) is the basis for a risk analysis per SANS 62305-2 requirements. It defines the number of direct lightning strikes as N_G/km²/year. The lightning ground flash density value determined for the geographic location of the buildings from the SAWS document were 7.4/km²/year.

The environment surrounding the structures is an important factor in determining the number of direct and indirect lightning strikes. Based on satellite imagery of the area and the provided drawing documents, the structures were determined to be surrounded by objects of the same height or smaller. The selection factor used for all three buildings is shown in Table 5.

Table 5: Structures location factor

Structure location factor – Relative location	**C_D**	**Relevant Factors**
Structure surrounded by higher objects such as trees, etc.	0,25	☐
Structure surrounded by objects of the same height or smaller	0,5	☒
Isolated structure: no other objects in the vicinity	1	☐
Isolated structure on a hilltop or a knoll	2	☐

The collection area relevant to direct and indirect lightning strikes to the incoming lines defined for the structures is calculated from the length of the lines. It represents the total area susceptible to direct and indirect lightning strikes for the lines. Supply lines include lines from Zone 0_A into Zone 0_B. Zone 0_A is where the danger is caused by the direct lightning flash and the complete electromagnetic field of lightning. The internal systems may be exposed to a full surge of lightning current. Whereas in Zone 0_B, internal systems may experience partial lightning surge currents [48].

The incoming power line reduction factor was selected as HV/LV for the Loch Logan Park and Free State Provincial Building. The length of the chosen conductor is shown in Table 6, in accordance with SANS 62305 requirements when the conductor's length is unknown. The reduction factor for the Boet Troskie Hall conductor was selected as an LV supply and the length is shown in Table 7.

Table 6: Collection area of the HV/LV power lines

Incoming Power Line	**Details**
Conductor Length	1 000 m
Collection Area for Direct Strikes	40 000 m²
Collection Area for Indirect Strikes	4 000 000 m²

Table 7: Collection area of the LV power lines

Incoming Power Line	**Details**
Conductor Length	250 m
Collection Area for Direct Strikes	10 000 m²
Collection Area for Indirect Strikes	1 000 000 m²

On average, a person spends around 6 651 hours per year at home, compared to 2 209 hours at work when considering 42.5 hours per week [49]. Table 8 shows the number of hours per year chosen for the study when people are present in the buildings.

Table 8: Human life present in the buildings

Building	**Hours per year**
Loch Logan Park	6 651
Free State Provincial Government Building	2 209
Boet Troskie Hall	2 209

The risk reduction factor for the risk of fire or explosion selected for each building is shown in Table 9. The values were obtained from a fire load study based on a C/VM2 verification method conducted in accordance with New Zealand regulations [50]. The factors chosen in Tables 9 to 12 are in line with the values specified in the SANS 62305 standard.

Table 9: Risk of fire reduction factor

Building	Type	Reduction factor
Loch Logan Park	Low Risk	0.001
Free State Provincial Government Building	Normal Risk	0.01
Boet Troskie Hall	Low Risk	0.001

The human life factors were selected for each building based on the categories as defined in the standard. A normal fire is classified as having a specific fire load density of between 400 MJ/m² and 800 MJ/m², whereas a low risk of fire consists of a specific fire load density of less than 400 MJ/m² [7]. Table 10 depicts the human life factors that contribute to a fire in each building.

Table 10: Human life factor for fire

Building	Type	Factor for Fire
Loch Logan Park	Hotel	0.1
Free State Provincial Government Building	Commercial	0.02
Boet Troskie Hall	School	0.1

A low level of panic was selected for the Boet Troskie Hall building as it complies with the requirements of a structure that is limited to two floors and the number of people is not greater than 100. The economic value factors were selected for each building based on the categories as defined in the standard. Table 11 depicts the economic value loss in a structure due to physical damage caused by a fire.

Table 11: Economic value factor for fire

Building	Type	Factor for Fire
Loch Logan Park	Hotel	0.2
Free State Provincial Government Building	Commercial	0.2
Boet Troskie Hall	School	0.2

For each building, the economic value based on the damage factor for an overvoltage was chosen. This was based on the categories defined in the standard that would result in a failure of internal electronic and electrical systems. Table 12 shows the overvoltage factor that was selected for each building.

Table 12: Economic value damage factor for an overvoltage

Building	**Type**	**Factor for Overvoltage**
Loch Logan Park	Hotel	0.01
Free State Provincial Government Building	Office	0.01
Boet Troskie Hall	School	0.001

3.3 Lightning Simulation

A lightning simulation is an advanced and newly developed approach that was introduced in the 20th century and is used for research and development purposes that focus on the fundamentals of lightning protection.

3.3.1 Overview

Lightning can be divided into four main types: intra-cloud, cloud-to-cloud, cloud-to-air and cloud-to-ground. Among all the mentioned types, the cloud-to-ground type is the most dangerous [51] and out of all lightning flashes, only 33 percent will be cloud-to-ground flashes, while 66 percent will be intra-cloud or cloud-to-cloud flashes [52]. Based on the development and field evaluation of a lightning earth-flash counter study, it appeared likely that the propagation of electromagnetic waves from most cloud-to-ground flashes in South Africa ranged from 5 to 10 kHz [53]. The exact expected frequency of a lightning strike depends on the position of a structure within the space to be protected, and such a probability could not be determined by a geometrical definition of the protected space alone.

Lightning always strikes a physical object and never an empty space [54] and there are multiple strokes in 70 percentage of lightning to ground flashes [55]. A lightning strike consists of two types of lightning flashes to earth: an upward (earth-to-cloud) leader or downward (cloud-to-earth) leader and a streamer. The luminous diameter of the stepped leader can range between 1 to 10 m [56].

When the leader has drawn close to the streamer, it causes the strength of the electric field of objects on the surface of the earth near the leader to increase [57]. According to the classic theory of discharge, the sea level equivalent electric field required for lightning initiation is expected to be in the order of megavolt per metre (MV/m). The breakdown field strength is suggested to be 3 MV/m (at sea level) and the transition field streamer to the leader is suggested to be 2 MV/m [58].

The impulse part of the lightning current is classified into three types according to the wave profile: negative first stroke, negative subsequent stroke and positive stroke [59]. Negative cloud-to-ground discharges account for almost 90 percent of all recorded lightning. Positive lightning is considered much more damaging than negative lightning, as large amounts of energy tend to discharge to the concentrated ground contact point for more extended periods of time [60].

Lightning can be classified into two types of waveshapes: direct lightning strikes with a 10/350 µs waveshape and indirect lightning strikes with an 8/20 µs waveshape, also known as induced surges. These values indicate that a lightning current is an impulse that peaks at 10 µs and decays to 50% of its original value in 350 µs [15]. The meaning of a 10/350 µs impulse waveshape is depicted in Figure 17.

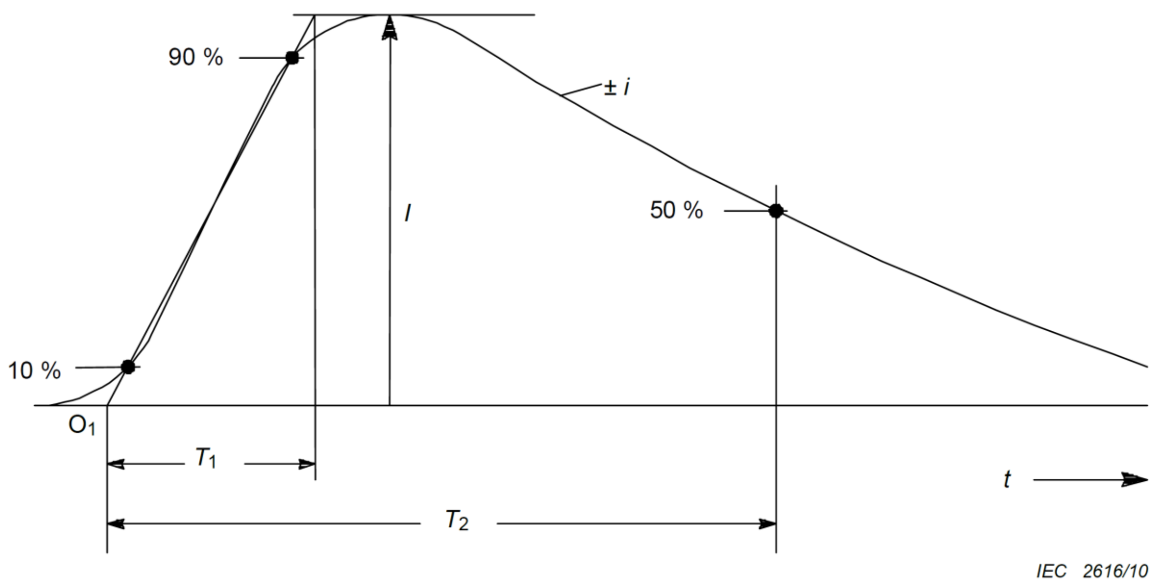

Figure 17: Illustration of a 10/350 µs waveshape [15]

where:

O1: Virtual origin

I: Peak current (kA)

T1: Front time (µs)

T2: Time to half value (µs)

A first positive impulse (10/350 µs), first negative impulse (1/200 µs) and subsequent negative impulse (0.25/100 µs) can all be defined using Equation 6. This is primarily used to conduct analysis as a time function of lightning current.

$$i = \frac{I}{k} \times \frac{(\frac{t}{T_1})^{10}}{1 + (\frac{t}{T_1})^{10}} \times \exp\left(-\frac{t}{t_2}\right) \quad (6)$$

where:

I: Peak current

k: Correction factor for peak current

t: Time

T1: Front time constant

t2: Tail time constant

The parameters listed in Table 13 apply to the current shapes of the first positive impulse, the first negative impulse and subsequent negative impulses for various LPLs.

Table 13: Parameters of lightning current analysis [15]

Parameters	**First Positive Impulse**			**First Negative Impulse**			**Subsequent Negative Impulse**		
	LPL			LPL			LPL		
	I	II	III-IV	I	II	III-IV	I	II	III-IV
I (kA)	200	150	100	100	75	50	50	37.5	25
k	0.93			0.986			0.993		
T_1 (µs)	19			1.82			0.454		
T_2 (µs)	485			285			143		

Lightning can cause possible damage to a structure in various ways, namely [15]:

- Thermal effects, also known as resistive heating, are caused by an electric current flowing through a conductor's resistance or in the LPS;
- The amplitude and duration of the current, as well as the elastic characteristics of the affected mechanical structure, determine the mechanical effects caused by the lightning current and the severity of the damage;
- Combined effects, in which both thermal and mechanical effects occur at the same time in practice; and
- Sparking, which should be considered in flammable environments or when combustible materials are present.

When conducting a lightning simulation, there are three function models to consider: double exponential, Pulse and Heidler. The double exponential function is commonly used in experimental studies, but it cannot accurately represent a lightning current. This is because it unrealistically starts with the maximum current steepness at time t = 0, whereas the front of a lightning short-stroke current has a slowly rising portion followed by a fast current rise.

With the Pulse and Heidler functions, this disadvantage can be avoided. The SANS 62305 standard, in particular, uses the Heidler function as a representation of standard lightning short strokes. The formulas of the models are shown in equations 7 to 9 [13].

Double exponential: $$f(t) = \frac{\text{fpeak}}{k}\left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}}\right) \quad (7)$$

Pulse: $$f(t) = \frac{\text{fpeak}}{k}\left(1 - e^{-\frac{t}{\tau_1}}\right)^n e^{-\frac{t}{\tau_2}} \quad (8)$$

Heidler: $$f(t) = \frac{\text{fpeak}}{k} \frac{\left(\frac{t}{\tau_1}\right)^n}{1 + \left(\frac{t}{\tau_1}\right)^n} e^{-\frac{t}{\tau_2}} \quad (9)$$

where:

f_{peak}:	Peak value (1 for normalised function)
k:	Corrective factor of the peak value
n:	Steepness factor
τ_1:	Front time or rise time to peak parameter (µs)
τ_2:	Decay time or time to half value parameter (µs)

3.3.2 Methodology

The lightning simulation approach is composed of a time and frequency domain that was used to illustrate various aspects of the results. The time domain was used to depict the current distribution accurately, while the frequency domain was used to depict the potential distribution across the external lightning protection network graphically.

Time Domain

The lightning transient impulse does consist of multiple frequencies. For this simulation, approximately 167 different frequencies were selected based on the normalised frequency spectrum (Nyquist Frequency) [13]. The characteristics of the first negative strike for LPL III or IV may be found in SANS 62305-1.

When considering an LPL III or IV impulse, Figure 18 illustrates the simulated first negative waveshape in units of magnitude. The waveshape would peak at 50 kA on 1.82 µs and decay to half of the peak magnitude of 25 kA on 285 µs.

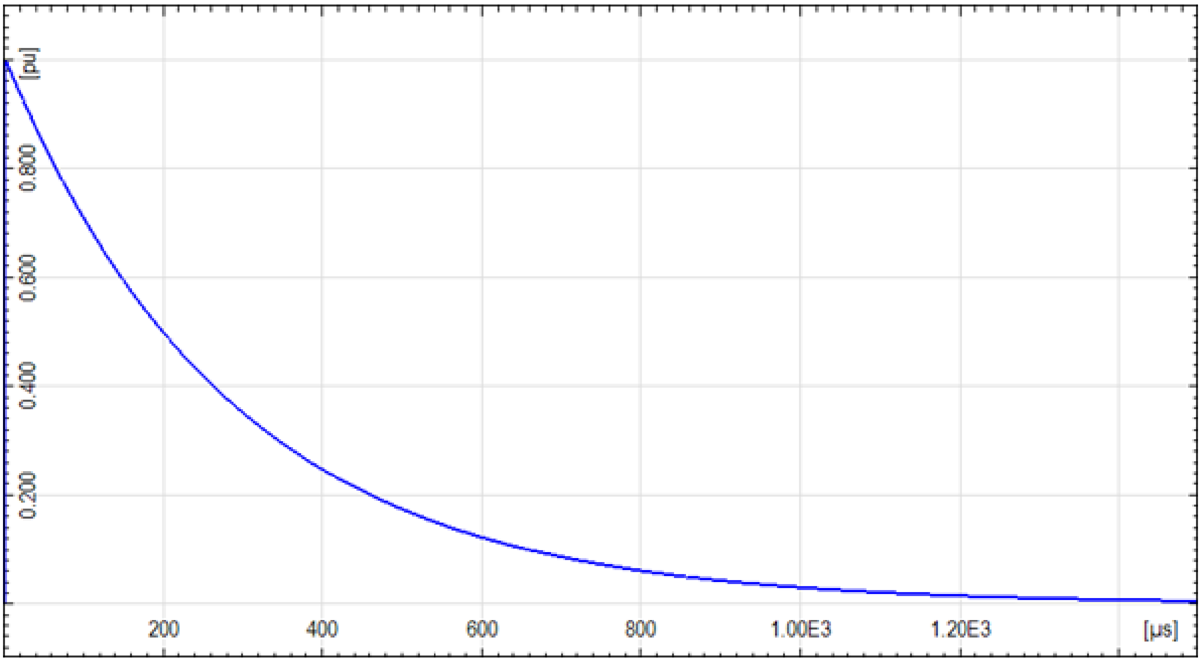

Figure 18: First negative waveshape used for time domain simulation

The impulse consisted of approximately 167 different frequency samples, which were selected based on the normalised frequency spectrum shown in Figure 19. The normalised frequency spectrum is based on the Fourier transform and converts the time domain to the frequency domain by utilising the specified frequency samples. It is then plotted in a unit of magnitude over a frequency spectrum. The highest peak unit would occur in the lower frequency range and would decay with increasing frequency range.

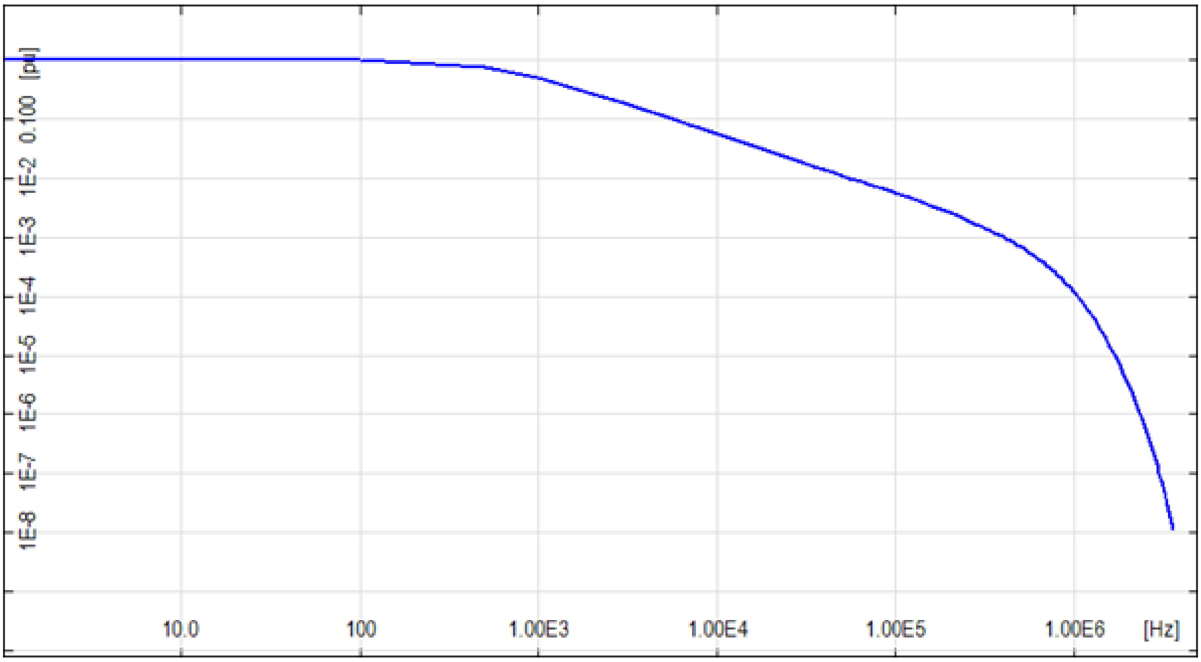

Figure 19: Normalised frequency spectrum

Frequency Domain

To evaluate the performance of a grounding system for an impulse/transient, calculations are performed in the frequency domain and converted back to the time domain. This is similar to lightning impulse and surge current transient calculations, which are characterised and measured in amplitude per microsecond (μs).

By only considering the rise time and the root mean squared (RMS) value of the peak current, sinusoidal waveforms can be used to represent an impulse for better graphical illustrations. This is only a graphical representation of the GPR and should not be used for complex calculations. This is an approximate approach, but it is occasionally useful for engineering purposes.

The fundamental concept is to represent the transient using a single frequency waveform with "equivalent" frequency and effective value. The equivalence of a transient function to a sinusoidal function is limited to a brief initial period. In any case, transient effects are primarily caused by the rising front. For detailed system analysis, time domain transient analysis (described in the following section) is to be used.

Equation 10 illustrates how to calculate the equivalent frequency and Equation 11 illustrates how to calculate the equivalent effective current [13].

$$f_{eq} = \frac{1}{4T_1} \qquad (10)$$

where:

F_{eq}: Equivalent frequency of the single frequency waveform (MHz)

T_1: Front time or rise time to peak of the transient (µs)

The equivalent effective current can be calculated as follows [13]:

$$I_{eff} = \frac{I_{peak}}{\sqrt{2}} \qquad (11)$$

where:

I_{peak}: Current peak of the transient (A)

I_{eff}: Effective current of the single frequency waveform (A)

SANS 62305-1 specifies a maximum impulse value of 50 kA for the LPL III or IV first negative strike. The RMS value of 35.4 kA, 250 kHz sinusoid should be used to model this as a representative sine wave for the first negative stroke. Figure 20 depicts a first positive strike in order to illustrate the concept that must be followed [61].

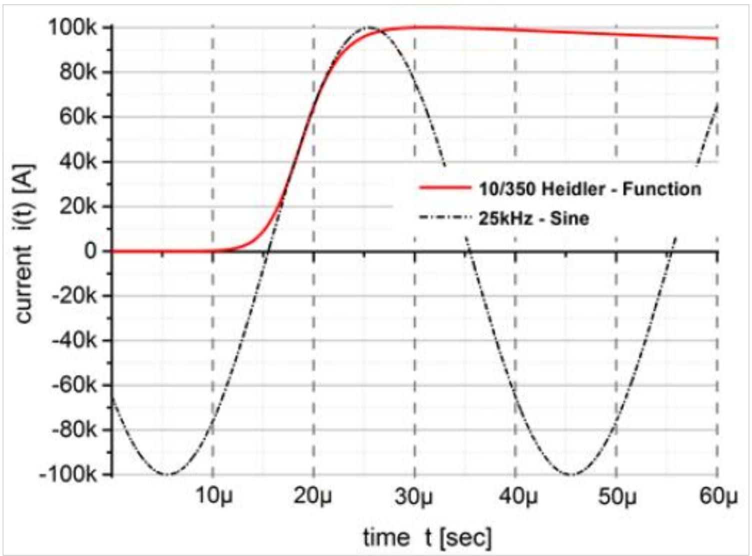

Figure 20: Representing an impulse using a sinusoid [61]

3.3.3 Constructed Soil Model

A uniform soil model is frequently used for preliminary calculations or calculations with a high frequency. At high frequencies, the penetration depth of electromagnetic fields into the soil is limited. This is because as frequency approaches infinity, the penetration depth tends to a constant value dependent on soil resistivity and permittivity, thus the results are unaffected by the soil resistivity of the depth layers.

While vertical changes are typically more significant than horizontal ones, it is critical to consider the grounding system's size when applying this concept correctly. In the case of small grounding systems, horizontal variations in soil resistivity have little effect on the soil model and a multilayer soil model is usually appropriate. In general, the soil structure varies in both vertical and horizontal directions, as illustrated in Figure 21 [13].

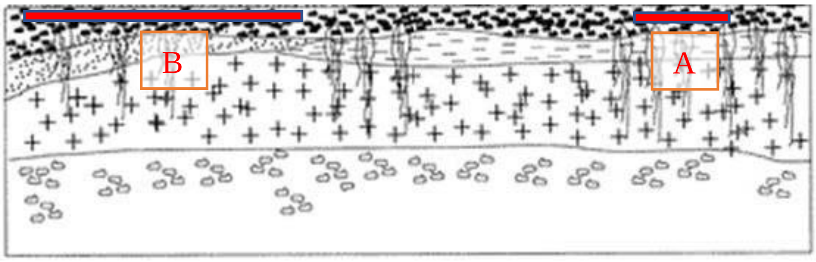

Figure 21: Small "A" and intermediate "B" soil structure and grounding system [13]

Due to access constraints, a uniform soil resistivity of 100 Ω.m was used for the lightning simulation. The soil model can be graphically interpreted, as shown in Figure 22.

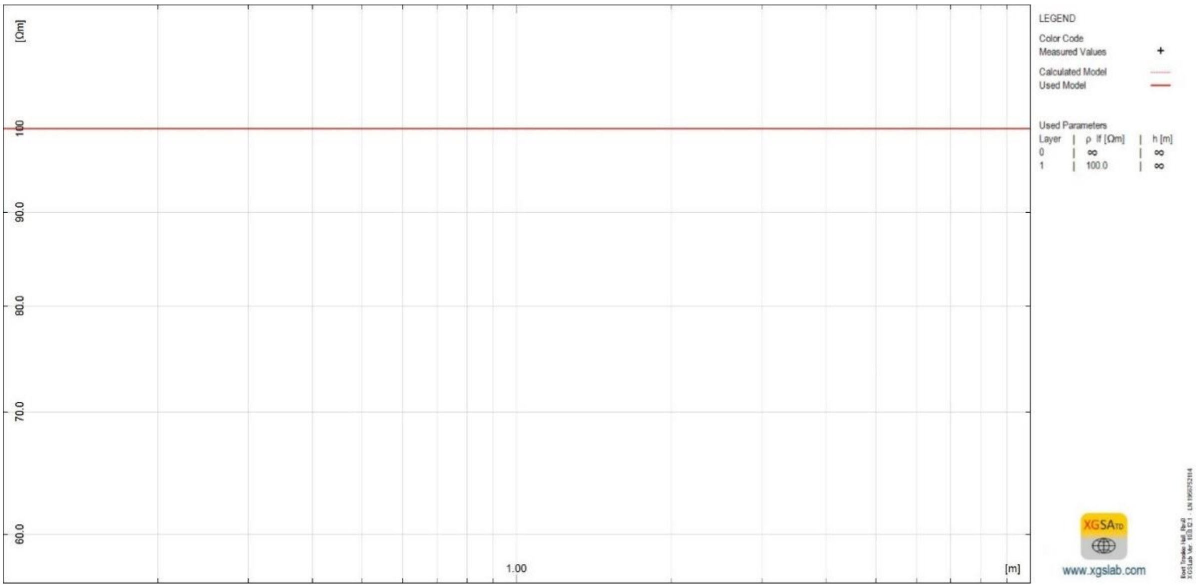

Figure 22: Soil model

The PEEC approach can incorporate circuit and electromagnetic theory into a single calculation model, making it adaptable and ideal for engineering applications. It can analyse complex scenarios with additional external parameters, including voltages, currents and impedances [13].

3.4 Proposed Lightning Protection System Design

3.4.1 Modelling Configuration

An air-termination system's interception efficiency is determined by the minimum lightning current parameters and the associated rolling sphere radius. The rolling sphere method can be used to determine the geometrical boundary of areas that are protected from direct lightning flashes. The rolling sphere radius 'r' (final jump distance) is correlated with the peak value of the first impulse current, according to the electro-geometric model and the relationship is given in equation 12 [15].

$$r = 10 \times I^{0.65} \tag{12}$$

where:

r:	Rolling sphere radius (m)
I:	Peak current (kA)

A proposed LPS design was carried out for each building, as shown in figures 23 to 25. Each structure was drawn in SketchUp, a 3D modelling computer program for drawing applications such as architectural, interior design, landscape architecture, civil and mechanical engineering. These models will be used in the lightning simulation study.

The outcomes of the risk analysis done on each building are shown in Chapter 4, detailing the risk of loss of human life and economic value during a lightning event. The measures are shown before and after any protection measures are implemented. The Loch Logan building and the Free State Provincial Government building were calculated to have a class of LPS III implemented as defined in the standard, SANS 62305, to reduce losses to a tolerable value. While an LPS was not required for the Boet Troskie Hall building, a class of LPS IV was developed for the purposes of the lightning simulation study.

3.4.2 Loch Logan Park Building

Figure 23 depicts the external LPS designed for the Loch Logan Park building. The structure necessitates at least 10 down-conductors, which were impractical to keep due to limited space. A total of six down-conductors were used in the simulation, with an earth electrode on each down-conductor.

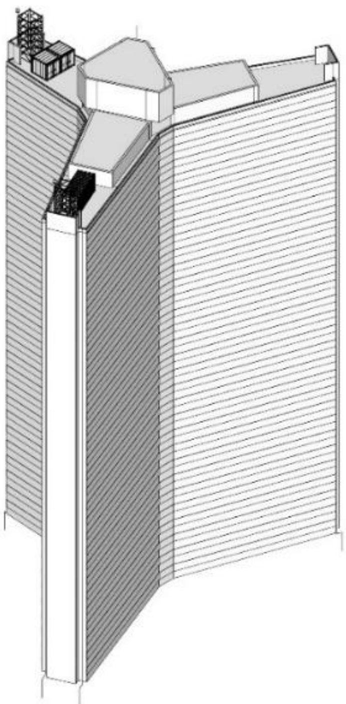

Figure 23: Loch Logan Park building

3.4.3 Free State Provincial Government Building

Figure 24 depicts the external LPS designed for the Free State Provincial Government building. The structure necessitates at least 16 down-conductors, which were impractical to keep due to limited space. A total of 10 down-conductors were used in the simulation, with an earth electrode on each down-conductor.

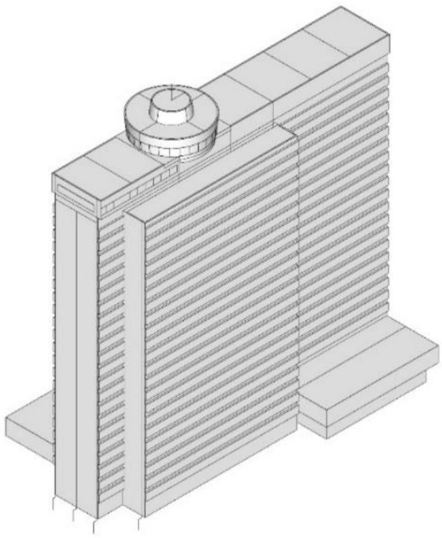

Figure 24: Free State Provincial Government building

3.4.4 Boet Troskie Hall Building

There are eight down conductors that run parallel with a spacing of 22 metres and are located at all corners of the octagon-shaped building. Although the risk analysis result showed that an external LPS was not required, it was included in the study in accordance with a class of LPS IV for the lightning simulation. Figure 25 depicts the external LPS for the Boet Troskie Hall.

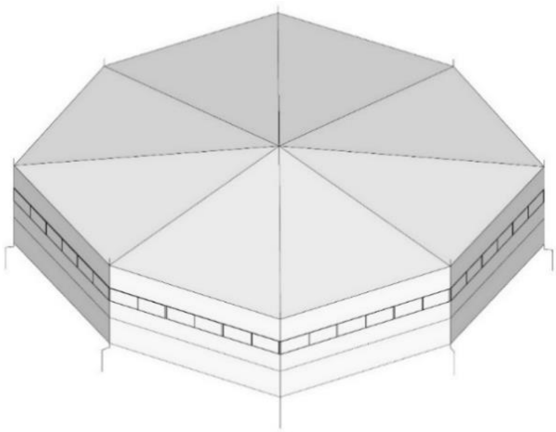

Figure 25: Boet Troskie Hall building

3.4.5 External Lightning Protection System Elements Overview

Table 14 shows the conductive elements used for the external LPS, with the Free State Provincial Government building having the most materials. Since it would be impractical to implement a Type B earthing system for all of the structures, a Type A earthing arrangement was used.

Table 14: External LPS elements overview

Items	Quantity	Length (m)	Material
Loch Logan Park building			
Air-termination System	3	2.5	Aluminium
Down-conductor System	6	75	Aluminium
Earth-termination System	6	3	Copper
Free State Provincial Government building			
Air-termination System	1	2.5	Aluminium
Down-conductor System	10	80	Aluminium
Earth-termination System	10	3	Copper
Boet Troskie Hall building			
Air-termination System	1	2.5	Aluminium
Down-conductor System	8	11	Aluminium
Earth-termination System	8	3	Copper

3.5 Separation Distance

The distance between two conductive parts at which no dangerous sparking can occur is defined as the separation distance. This is normally between the external LPS components and other electrically conducting elements internal to the structure.

Doors and windows are also considered because they are typically made of a metallic structure where lightning current flashes can occur [14]. The simplified method for calculating the separation of a lightning impulse is shown in Equation 13.

$$s = \frac{k_i}{k_m} \times k_c \times l \quad (13)$$

where:

k_i: Selected Class of LPS

k_m: Electrical insulation material

k_c Lightning current flowing on the air-termination and down-conductor

l: The distance in meters between the point where the separation distance is to be considered and the nearest equipotential bonding point or the earth termination along the air-termination and down-conductor

As shown in Table 15, the separation distance for each building was determined in accordance with SANS 62305-3 using the simplified formula shown in Equation 13. Due to the insufficient down-conductors on the Free State Provincial Government building, a greater separation distance must be maintained in order to avoid dangerous sparking to any metallic parts.

Table 15: Calculated separation distance overview

Building	**Calculated Separation Distance (m)**
Loch Logan Park building	0.84
Free State Provincial Government building	1.36
Boet Troskie Hall	0.42

3.6 Lightning Simulation Software Background

For this study, XGSLab was used. It was originally developed in the 19th century and the time domain feature was introduced in 2017 by conducting calculations based on Fourier transforms. XGSLab is based on a full wave solver of Maxwell equations in the presence of a conducting layered half-space, taking Green functions and Sommerfeld integrals into account. This powerful solver was developed using the partial element equivalent circuit (PEE) numerical method and it can simulate systems of conductors integrated with circuit components such as generators and impedances [13].

Green functions are fundamental solutions of inhomogeneous differential equations that satisfy the boundary conditions on electromagnetic fields at interfaces between different media. They can be used as solutions of the Laplace equation, that governs the scalar potential in a uniform or stratified propagation medium in quasi-static conditions. They can also be used for calculating the scalar potential of a uniform or stratified propagation medium in quasi-static conditions [13].

The accurate solution of the Maxwell equations relating to infinitesimal current elements radiating in the presence of a lossy half-space meeting the boundary conditions on the electromagnetic fields at the half-space interface is represented by Sommerfeld integrals. In a multilayer soil model, Sommerfeld integrals can be used to calculate the vector potential of horizontal or vertical electric dipoles [13].

3.7 Summary

This chapter demonstrated the methodology for lightning risk analysis and lightning simulation by providing an overview and approach to the final results, which are detailed in Chapter 4. According to the results of the risk analysis, a class of LPS III was designed for the Loch Logan Park building and the Free State Provincial Government building. The Boet Troskie Hall building did not require an external LPS and a class of LPS IV was modelled for illustration purposes.

Due to the existing concrete slabs surrounding the buildings, it was impractical to implement a type B earthing system, therefore, a type A earthing arrangement with a vertical earth electrode at each down-conductor was used. Because soil resistivity tests were not possible due to limited access and Covid-19 regulations, a generic soil resistivity of 100 Ω.m was chosen for all three buildings as it is categorised as moist soil [62].

In Chapter 4, the lightning risk analysis results for each building are shown, focusing on the type of risk associated with the source of damage that can be expected by using the principles mentioned in this chapter. The lightning simulation is performed on each building that has been modelled with the appropriate LPL.

CHAPTER 4: RESULTS

4.1 Introduction

In Chapter 3, the methodology of the study was illustrated by examining the methods for conducting the lightning risk analysis and obtaining a LPL for each building where an external LPS was modelled. The methodology for lightning simulation, as well as modelling and configuration, were also introduced.

In this chapter, the lightning risk analysis results for each building are shown, focusing on the type of risk associated with the source of damage that can be expected by using the principles mentioned in the previous chapter. The lightning simulation is performed for each building that has been modelled with the appropriate LPL and the results are outlined in this chapter.

4.2 Occurrence of Lightning Strikes

In this section, the occurrence of lightning strikes is calculated in the lightning risk analysis prior to any protection measures being implemented. The risk mitigation is shown in Section 4.3 after implementing protection measures, namely the external LPS.

Due to the frequency of annual lightning activity and the size of the building, there is a risk of human loss and structural damage, which is considered a financial loss. The lightning ground flash density is multiplied by the equivalent collection area of the structure, with correction factors for the structure's physical characteristics and environmental factors taken into account.

Table 16 summarises the frequency of direct and indirect lightning strikes to buildings calculated by the DEHNsupport toolbox software using the input data from Chapter 3. The Free State Provincial Government building had the highest risk of being struck by lightning, projected to be once a year, while the Boet Troskie Hall building has the lowest risk, projected to be once every eighteen years. The indirect lightning strikes for all three buildings were calculated to be nearly equivalent to a projected value of six to seven strikes per year near these areas.

Table 16: Occurrence of lightning strikes for each building

Building	**Direct Lightning Strike Frequency (strikes per year)**	**Direct Lightning Strike Frequency (years)**	**Indirect Lightning Strike Frequency (strikes per year)**
Loch Logan Park	0.7792	1.3	6
Free State Provincial Government	1.0788	1	7
Boet Troskie Hall	0.0547	18	7

The calculated collection area for direct and indirect lightning strikes near the building is shown in Table 17, considering the models from Chapter 3. The dimensions of a building are critical in determining the risk of a direct strike. The collection areas for direct and indirect lightning strikes are based on the dimensions obtained from Google Earth, an open-source platform showing the geographical location of the world.

Table 17: Calculated collection area for direct and indirect lightning strikes

Building	**Direct Lightning Strike Collection Area (m²)**	**Indirect Lightning Strike Collection Area (m²)**
Loch Logan Park	210 591	835 708
Free State Provincial Government	291 567	897 698
Boet Troskie Hall	14 788	893 598

From Table 17, the Free State Provincial Government building was found to have the highest risk of being struck by lightning due to its larger direct lightning strike collection area of 291 567 m². In contrast, the collection area for indirect lightning strikes was nearly equivalent for all three buildings, with the Free State Provincial Government building having the highest value of 897 698 m² due to its height.

The direct lightning strike collection area is primarily determined by the height of the building and the surface area of the ground beneath the building. The Boet Troskie Hall building is less likely to be struck by lightning than other buildings due to its significantly smaller direct lightning strike collection area of 14 788 m².

4.3 Risk Analysis Mitigation

The calculated factors for the relevant risks are shown in the bar charts that follow. The red bars represent the risk as a percentage prior to the application of a LPS or other risk reduction factors. Lowering the risk to a tolerable level can be accomplished by gradually adding protection measures to the calculation. The risk was calculated in relation to the tolerable value and the outcomes are represented by the green bar as the residual risk.

In the event of a lightning strike, the probability of human life loss, R_1, is calculated using a tolerable value of 1 out of 100 000 people per year as defined in the lightning protection standard. The probability for the risk of economic value loss, R_4, is calculated using a tolerable value of 1 in 1 000 per year as defined in the lightning protection standard [7]. The risks of loss of service to the public, R_2 and the risk of loss of cultural heritage, R_3, do not apply to the buildings considered for the study.

4.3.1 Loch Logan Park Building

In Figure 26, the risk of loss of human life was calculated to be above the tolerable value of 1 out of 100 000 people per year, as indicated by a 100 percent. The risk before measures was calculated to be 1 187 percent and was mitigated to 89 percent by implementing the protection measures shown in section 4.4. The probability of loss of human life is calculated to be 1 out of 8 403 people per year and was reduced to 1 out of 112 486 people per year by implementing protection measures.

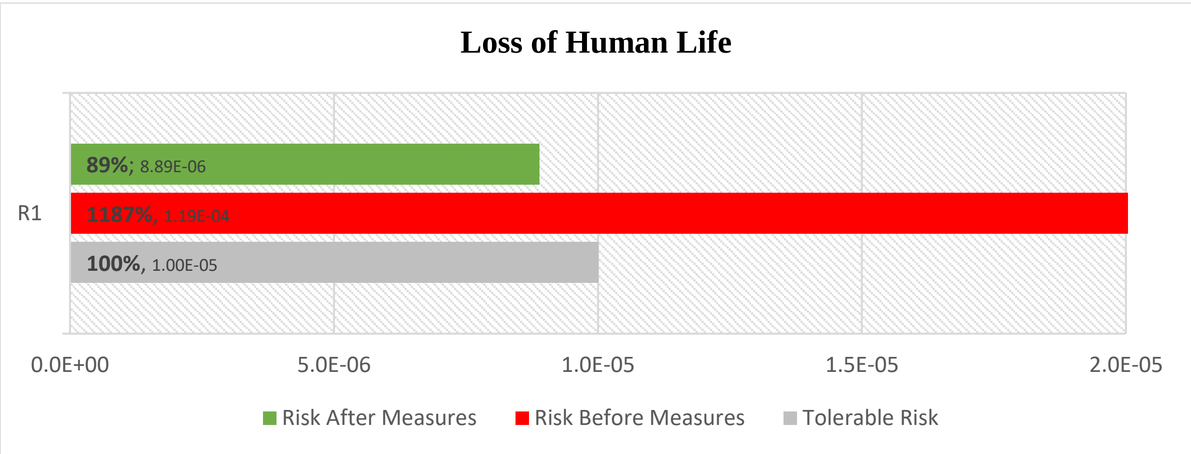

Figure 26: Risk R_1 Calculation results for Loch Logan Park building

An overview of the source of damage to the Loch Logan Park building is shown in Figure 27 and is defined as a direct strike to the building, source S_1. The risks were identified as R_A, an electric shock due to touch and step voltages inside the building and R_B, physical damage caused by dangerous sparking inside the building, triggering a fire or an explosion if there are gas cylinders in the building.

The values shown on the y-axis in figures 27, 29, 31, 33, 35 and 37 are used for a visual representation to identify the highest risk components as a factor of zero to one. Each risk component, from R_A to R_Z, is described in detail in Annexure A.

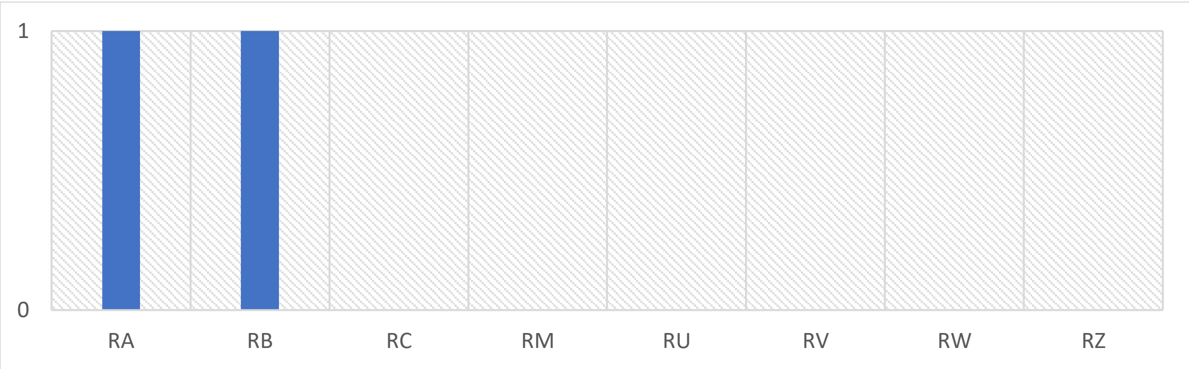

Figure 27: Risk components R_1 before measures for Loch Logan Park building

In Figure 28, the risk of loss of economic value was calculated to be above the tolerable value of 1 out of a 1 000 (ZAR), as indicated by a 100 percent. The risk before protection measures was calculated to be 3 723 percent, which could be reduced to 75 percent by implementing protection measures as shown in section 4.4. The probability of loss of economic value was calculated to be 1 out of every 27 (ZAR) lost per year before protection measures. It was reduced to 1 out of every 1 335 (ZAR) per year by implementing protection measures.

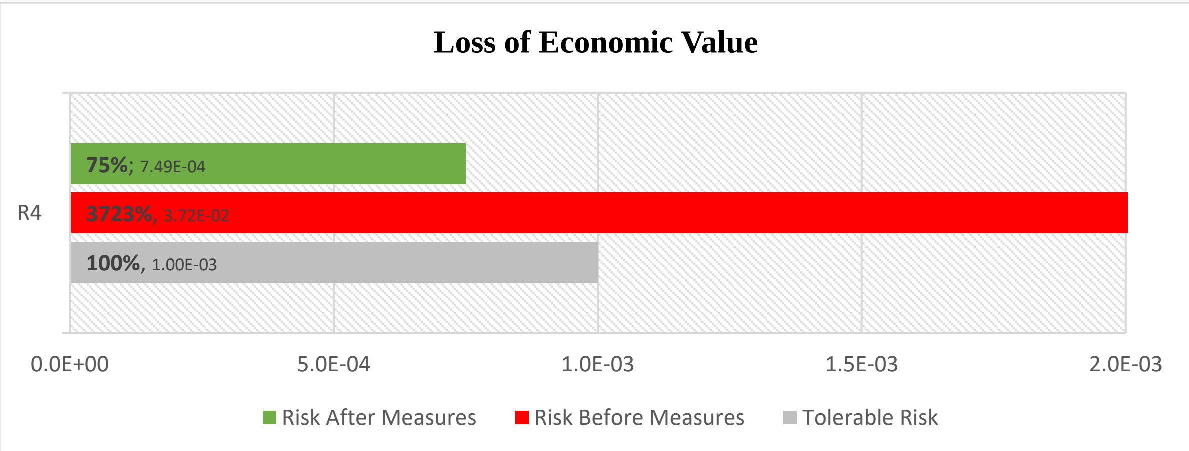

Figure 28: Risk R_4 calculation results for Loch Logan Park building

An overview of the source of damage for the Loch Logan Park building is shown in Figure 29 and is defined as an indirect lightning strike to the building, source S_2. The highest risk was identified as R_M, failure of internal systems caused by LEMP.

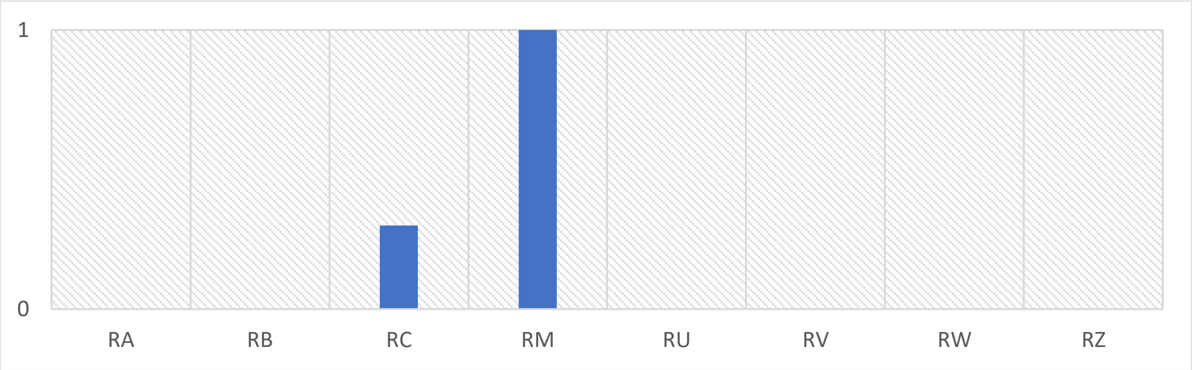

Figure 29: Risk components R_4 before measures for Loch Logan Park building

4.3.2 Free State Provincial Government Building

In Figure 30, the risk of loss of human life was calculated to be above the tolerable value of one out of 100 000 people per year, as indicated by a 100 percent. The risk before measures was calculated to be 818 percent and was mitigated to 55 percent by implementing the protection measures shown in Section 4.4. The probability of loss of human life was calculated to be one out of 12 225 people per year and was reduced to one out of 183 486 people per year by implementing protection measures.

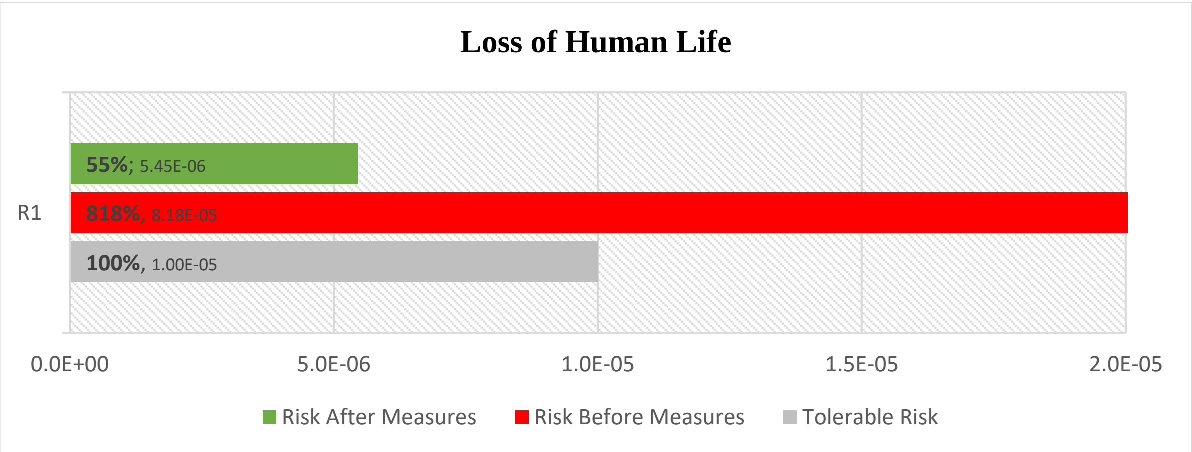

Figure 30: Risk R_1 calculation results for Free State Provincial Government building

An overview of the source of damage to the Free State Provincial Government building is shown in Figure 31 and is defined as a direct strike to the building, source S_1. The highest risk was identified as R_B, physical damage caused by dangerous sparking inside the building, triggering a fire.

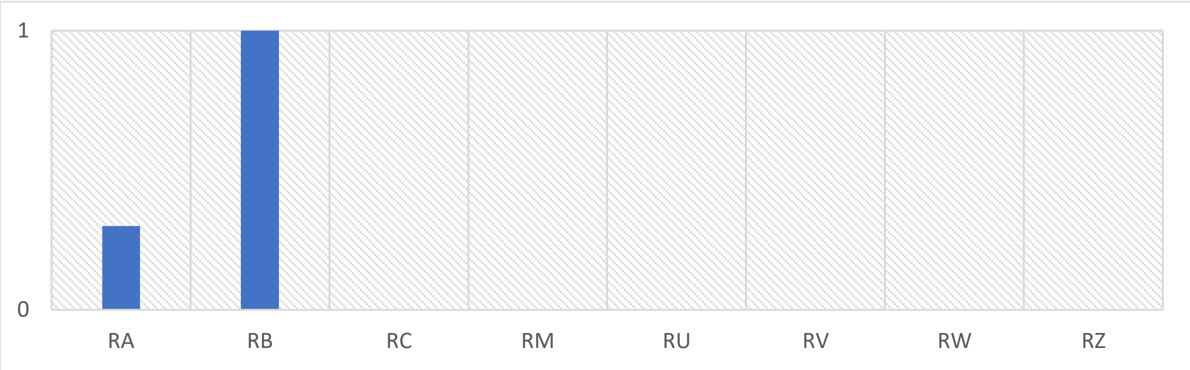

Figure 31: Risk components R_1 before measures for Free State Provincial Government building

In Figure 32, the risk of loss of economic value was calculated to be above the tolerable value of one out of a 1 000 (ZAR), as indicated by a 100 percent. The risk before protection measures was calculated to be 4 428 percent, which could be reduced to 95 percent by implementing protection measures as shown in section 4.4. The probability of loss of economic value was calculated to be one out of every 23 (ZAR) lost per year before protection measures. It was reduced to one out of every 1 053 (ZAR) per year by implementing protection measures.

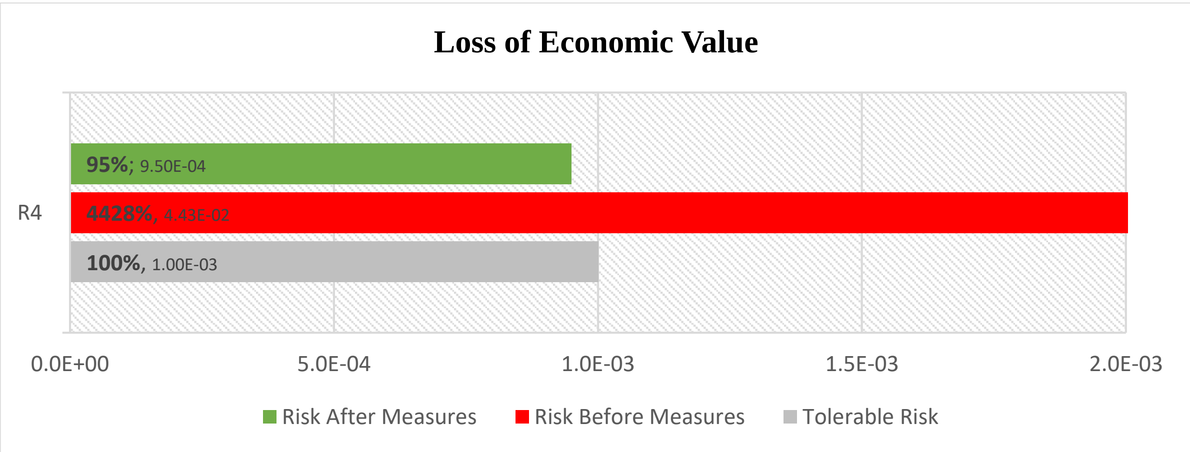

Figure 32: Risk R_4 calculation results for Free State Provincial Government building

An overview of the source of damage to the Free State Provincial Government building is shown in Figure 33 and is defined as an indirect lightning strike to the building, source S_2. The highest risk was identified as R_M, failure of internal systems caused by LEMP.

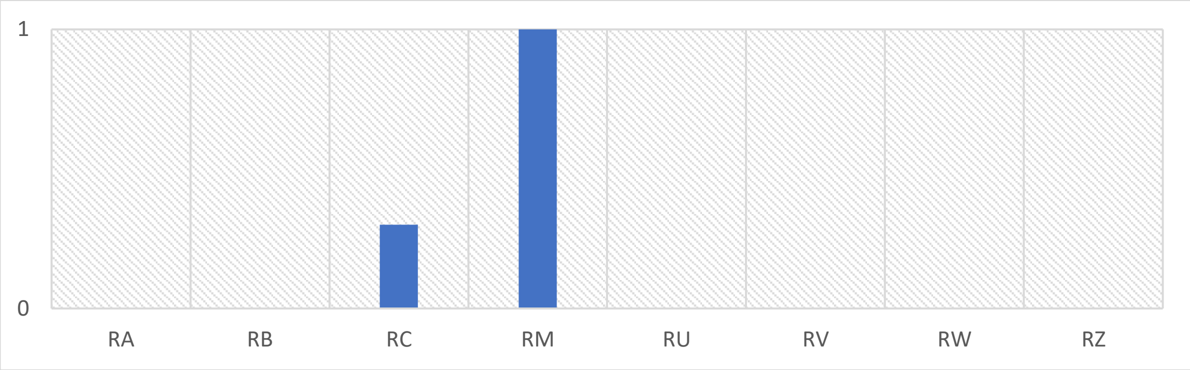

Figure 33: Risk components R_4 before measures for Free State Provincial Government building

4.3.3 Boet Troskie Hall Building

In Figure 34, the risk of loss of human life was calculated to be below the tolerable value of one out of 100 000 people per year, as indicated by a 100 percent. The risk before measures was calculated to be 44 percent, therefore, no protection measures are required. The probability of loss of human life was calculated to be one out of 226 244 people per year without the implementation of protection measures.

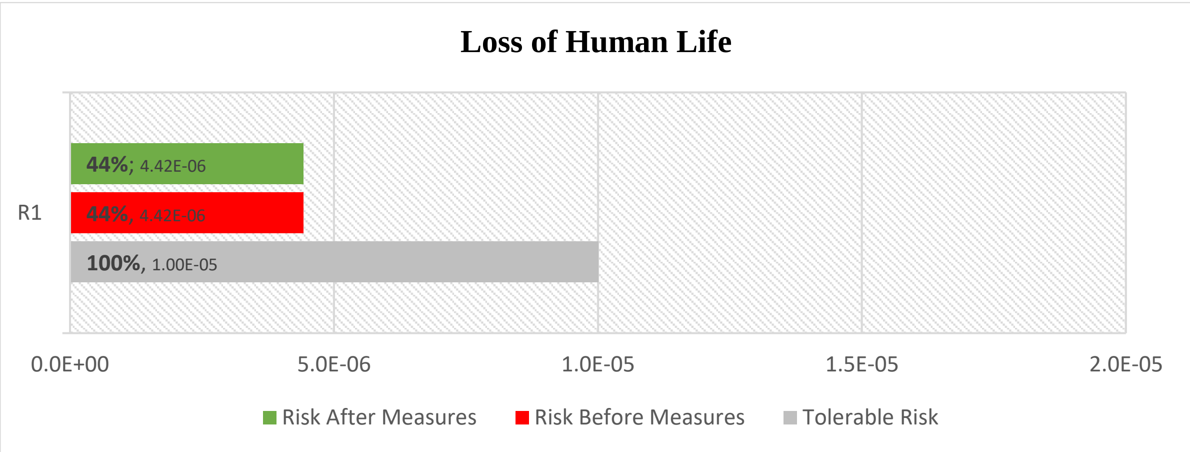

Figure 34: Risk R_1 calculation results for Boet Troskie Hall building

An overview of the source of damage to the Loch Logan Park building is shown in Figure 35 and is defined as a direct strike to the building, source S_1. The highest risk was identified as R_B, physical damage caused by dangerous sparking inside the building, triggering a fire or an explosion if there are gas cylinders in the building. This risk, however, is below the tolerable value of one out of 100 000 people per year and therefore, no protection measures are required.

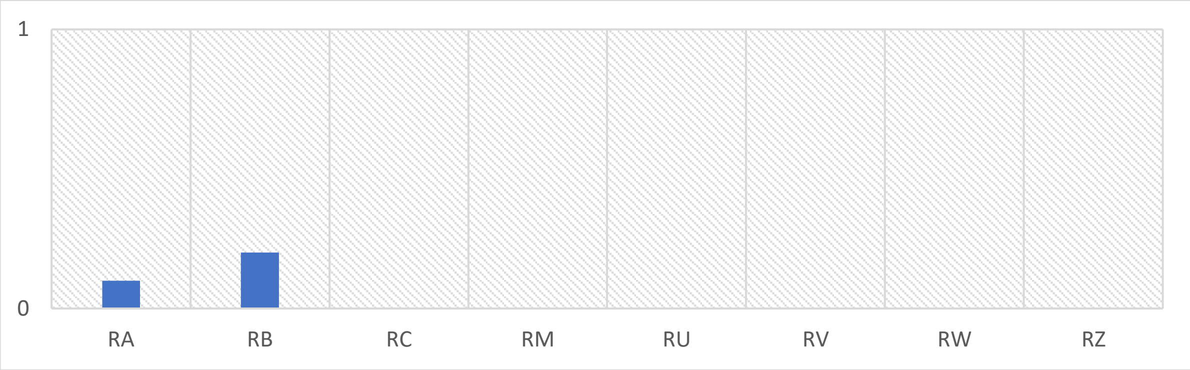

Figure 35: Risk components R_1 before measures for Boet Troskie Hall building

In Figure 36, the risk of loss of economic value was calculated to be above the tolerable value of one out of a 1 000 (ZAR), as indicated by a 100 percent. The risk before protection measures was calculated to be 323 percent, which could be reduced to 23 percent by implementing protection measures, as shown in section 4.4. The probability of loss of economic value is calculated to be one out of every 310 (ZAR) lost per year before protection measures. It was reduced to one out of every 4 444 (ZAR) per year by implementing protection measures.

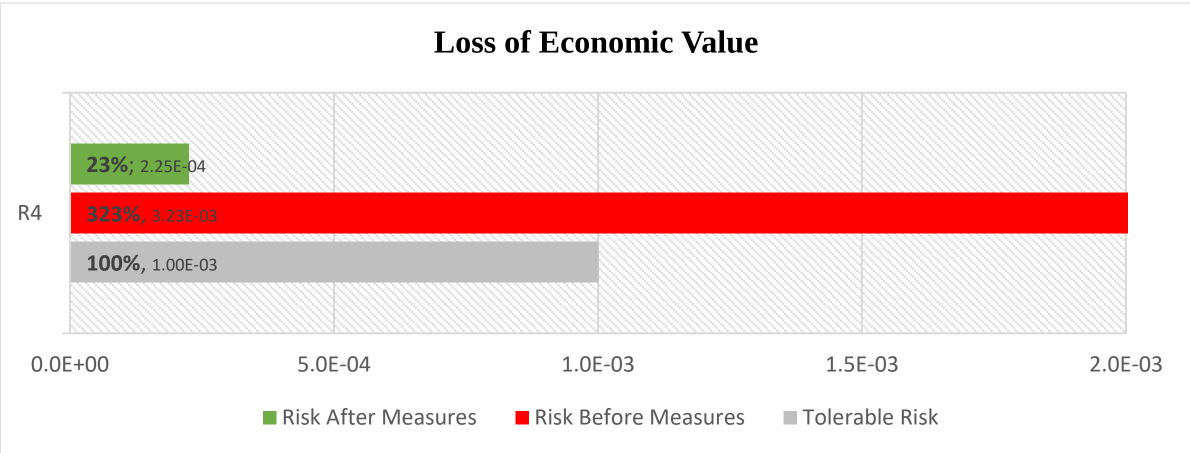

Figure 36: Risk R4 calculation results for Boet Troskie Hall building

An overview of the source of damage for the Boet Troskie Hall building is shown in Figure 37 and is defined as an indirect lightning strike to the building, source S_2. The highest risk was identified as R_M, failure of internal systems caused by LEMP.

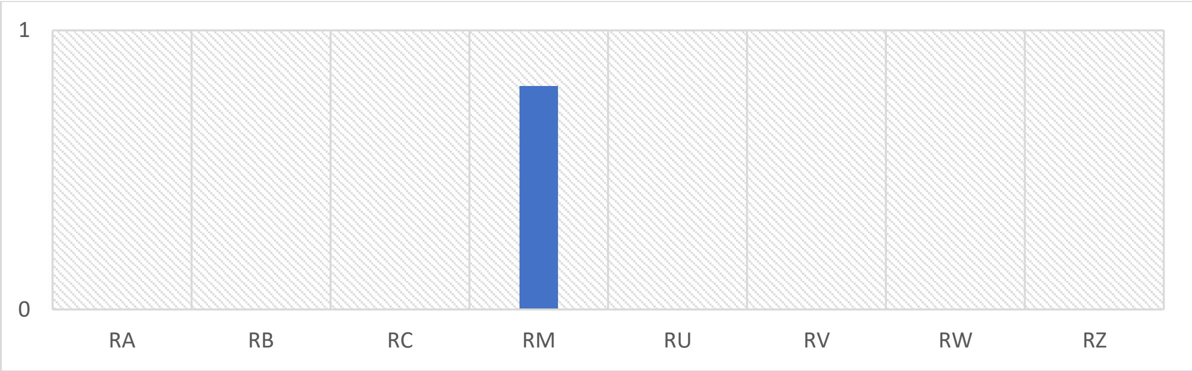

Figure 37: Risk components R_4 before measures for Boet Troskie Hall building

4.4 Recommendations for Protection

Implementing the recommended protection measures will not reduce the frequency of direct lightning strikes to buildings, as determined in the study. But it will reduce the damage caused by lightning and its impact on human life and economical value. Table 18 summarises the risk reduction measures calculated after implementing a LPS based on the site conditions and specifications for each building, as well as the protection measures implemented to mitigate risk components that were above tolerable values. For each area, the reduction factors are calculated in accordance with the requirements of SANS 62305 and is represented in scientific notation.

Table 18: Lightning risk analysis protection measures outcomes for each building

Building	Measures	Reduction Factor	
Loch Logan Park Free State Provincial Government	Lightning protection system (LPS): **Class of LPS III**	pB	1.0E-01
Loch Logan Park Free State Provincial Government	Lightning equipotential bonding: **Equipotential bonding for LPL III or IV**	pEB	5.0E-02
Loch Logan Park	Fire precautions:	rp	5.0E-01

Free State Provincial Government	**Fire extinguishers, manual fire alarm systems, hydrants, fire-proof compartments, protected escape routes**		
Loch Logan Park	Coordinated SPD protection: **LPL II**	pSPD	2.0E-02
Free State Provincial Government			
Boet Troskie Hall	Coordinated SPD protection: **LPL III or IV**	pSPD	5.0E-02

To mitigate the risk, an LPS should be designed according to a LPL III for the Loch Logan Park and Free State Provincial Government buildings to reduce physical damage due to direct lightning strikes. To reduce potential differences caused by lightning current, equipotential bonding of separated metallic parts to the LPS should be performed for the Loch Logan Park and Free State Provincial Government buildings. This can be achieved by conductive connections or Type I SPDs at the main distribution boards in accordance with LPL III or IV. There should be fire prevention measures implemented for the Loch Logan Park and Free State Provincial Government buildings that consist of either fire extinguishers, manual fire alarm systems, hydrants, fire-proof compartments or protected escape routes.

Following the calculations for the loss of human life in Loch Logan Park and the Free State Provincial Government buildings, the risk components R_A and R_B were the most significant. This related to injuries to people caused by electric shock due to touch and step voltages inside and outside of the building, up to three metres around the down-conductors in the event of a direct lightning strike to the structure. Physical damage can occur, which is caused by dangerous sparking inside the buildings, resulting in a fire explosion that may endanger the environment in the presence of gas cylinders.

For the calculations for the loss of economic value at Loch Logan Park and the Free State Provincial Government buildings, the risk component R_M was the most significant. This related to the failure of electrical and electronic systems in the event of a lightning strike to the ground near the buildings due to LEMP. Some risk remained in risk component R_C, being the risk of failure of electrical and electronic systems in the event of a lightning strike to the systems directly.

To demonstrate the differences between the outcomes, an LPS in accordance with LPL IV was implemented for the Boet Troskie Hall building. The risk component R_M was the most significant when considering the loss of economic value, relating to the failure of electrical and electronic systems in the event of a lightning strike to the ground near the buildings due to LEMP.

4.5 Lightning Simulation Results

The lightning simulation was conducted after the lightning protection measures were implemented on each structure. The figures are simplified and only show the modelling of each building along with the location of the first negative lightning strike. Annexure B to G contains detailed information about each building's dimensions and lightning parameters as evaluated in the simulation software.

4.5.1 Loch Logan Park Building

In the first point of the investigation, a direct lightning strike with the waveshape described in Chapter 3 was terminated onto the Loch Logan Park building proposed LPS. The earth resistance of the designed earthing system was simulated to be 4.965 Ω with a GPR of 2 848.70 MV. This was achieved by injecting a first negative lightning current impulse of 50 kA into the proposed LPS.

The Loch Logan Park building is made up of six external lightning down-conductors that exhibit the properties described in Chapter 3. Due to the worst-case scenario considered for the study, only the highest and lowest current distribution waveforms are illustrated, which were calculated at the third and fifth down-conductors during a direct lightning strike to the air-termination system.

Figure 38 illustrates a 3D view of the LPS implemented on the building, whereas Figure 39 depicts a 2D top, front and side view. The lightning strike is carried out directly to an air-termination rod, which is represented by a red lightning symbol at the top of the building.

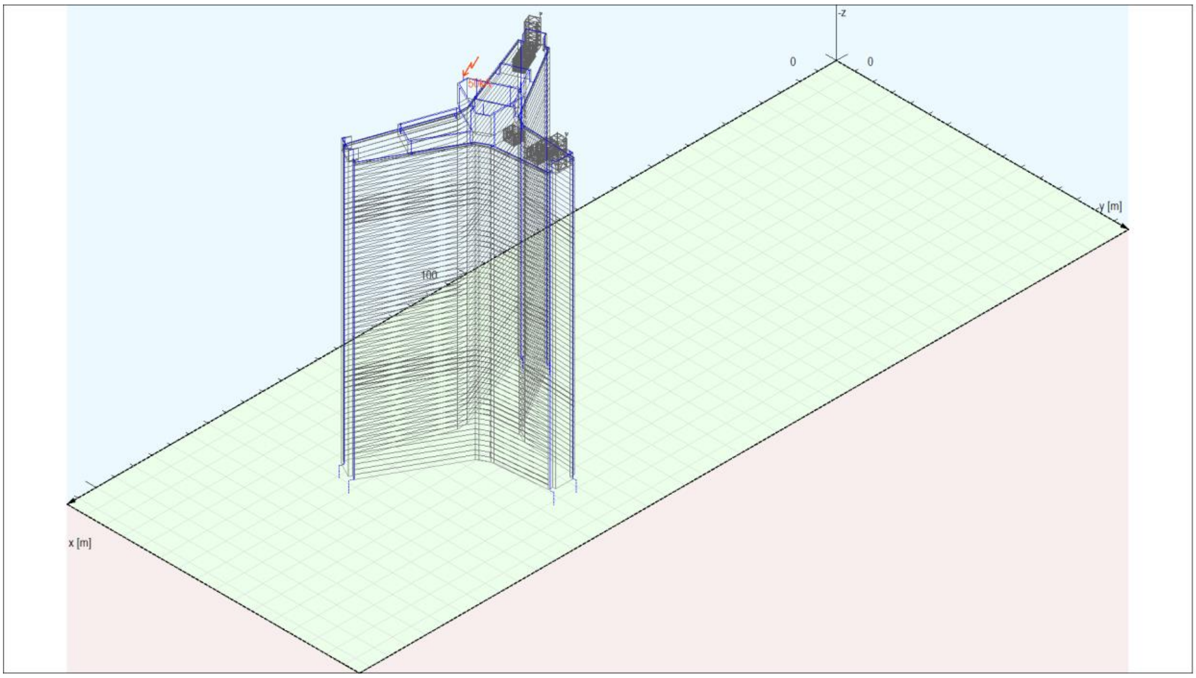

Figure 38: Loch Logan Park building illustration of direct strike location - 3D view

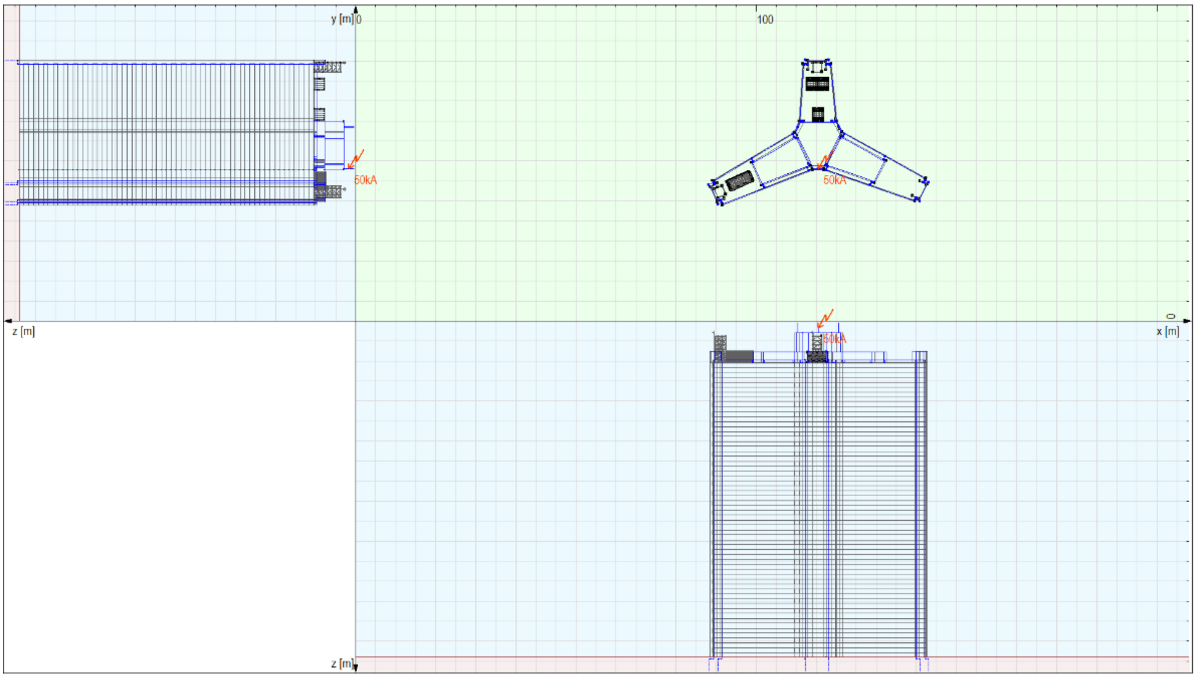

Figure 39: Loch Logan Park building illustration of direct strike location - 2D view

The current distribution remained relatively constant for each down-conductor, with an average value of 10.59 kA. Due to constructive interference in higher buildings, the sum of all calculated currents exceeds the 50 kA injection current, preserving the constant specific energy. Figure 40 depicts an overview of the current distribution calculated across each down-conductor in the system.

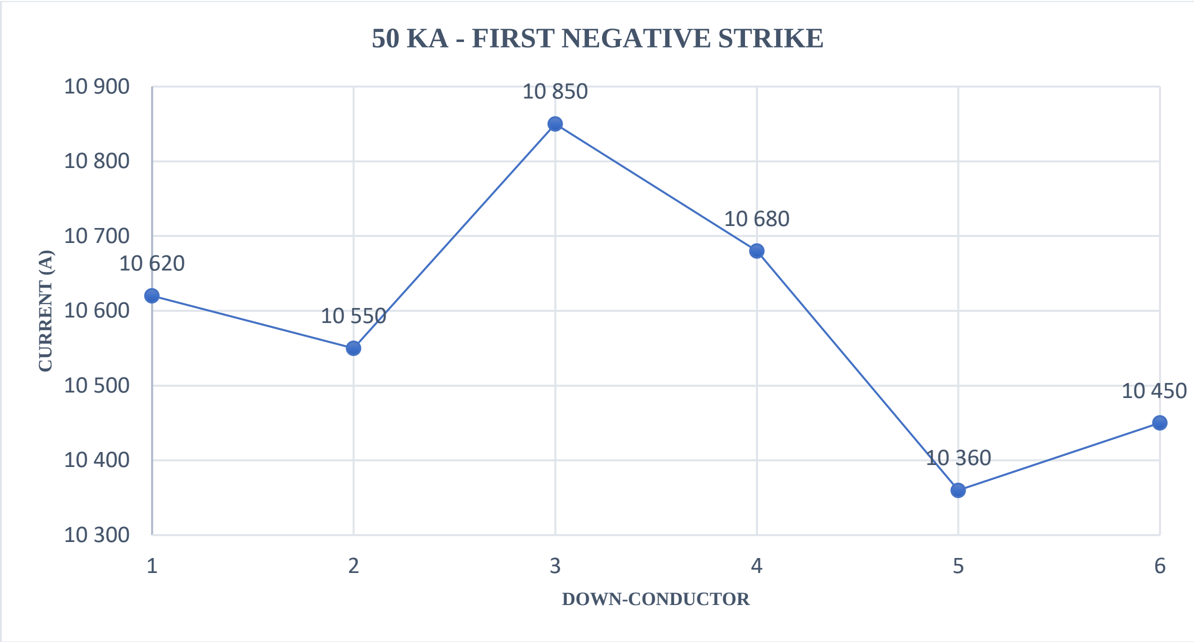

Figure 40: Loch Logan Park building current distribution summary

In figures 41 and 42, the x-axis illustrates the waveshapes' duration in microseconds, while the y-axis depicts the peak current in amperes. The current distribution values were calculated as 10.85 kA closest to the point of strike and 10.36 kA furthest from the point of strike, respectively. Figures 41, 42, 48, 49, 55, and 56 depict the magnitude of the current in ampere along the y-axis, while the x-axis indicates the duration of the waveform in microseconds.

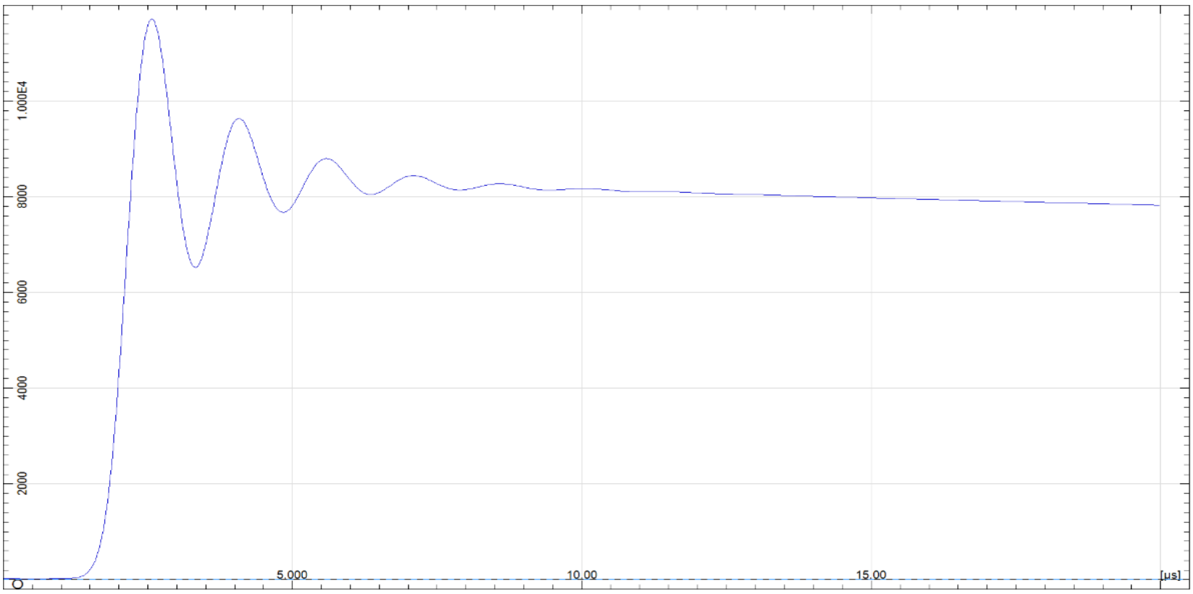

Figure 41: Loch Logan Park building 3rd down-conductor current distribution

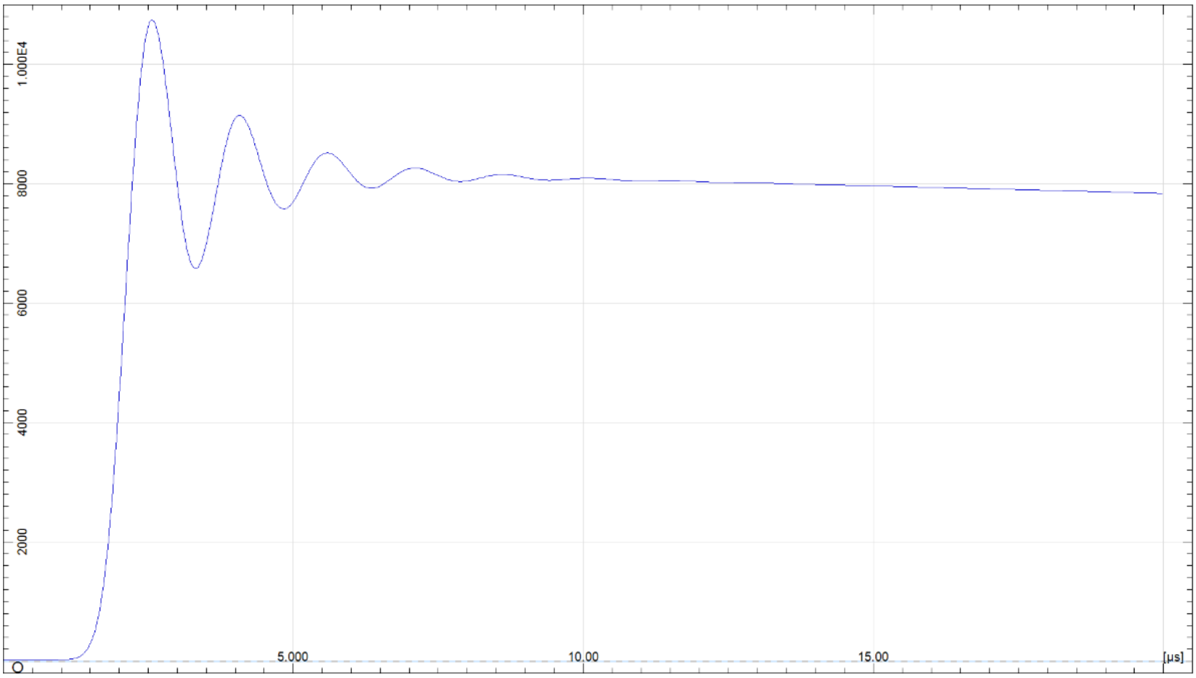

Figure 42: Loch Logan Park building 5th down-conductor current distribution

The potential distribution values in the frequency domain were calculated over the LPS for the Loch Logan Park building during a direct lightning strike. Figure 43 illustrates a 3D view of the LPS implemented on the building, whereas Figure 44 depicts a 2D top, front and side view. The lightning strike is carried out directly to an air-termination rod, where the potential would be at its highest.

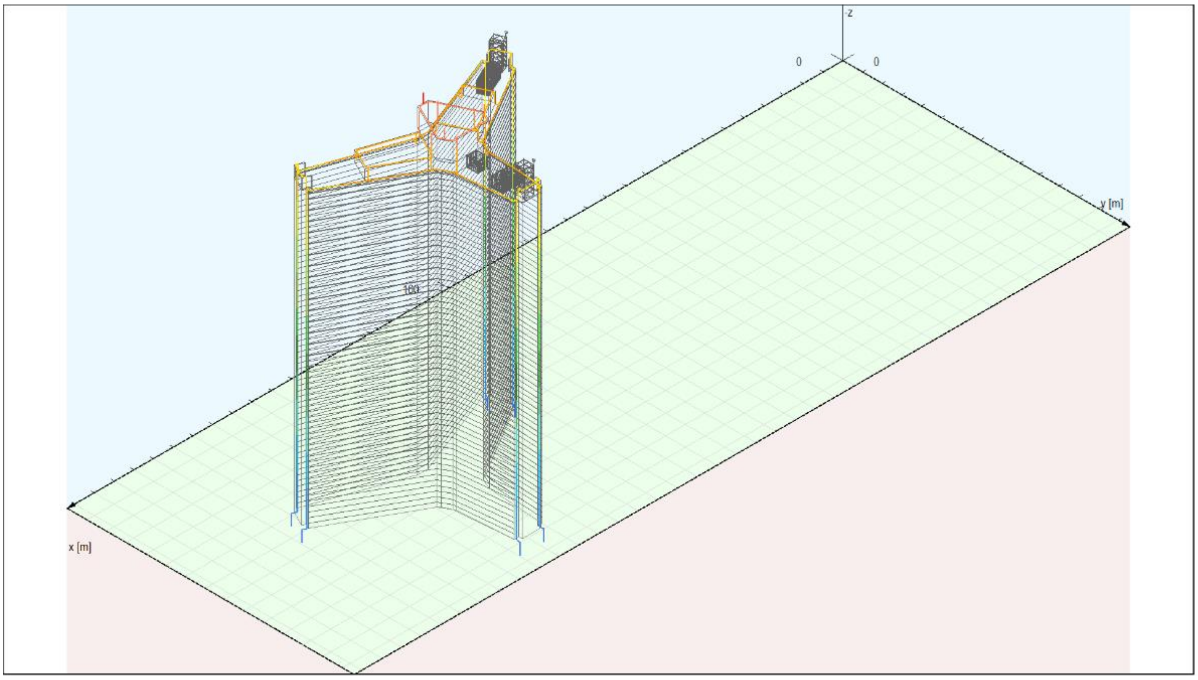

Figure 43: Loch Logan Park building LPS potential distribution – 3D view

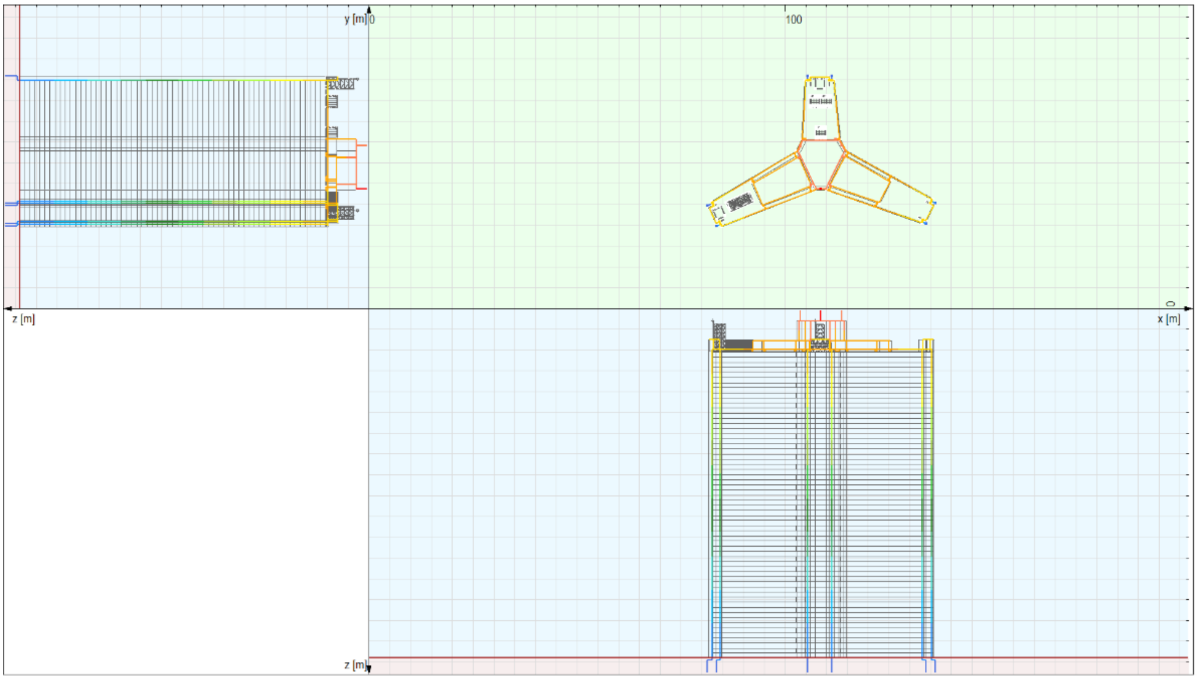

Figure 44: Loch Logan Park building LPS potential distribution – 2D view

The potential distribution of the building's LPS was calculated using the RMS value of 35.4 kA and a 250 kHz sinusoid for the first negative stroke. The highest value was calculated to be 3 907 kV close to the injection point and the lowest value was calculated to be 196.4 kV at the soil surface. The values of the minimum and maximum potential distributions for the Loch Logan Park building are calculated and illustrated in Table 19.

Table 19: Loch Logan Park building minimum and maximum potential distribution values

Minimum distribution-potential (V)	196 400
Maximum distribution-potential (V)	3 907 000

The conductors closer to the injection point have a significantly higher potential than those further away. Because of the building's height, a greater separation distance must be maintained between the LPS and any conductive elements in order to prevent sparking over. The separation distance that should be maintained is shown in Chapter 3.

4.5.2 Free State Provincial Government Building

In the second point of the investigation, a direct lightning strike with the waveshape described in Chapter 3, was terminated onto the Free State Provincial Government building's proposed

LPS. The earth resistance of the designed earthing system was simulated to be 3.255 Ω with a GPR of 1 867.45 MV. This was achieved by injecting a first negative lightning current impulse of 50 kA into the proposed LPS.

The Free State Provincial Government building is made up of 10 external lightning down-conductors that exhibit the properties described in Chapter 3. Due to the worst-case scenario considered for the study, only the highest and lowest current distribution waveforms are illustrated, which were calculated at the third and eighth down-conductors during a direct lightning strike to the air-termination system.

Figure 45 illustrates a 3D view of the LPS implemented on the building, whereas Figure 46 depicts a 2D top, front and side view. The lightning strike is carried out directly to an air-termination rod, which is represented by a red lightning symbol at the top of the building.

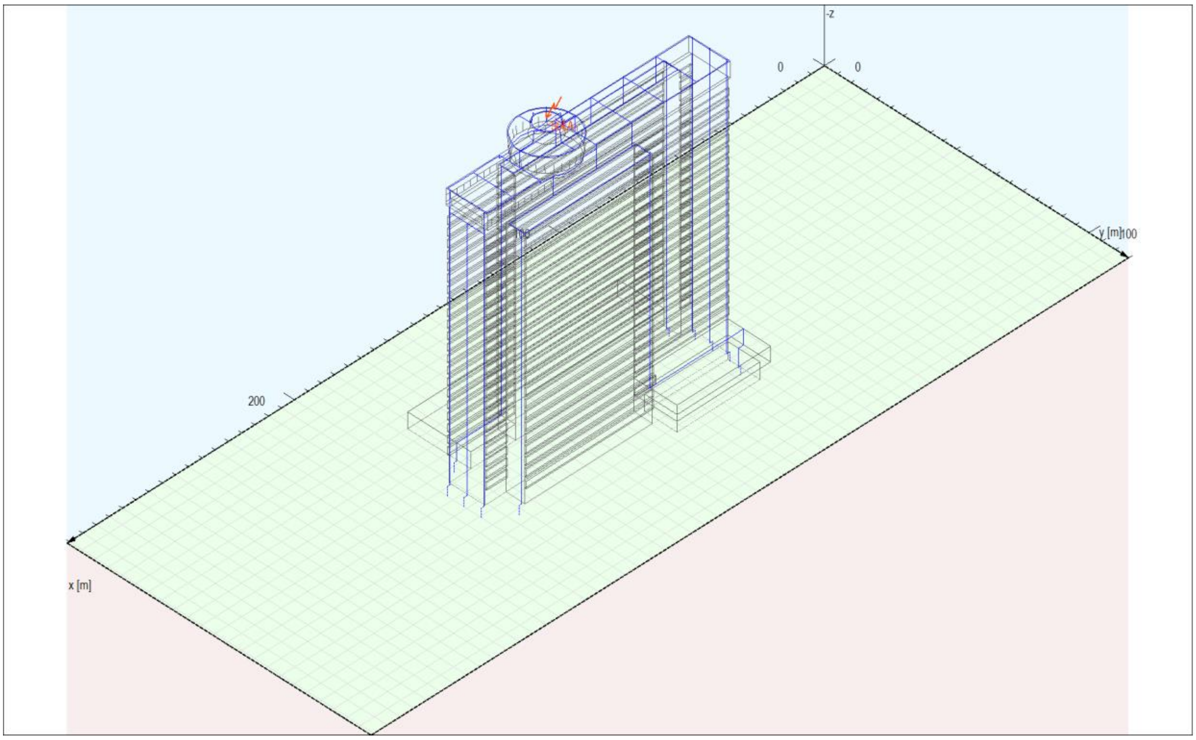

Figure 45: Free State Provincial Government building illustration of direct strike location - 3D view

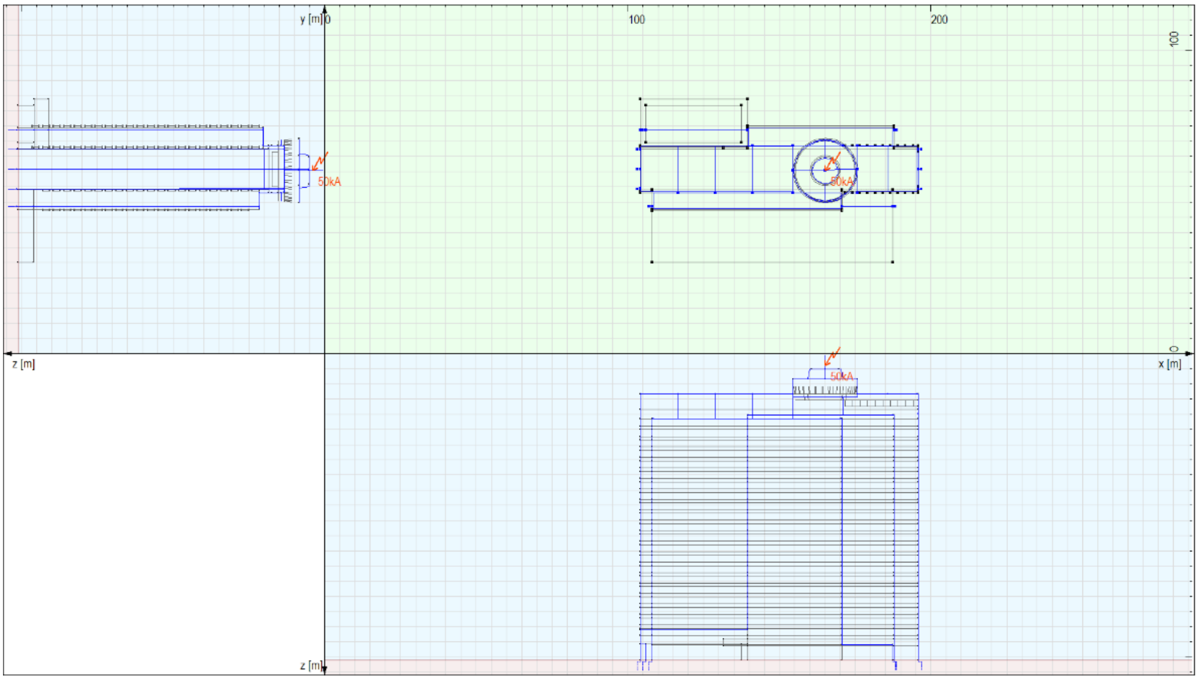

Figure 46: Free State Provincial Government building illustration of direct strike location - 2D view

The current distribution remained relatively constant for each down-conductor, with an average value of 7.39 kA. Due to constructive interference in higher buildings, the sum of all calculated currents exceeds the 50 kA injection current, preserving the constant specific energy. Figure 47 depicts an overview of the current distribution calculated across each down-conductor in the system.

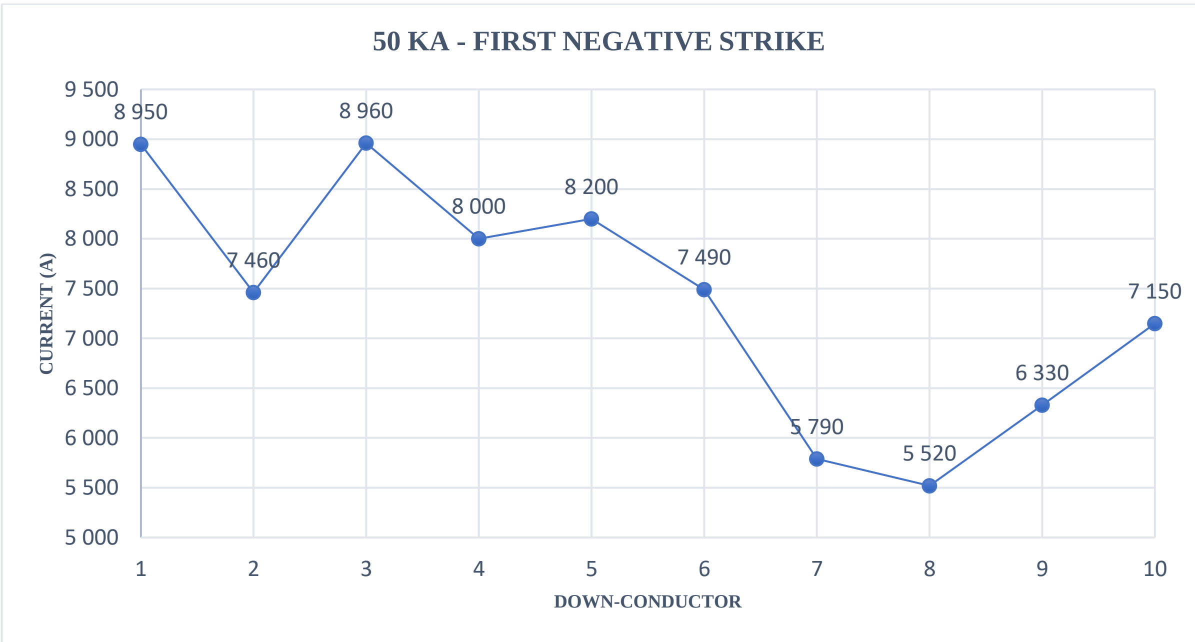

Figure 47: Free State Provincial Government building current distribution summary

In figures 48 and 49, the x-axis illustrates the waveshapes' duration in microseconds, while the y-axis depicts the peak current in amperes. The current distribution values were calculated as 8.96 kA closest to the point of strike and 5.52 kA furthest from the point of strike, respectively.

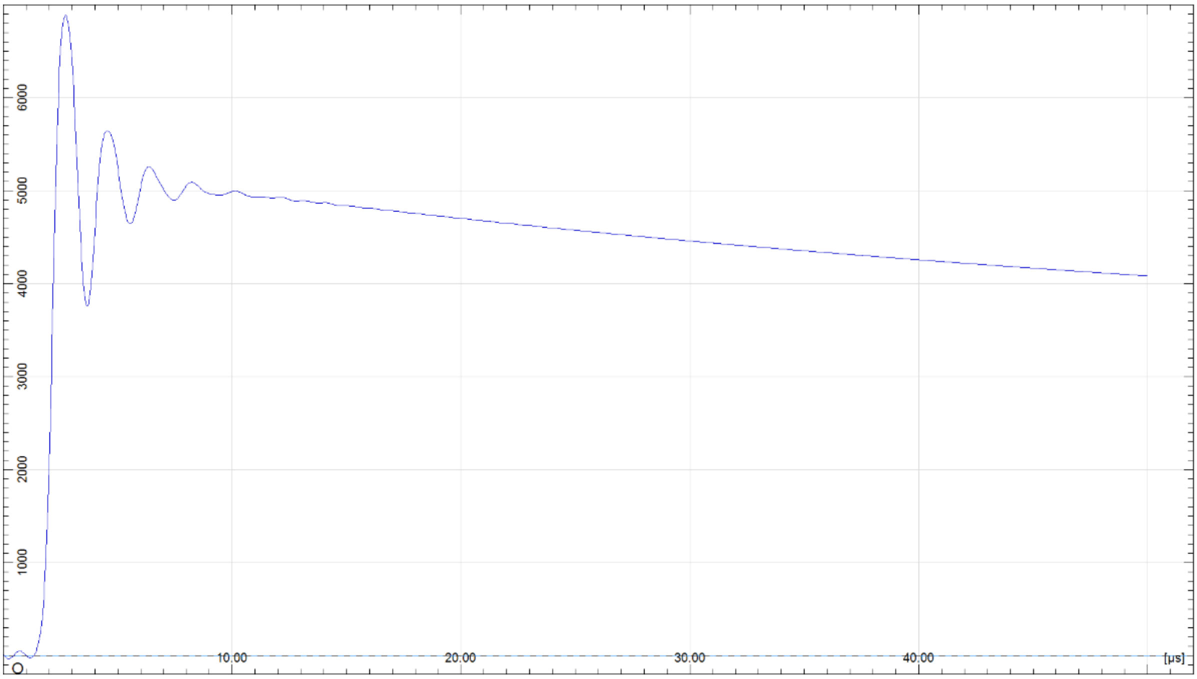

Figure 48: Free State Provincial Government building 3rd down-conductor current distribution

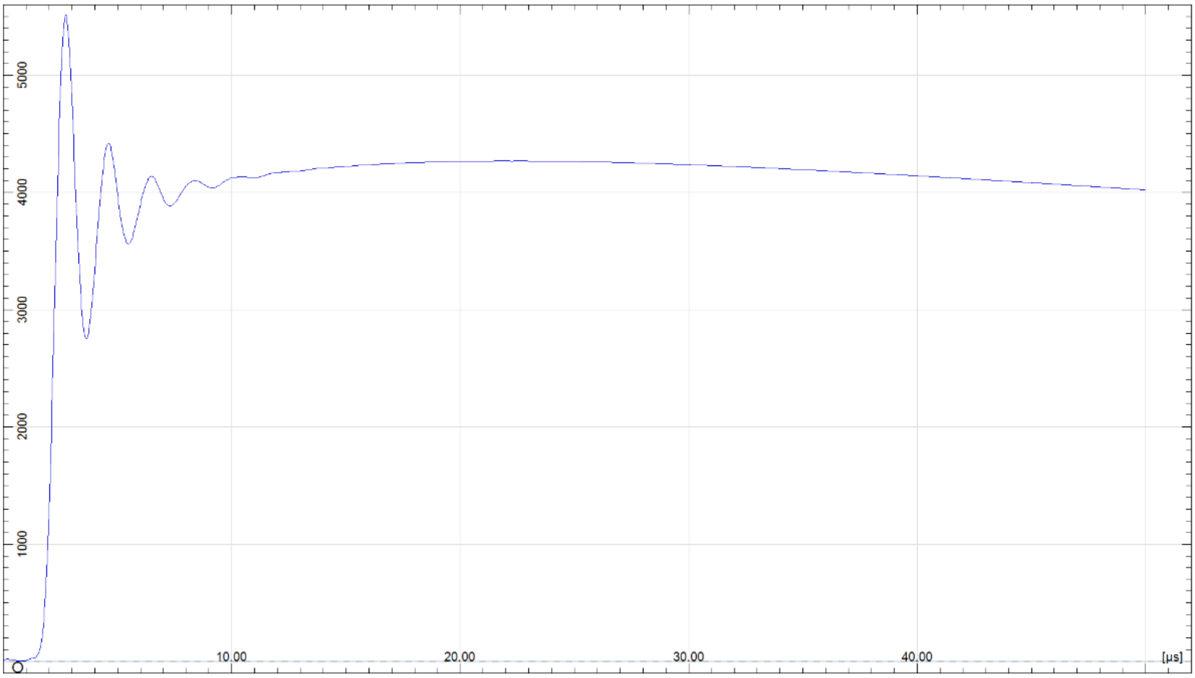

Figure 49: Free State Provincial Government building 8th down-conductor current distribution

The potential distribution values in the frequency domain were calculated over the LPS for the Free State Provincial Government during a direct lightning strike. Figure 50 illustrates a 3D view of the LPS implemented on the building, whereas Figure 51 depicts a 2D top, front and side view. The lightning strike is carried out directly to an air-termination rod, where the potential would be at its highest.

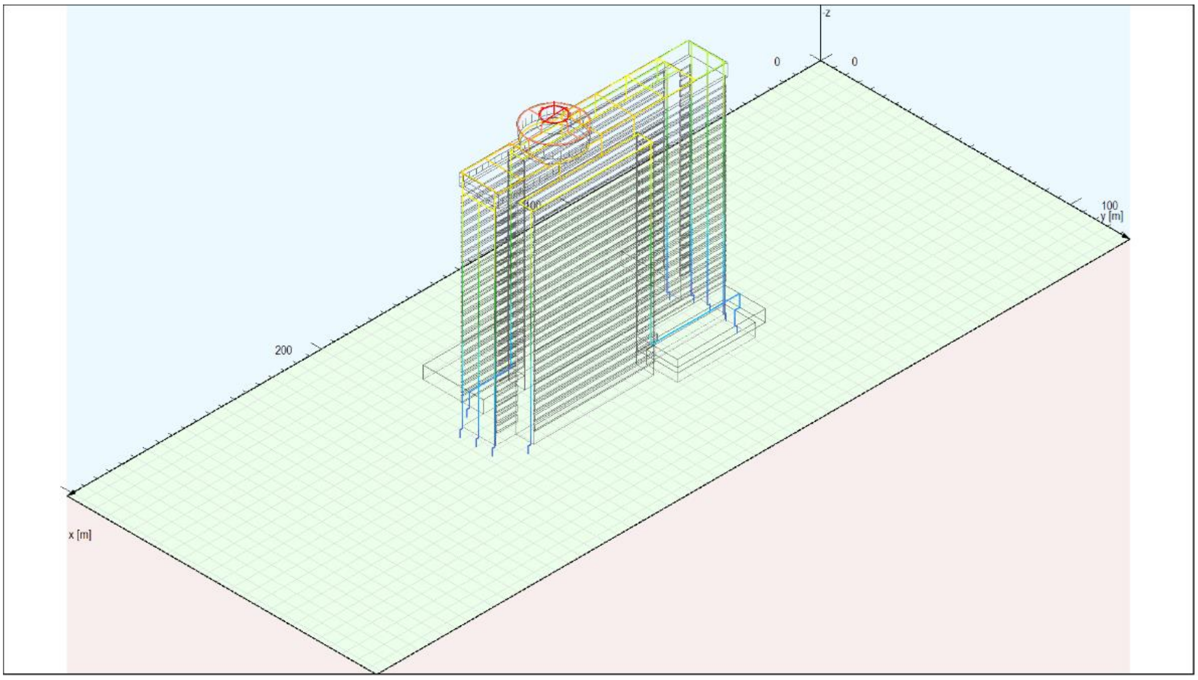

Figure 50: Free State Provincial Government building LPS potential distribution – 3D view

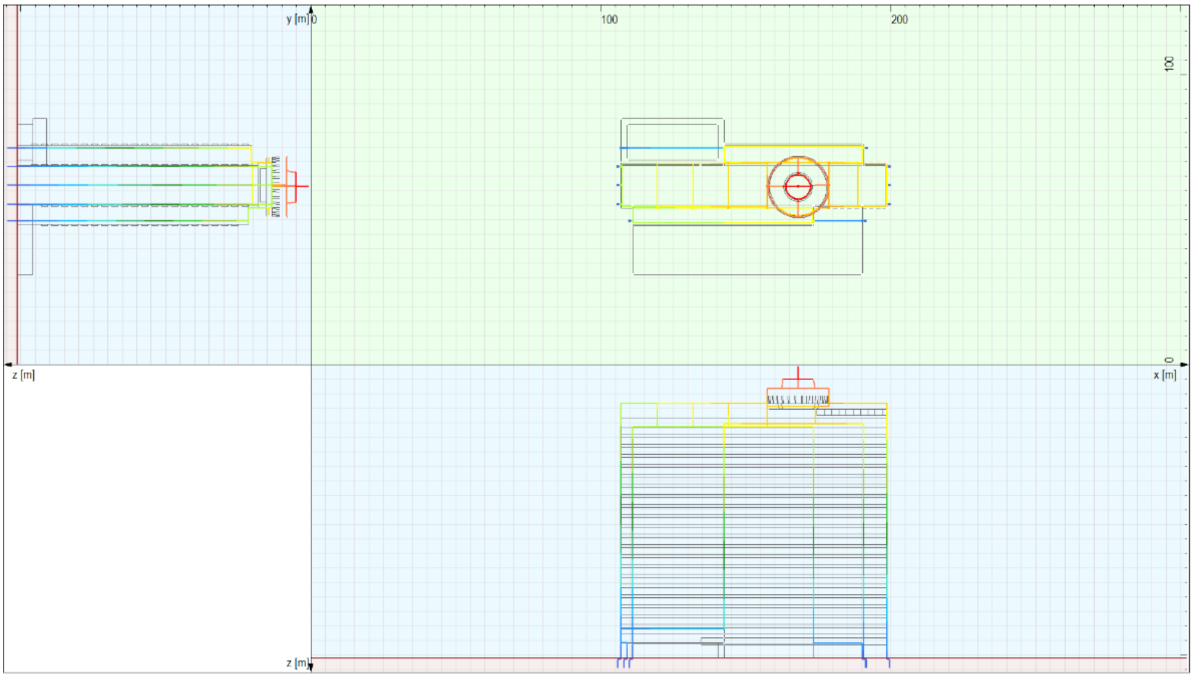

Figure 51: Free State Provincial Government building LPS potential distribution – 2D view

The potential distribution of the building’s LPS was calculated using the RMS value of 35.4 kA and a 250 kHz sinusoid for the first negative stroke. The highest value was calculated to be

4 779 kV close to the injection point and the lowest value was calculated to be 118.8 kV at the soil surface. The values of the minimum and maximum potential distributions for the Loch Logan Park building are calculated and illustrated in Table 20.

Table 20: Free State Provincial Government building minimum and maximum potential distribution values

Minimum distribution-potential (V)	118 800
Maximum distribution-potential (V)	4 779 000

The conductors closer to the injection point have a significantly higher potential than those further away. Because of the structure's height, a greater separation distance must be maintained between the LPS and any conductive elements in order to prevent sparking over. The separation distance that should be maintained is shown in Chapter 3.

4.5.3 Boet Troskie Hall Building

In the third point of the investigation, a direct lightning strike with the waveshape described in Chapter 3 was terminated onto the Boet Troskie Hall building's proposed LPS. The earth resistance of the designed earthing system was simulated to be 3.497 Ω with a GPR of 2 006.32 MV. This was achieved by injecting a first negative lightning current impulse of 50 kA into the proposed LPS.

The Boet Troskie Hall building is made up of eight external lightning down-conductors that exhibit the properties described in Chapter 3. Due to the worst-case scenario considered for the study, only the highest and lowest current distribution waveforms are illustrated, which were calculated at the first and fourth down-conductors during a direct lightning strike to the air-termination system.

Figure 52 illustrates a 3D view of the LPS implemented on the building, whereas Figure 53 depicts a 2D top, front and side view. The lightning strike is carried out directly to the air-termination rod in the centre of the building, which is represented by a red lightning symbol at the top of the building.

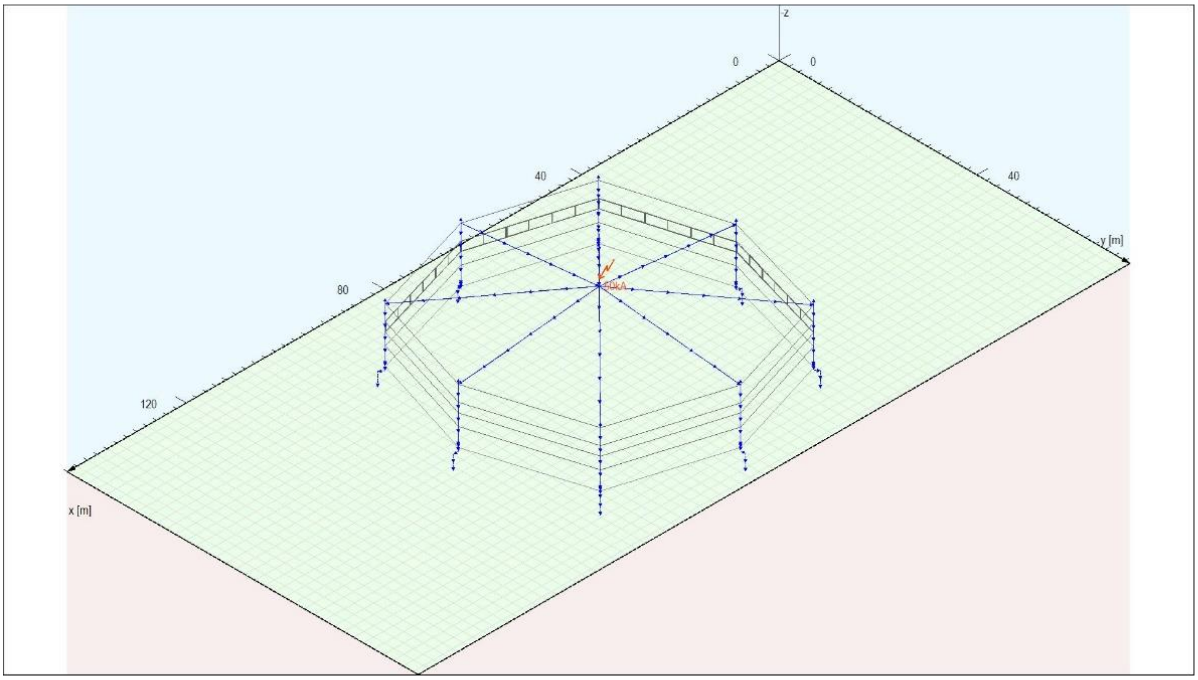

Figure 52: Boet Troskie Hall building illustration of direct strike location - 3D view

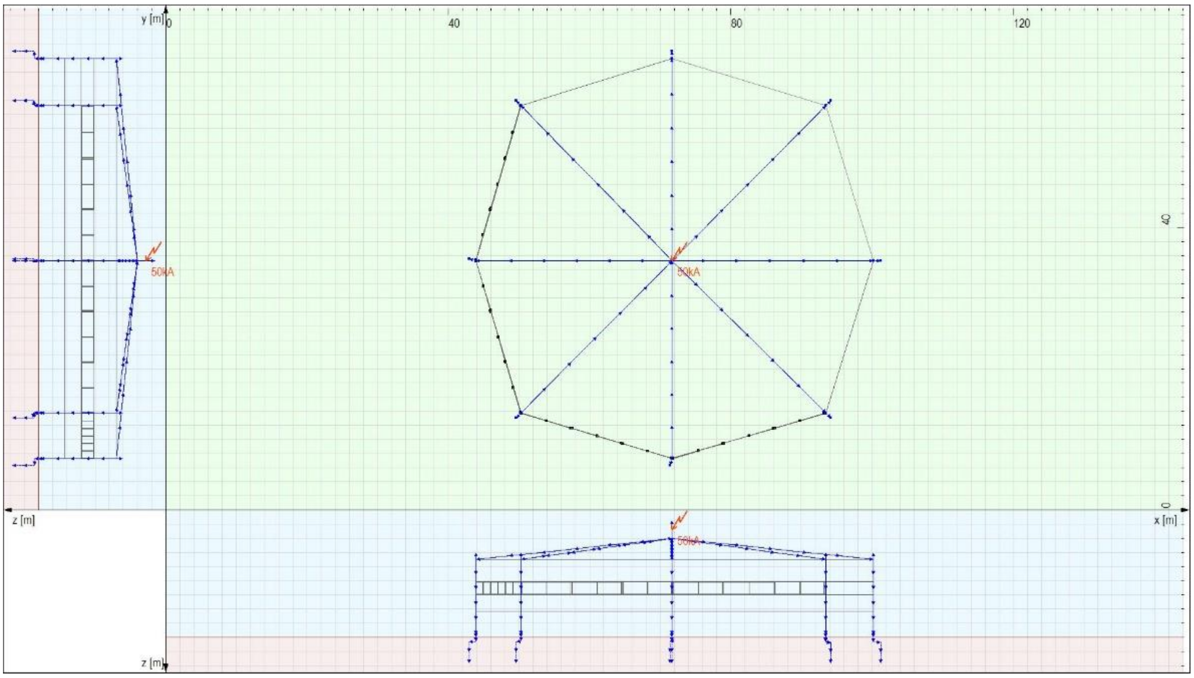

Figure 53: Boet Troskie Hall building illustration of direct strike location - 2D view

The current distribution remained relatively constant for each down-conductor, with an average value of 6.28 kA. Due to constructive interference in higher buildings, the sum of all calculated currents exceeds the 50 kA injection current, preserving the constant specific energy. Figure 54 depicts an overview of the current distribution calculated across each down-conductor in the system.

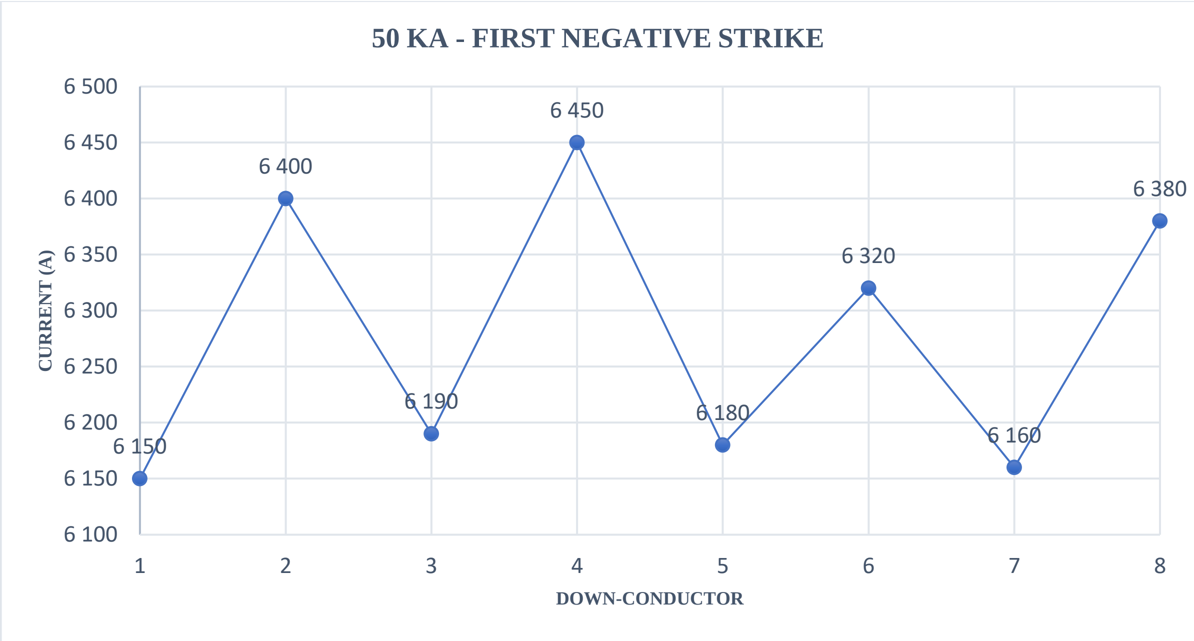

Figure 54: Boet Troskie Hall building current distribution summary

In figures 55 and 56, the x-axis illustrates the waveshapes' duration in microseconds, while the y-axis depicts the peak current in amperes. The current distribution values were calculated as 6.45 kA closest to the point of strike and 6.15 kA furthest from the point of strike, respectively.

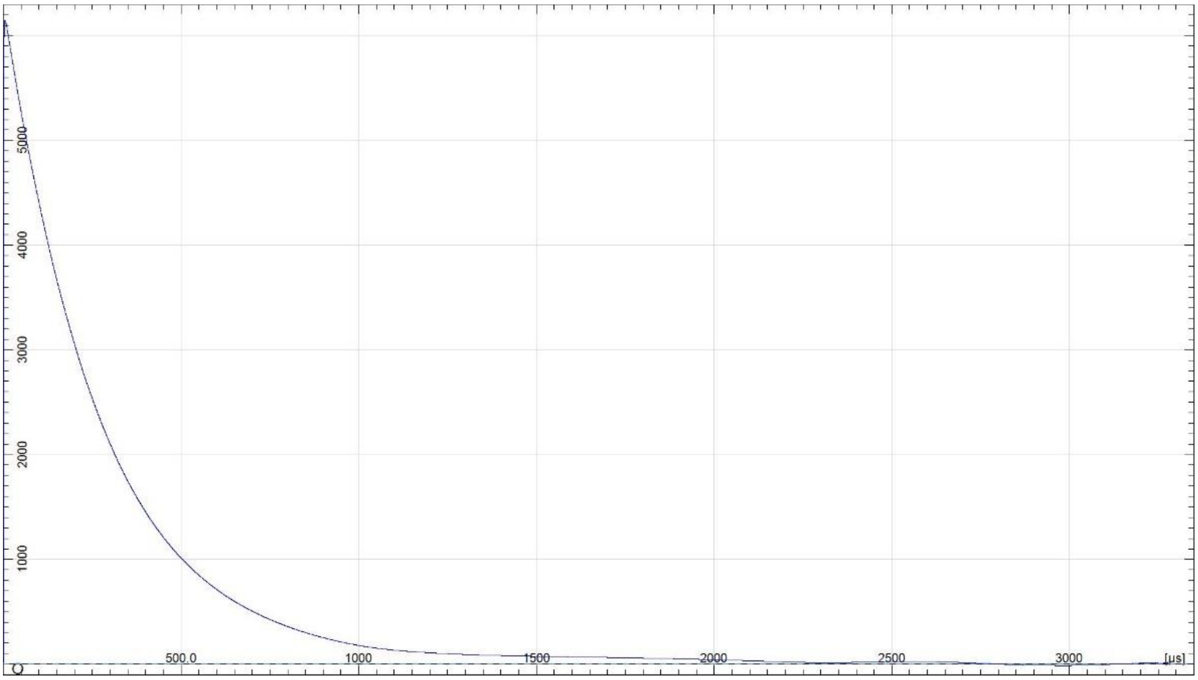

Figure 55: Boet Troskie Hall building 1st down-conductor current distribution

Figure 56: Boet Troskie Hall building 4th down-conductor current distribution

The potential distribution values in the frequency domain were calculated over the LPS for the Boet Troskie Hall building during a direct lightning strike. Figure 57 illustrates a 3D view of the LPS implemented on the building; whereas Figure 58 depicts a 2D top, front and side view. The lightning strike is carried out directly to an air-termination rod, where the potential would be at its highest.

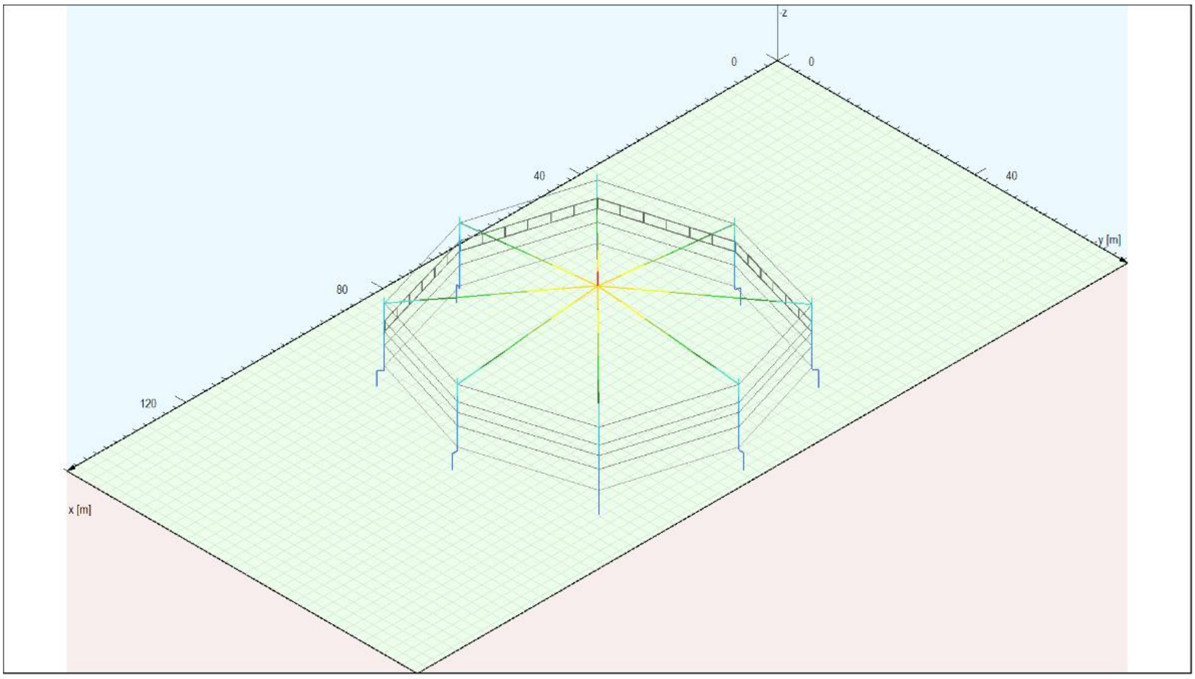

Figure 57: Boet Troskie Hall building LPS potential distribution – 3D view

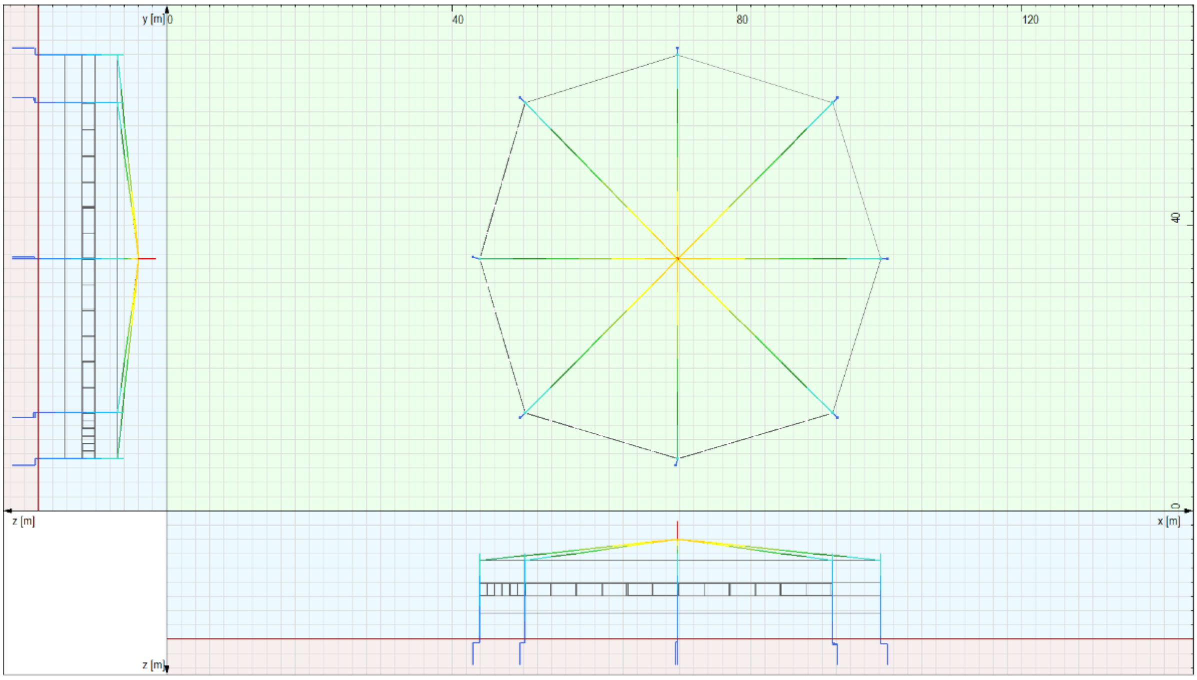

Figure 58: Boet Troskie Hall building LPS potential distribution – 2D view

The potential distribution of the building's LPS was calculated using the RMS value of 35.4 kA and a 250 kHz sinusoid for the first negative stroke. The highest value was calculated to be 659.8 kV close to the injection point, and the lowest value was calculated to be 115.8 kV at the soil surface. The values of the minimum and maximum potential distributions for the Boet Troskie Hall building are calculated and illustrated in Table 21.

Table 21: Boet Troskie Hall building minimum and maximum potential distribution values

Minimum distribution-potential (V)	115 800
Maximum distribution-potential (V)	659 800

The conductors closer to the injection point have a significantly higher potential than those further away. Because of the structure's height, a greater separation distance must be maintained between the LPS and any conductive elements in order to prevent sparking over. The separation distance that should be maintained is shown in Chapter 3.

4.6 Summary

This chapter focused primarily on the time and frequency domain analysis of a first negative lightning strike. Each building was independently simulated to calculate the current and potential distribution across the proposed LPS in order to distinguish the impact of a lightning strike while taking into account the unique properties and environmental effects.

The earthing system resistance, GPR and current distribution over each lightning down-conductor were calculated in the time domain using 167 different frequencies based on the normalised frequency spectrum (Nyquist Frequency). Because there are many differentiations and results to illustrate using the time domain, the frequency domain was used to represent the potential distribution across the LPS in a graphical representation.

The analysis revealed that the current distribution was relatively constant across each down-conductor for each building, whereas the potential distribution graphical illustration demonstrated a significant difference across the LPS. The following chapter discusses the study's overall findings, implications, conclusion, as well as an interpretation of the results.

CHAPTER 5: CONCLUSION

5.1 Introduction

In Chapter 4, the results of the risk analysis and lightning simulations conducted for each building independently were discussed. The probability and impact of a direct lightning strike to any of the pre-defined structures were discussed, taking into account the unique properties and environmental effects. A graphical representation of the current and potential distribution was illustrated and the earthing impedance was calculated for each structure.

The research findings are discussed in Chapter 5. This chapter also includes recommendations and interpretation of the results based on the research findings.

5.2 Problem Statement

Using adequate protection measures implemented on building structures can lead to lightning risk being mitigated to a tolerable level. The problem is that there are many environmental and structural factors that can affect the likelihood of damage and loss occurring with or without protection measures and these factors influence the current and potential distribution on a building that needs to be quantified in order to identify mitigation techniques. Designing protective measures for buildings based on lightning simulation software also proves challenging as specialised knowledge in this field is required. The sub-problem to be studied is outlined as follows:

- The number of down-conductors required is specific to each building type, and specialised software is required to determine the required number.

The Loch Logan Park building was simulated to have the highest earthing resistance with a value of 4.965 Ω, resulting in the highest GPR of 2 848.7 MV and an average current distribution of 10.59 kA over the down-conductors. This is due to the low number of earthing in the ground and the building with the fewest number of down-conductors of six.

When considering the overall earthing resistance of all the buildings, an average of 3.91 Ω was achieved, which is dependent on the amount of earthing in the ground considering the same soil resistivity of 100 Ω.m that was standardised for all the buildings. In accordance with the requirements of SANS 62305, a value of 10 Ω or less is recommended.

The current distribution across the down-conductors was simulated to be fairly consistent with an average of 8.09 kA. Considering a first negative lightning impulse of 50 kA, each down-conductor contributed an approximately 16% split. This can, however, be reduced by adding more down-conductors, which would also reduce the required separation distance to maintain to prevent flash over to any metallic elements.

The average potential distribution over the down-conductors of the Free State Provincial Government and Loch Logan Park buildings resulted in 4.19 MV, whereas the Boet Troskie Hall building only had a significantly lower potential difference of 544 kV. It was observed that the height of the buildings has a significant influence on the potential distribution over each down-conductor due to an increase in impedance over the conductors. As a result, for taller buildings, consider adding more down-conductors as well as keeping the conductors as straight and short as possible to reduce the impedance over the conductor in the event of a lightning strike.

The SANS 62305 lightning standard can be used as a guide to determine the number of down-conductors and earthing requirements for a building. When constraints are encountered, however, it is deemed necessary to conduct a lightning study that is specific to the application at hand.

- The separation distance must be calculated for each type of building based on its unique properties. The problem is that the lightning protection level (LPL) as determined by a lightning risk analysis is required for the separation distance calculation.

A separation distance must be kept between the LPS and any conductive elements due to the height and structural characteristics of each building in order to prevent sparking over. It was found that the Free State Provincial Government building needed the greatest separation distance to be maintained. This is due to the building's structural design, down-conductor restrictions, and particularly its height.

The Free State Provincial Government building would need an additional six down-conductors to reduce the separation distance from 1.36 m to 1.25 m, which would only improve the system by 11 cm. The additional four required down-conductors on the Loch Logan Park building would reduce the separation distance from 0.84 m to 0.76 m, benefiting the system by only eight cm. On the other hand, the Boet Troskie Hall structure utilised the required number of down-conductors, resulting in a separation distance of 0.42 m.

Given the space limitations of the Free State Provincial Government and Loch Logan Park buildings, there was no discernible difference in the current split, and it would be sufficient with simulated down-conductors. It was determined that taller buildings need a greater separation distance in addition to taking the stricter LPL into account. The separation distance, which is specific to each building and cannot be generalised, is clearly understood as illustrated in this study.

5.3 Research Objectives Reviewed

This study aims to investigate the current and potential distribution of lightning on a building to determine adequate protective measures by considering environmental and structural factors. Three predefined buildings were used as examples of different construction materials and textures. The objectives of the study are outlined below:

- To conduct a lightning risk analysis of three specific buildings located in Bloemfontein;

With a lightning flash density of 7.4 per square kilometre per year, Bloemfontein falls into the category of severe to extreme lightning risk, where each building was assessed independently. Taking into account the number of hours of human life spent in the building and the appropriate distinctive parameters.

In Section 4.2 of the study, the selected properties illustrated the calculated direct strike collection area. The Free State Provincial Government building has the highest risk of being struck by lightning, projected to be once a year, followed by the Loch Logan Park building approximately every 1.3 years, while the Boet Troskie Hall building has the lowest risk, projected to be once every eighteen years. The indirect lightning strikes for all three buildings were calculated to be nearly equivalent to a projected value of six to seven strikes per year near these areas.

The Loch Logan Park and Free State Provincial Government buildings were more susceptible to electric shock injuries. This is due to touch and step voltages inside and outside the structure, up to three metres around the down-conductors in the event of a direct lightning strike. Additionally, there will be physical damage caused by dangerous sparks within the buildings, resulting in a fire explosion that may endanger the surrounding environment if gas cylinders are present. A failure of electrical and electronic systems in the event of a lightning strike near and to the two structures was calculated to be a risk, taking into account the loss of economic value. As a result, it was suggested that a class of LPS III with the appropriate additional protection measures be implemented to mitigate these risks to a defined tolerable level.

The Boet Troskie Hall building was exposed to nearby lightning strikes, resulting in a failure of electrical and electronic systems when considering the loss of economic value. Although it was deemed adequate to implement SPDs, an external LPS of class IV was recommended for simulation purposes.

- To propose an external lightning protection system (LPS) on the buildings using computer-based software;

Each building was modelled in 3D using a computer program for applicable drawing applications. The dimensions of the pre-defined buildings and the surrounding objects were observed from Google Earth and duplicated for illustration purposes.

The appropriate class of LPS was designed and implemented for each building in Section 3.4 of the study for illustration purposes and is in accordance with the requirements of the lightning protection standard, SANS 62305. The rolling sphere method, which is recommended for complex structures, was used to determine the placement of the air-termination system on each building, followed by a Type A earthing system to illustrate the ideal conditions due to physical installation constraints such as pavement and concrete platforms surrounding the buildings.

Where applicable, the same lightning protection materials were used in the design of the LPS to maintain consistency. Due to space constraints and keeping an adequate separation distance to prevent lightning from flashing to the surrounding metallic elements, the down-conductors were reduced and only implemented were deemed sufficient. In Section 3.4.5, the Free State Provincial Government building contains the most down-conductors, with a total of 10 down-conductors, due to its larger circumference. While the Boet Troskie Hall building contains eight and the Loch Logan Park building contains only six.

- To simulate a direct lightning strike to the structure and observe the impact in terms of current and potential distribution using computer software;

To illustrate various aspects of the results, a lightning simulation in the time and frequency domain was used. The time domain was used to accurately depict the current distribution, whereas the frequency domain was used to graphically depict the potential distribution across the external lightning protection network. To evaluate the performance of each grounding system, calculations were performed in the frequency domain for better graphical illustrations.

When considering a LPL III or IV lightning impulse as per the outcomes of the lightning risk analysis, a first negative waveshape was used as this accounts for 90 percent of all occurrences with a magnitude of 50 kA. The lightning simulation was conducted on the designed air-termination system for each building. The distribution of lightning was measured across each down-conductor, that accurately reflects the effect of the location of the lightning strike.

In Section 4.5, the Free State Provincial Government building had the lowest calculated earth resistance of 3.255 Ω with a GPR of 1 867.45 MV due to the presence of 10 earth electrodes in the soil. The Loch Logan Park building, on the other hand, had the highest calculated earth resistance of 4.965 Ω with a GPR of 2 848.70 MV due to the constrained number of down-conductors of six. The Boet Troskie Hall building was calculated to be the median of the other two buildings, with an earth resistance of 3.497 Ω and a GPR of 2 006.32 MV.

The Loch Logan Park building had the highest current distribution values in Section 4.5.1. Averaging 10.59 kA across the down-conductor system and ranging from 10.85 kA closest to the point of the strike to 10.36 kA furthest from the point of strike. The Boet Troskie Hall had the lowest calculated value of 6.28 kA in Section 4.5.3, with a value of 6.45 kA closest to the point of strike and 6.15 kA furthest from the point of strike. While the Free State Provincial Government building had a median value of 7.39 kA in Section 4.5.2, with a value of 8.96 kA closest to the point of strike and 5.52 kA furthest from the point of strike.

The Free State Provincial Government building had the highest potential distribution value. Ranging from 4 779 kV closest to the point of strike to 118.8 kV furthest away from the point of strike, as measured at the base of the down-conductor at the surface. The Boet Troskie Hall building had the lowest value, ranging from 659.8 kV closest to the point of strike to 115.8 kV at the base of the down-conductor at the surface. The Loch Logan Park building was determined to have the median value of the other two structures, ranging from 3 907 kV to 196.4 kV.

- To evaluate the proposed lightning protection system (LPS) in terms of lightning mitigation.

The conclusion was reached that the GPR that can be expected is primarily determined by the calculated earthing resistance and the magnitude of lightning current injected at the point of strike. The GPR calculated is proportional to the lightning current injected of 50 kA and the earth resistance. As a result of the higher values, lightning is considered to have a high frequency, resulting in a more complex calculation derivation. The Free State Provincial Government building had the lowest GPR compared to the other two buildings due to more conductors used in the earth-termination system that improved the earthing resistance of the LPS. Due to access constraints, the lightning simulation was conducted using a uniform soil resistivity of 100 Ω.m. A uniform soil model is frequently used for preliminary calculations or high-frequency calculations. At high frequencies, electromagnetic fields have a limited penetration depth into the soil and thus the results are unaffected by the soil resistivity of the depth layers.

With reference to Section 4.5, the number of down-conductors has a significant impact on current distribution. Therefore, it is important to use an adequate quantity in accordance with the requirements of the SANS 62305 lightning standard. In comparison, the highest average value calculated for Loch Logan Park of 10.59 kA is due to a reduced number of down-conductors, creating more strain on the LPS. The current distribution across each down-conductor in a building was relatively consistent throughout the LPS network. It did not exhibit any significant variation from the injection point to the further point. However, using a sufficient number of down-conductors reduces the stress on each conductor and connection, as demonstrated by the Free State Provincial Government building with a comparative structure layout such as the Loch Logan Park building, which has an average current distribution value of 7.39 kA.

When considering the height of the structure, the length of the down-conductors has the greatest influence on the potential distribution across the external LPS, as this creates a higher impedance for the current to distribute to the earth-termination system. This can be compared to the tallest building, the Free State Provincial Government building, which has a potential difference of 4 360.2 kV and the shortest building, the Boet Troskie building, which has a potential difference of 544 kV. In conclusion, the higher the potential difference value calculated over an external network, the more caution should be taken in designing an adequate LPS in respective to the LPL obtained from the lightning risk analysis. This is deemed an important aspect in order to prevent any arcing from the LPS to any metallic elements.

With reference to Section 3.5, the separation distance calculation confirmed that the distance to maintain from the metallic part is proportional to the height of the building and the number of down-conductors. The Free State Provincial Government building required the most significant separation distance to be maintained, with a value of 1.36 m. In contrast, the Loch Logan Park building only required 0.84 m to prevent any arcing to metallic elements.

5.4 Problem Statement Reviewed

The original problem statement given in Chapter 1 stated: using adequate protection measures implemented on building structures can lead to lightning risk being mitigated to a tolerable level. The problem is that there are many environmental and structural factors that can affect the likelihood of damage and loss occurring with or without protection. These factors influence the current and potential distribution on a building that needs to be quantified in order to identify mitigation techniques. Designing protective measures for buildings based on lightning simulation software also proves challenging as specialised knowledge in this field is required.

A lightning risk analysis was conducted to determine the probability of a direct and nearby lightning strike to any of the buildings to establish the source of damage and the types of losses that may occur during an event. Based on the state of each building without protection measures, it was deemed necessary to implement a class of LPS III for the Free State Provincial Government building and Loch Logan Park building in order to provide protection for human life inside the buildings from electric shock due to touch and step voltages inside the building. Also to protect the building from economic stress due to physical damage caused by dangerous sparking inside the building, triggering a fire or an explosion if there are gas cylinders in the building. To prevent failure of electrical and electronic systems in a lightning event, it is advised to implement adequate measures, namely, SPDs and fire protection measures. According to the outcomes of the risk analysis performed for the Boet Troskie Hall building, there were no external LPS required and only SPDs were deemed sufficient. However, a class of LPS IV was implemented for lightning simulation purposes, as this is the lowest level of external protection.

The current and potential distribution were simulated over the external LPS in order to establish the effect and severity that lightning has on a building. This was, however, simulated to illustrate the need for adequate protection measures. The values measured for each building were compared to provide a clear understanding of the functionality of a LPS designed by a specialist and the provision of an uncompliant system would drastically affect the outcomes of the protection of human life and economic values.

5.5 Future Work That Can Still Be Done

With the current state of LPS being implemented and the significant cost involved in designing and implementing the system, more research should be conducted on the effect of lightning. Not only to determine the current and potential distribution values that a LPS would experience in the event of a direct lightning strike to the structure, but also to determine the electrical field strength and electromotive force. This would be used to determine whether the cost of materials required to implement a particular application can be reduced by up to a percentile where the system is deemed non-compliant and the associated losses exceed the benefits of having an LPS.

The second recommendation would be to investigate the effect that a lightning impulse would have on a particular building in the event of a nearby lightning strike or direct lightning strike to any nearby structure. This would be beneficial to determine the important aspects of SPDs and whether they are deemed sufficient to use as the only method of risk mitigation. Additionally, the location of SPDs should be considered, whether they should be installed only on incoming power supply lines or on downstream equipment. Thirdly, it would be prudent to investigate the effect of lightning on various types of materials and sizes used in LPSs. This would be the focal point for determining whether it is mandatory to use materials that have been tested to withstand the impact and forces of a direct lightning strike.

The fourth recommendation would be to determine whether education is sufficient to introduce the community to the various aspects of lightning protection in order to make this a subject in universities or other educational institutions.

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ANNEXURE A: LIGHTNING RISK COMPONENTS

Each type of damage, either alone or in combination with others, may result in a different type of consequential loss to the protected structure. The type of loss that may occur is determined by the structure's characteristics and content. The following types of loss are to be considered [7].

- L_1 - loss of human life (including permanent injury);
- L_2 - loss of service to the public;
- L_3 - loss of cultural heritage;
- L_4 - loss of economic value (structure, content and loss of activity).

To evaluate risks, it is necessary to define and calculate the relevant risk components (partial risks depending on the source and type of damage). Each risk is equal to the sum of its constituent risks. When calculating a risk, it is possible to categorise the risk components according to the source of the damage and the type of damage. The source of the damage and the associated risk is as follows [7]:

S_1 – Flashes to the structure/building

R_A – Component related to injury to living beings caused by electric shock due to touch and step voltages inside the structure and outside in the zones up to 3 m around down-conductors. Loss of type L_1 and, in the case of structures holding livestock, loss of type L_4 with possible loss of animals may also arise.

R_B – Component related to physical damage caused by dangerous sparking inside the structure, triggering fire or explosion which may also endanger the environment. All types of loss (L_1, L_2, L_3 and L_4) may arise.

R_C – Component related to failure of internal systems caused by LEMP. Loss of type L_2 and L_4 could occur in all cases along with type L_1 in the case of structures with risk of explosion and hospitals or other structures where failure of internal systems immediately endangers human life.

S_2 – Flashes near the structure/building

R_M – Component related to failure of internal systems caused by LEMP. Loss of type L_2 and L_4 could occur in all cases, along with type L_1 in the case of structures with risk of explosion, and hospitals or other structures where failure of internal systems immediately endangers human life.

S_3 – Flashes to a line connected to the structure

R_U – Component related to injury to living beings caused by electric shock due to touch voltage inside the structure. Loss of type L_1 and, in the case of agricultural properties, losses of type L_4 with possible loss of animals could also occur.

R_V – Component related to physical damage (fire or explosion triggered by dangerous sparking between external installation and metallic parts generally at the entrance point of the line into the structure) due to lightning current transmitted through or along incoming lines. All types of loss (L_1, L_2, L_3 and L_4) may occur.

R_W – Component related to failure of internal systems caused by overvoltages induced on incoming lines and transmitted to the structure. Loss of type L_2 and L_4 could occur in all cases, along with type L_1 in the case of structures with risk of explosion and hospitals or other structures where failure of internal systems immediately endangers human life.

S_4 – Flashes near a line connected to the structure

R_Z – Component related to failure of internal systems caused by overvoltages induced on incoming lines and transmitted to the structure. Loss of type L_2 and L_4 could occur in all cases, along with type L_1 in the case of structures with risk of explosion and hospitals or other structures where failure of internal systems immediately endangers human life.

ANNEXURE B: LOCH LOGAN PARK BUILDING CURRENT DISTRIBUTION

Figure A depicts the waveform and current value measured at the Loch Logan Park building's 1st down-conductor during a direct lightning strike. In contrast, Figure B depicts the waveform at the 2nd down-conductor.

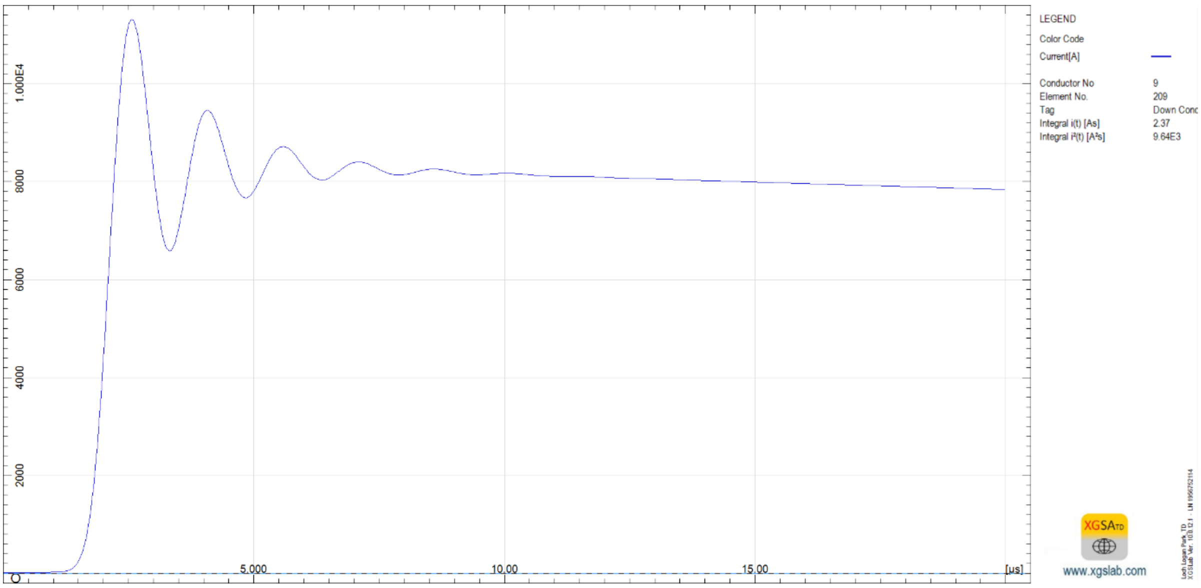

Figure A: Loch Logan Park building 1st down-conductor current distribution

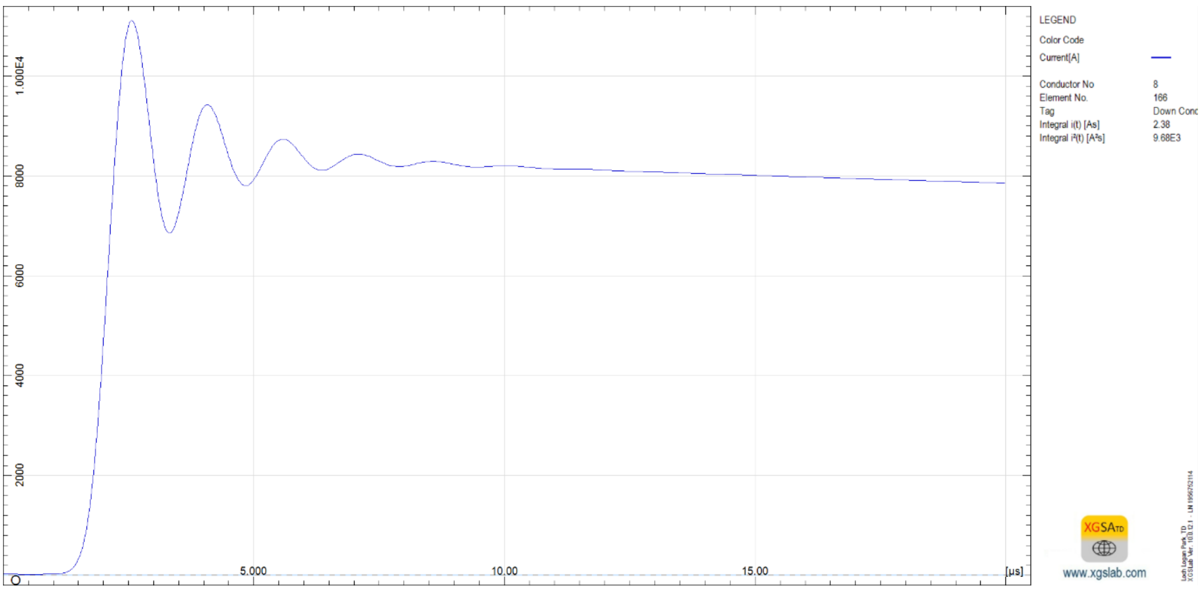

Figure B: Loch Logan Park building 2nd down-conductor current distribution

Figure C depicts the waveform and current value measured at the Loch Logan Park building's 4th down-conductor during a direct lightning strike. In contrast, Figure D depicts the waveform at the 6th down-conductor.

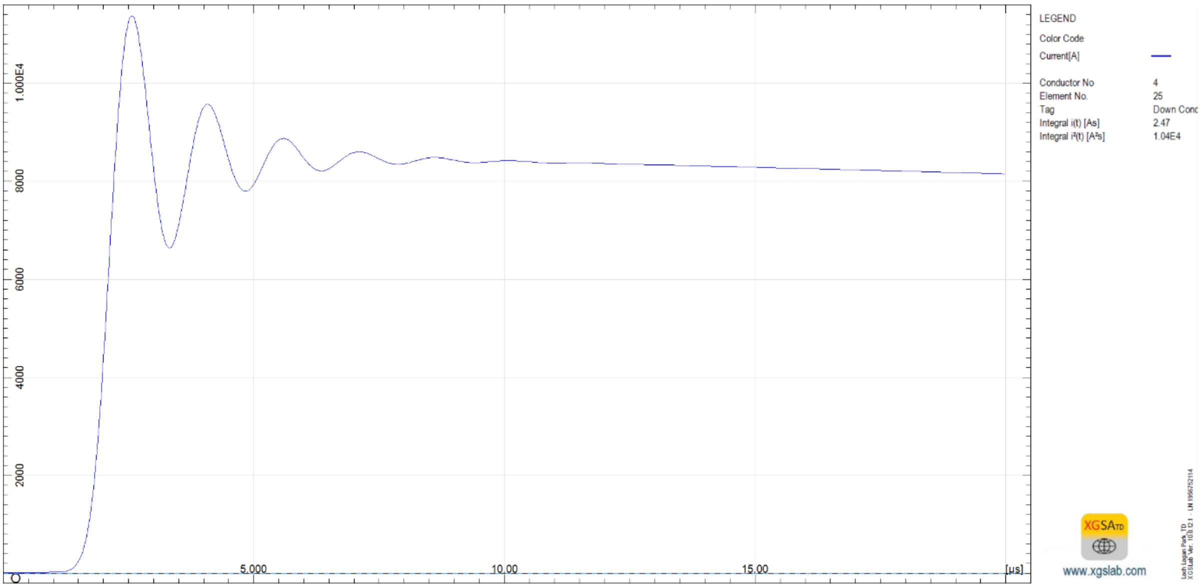

Figure C: Loch Logan Park building 4th down-conductor current distribution

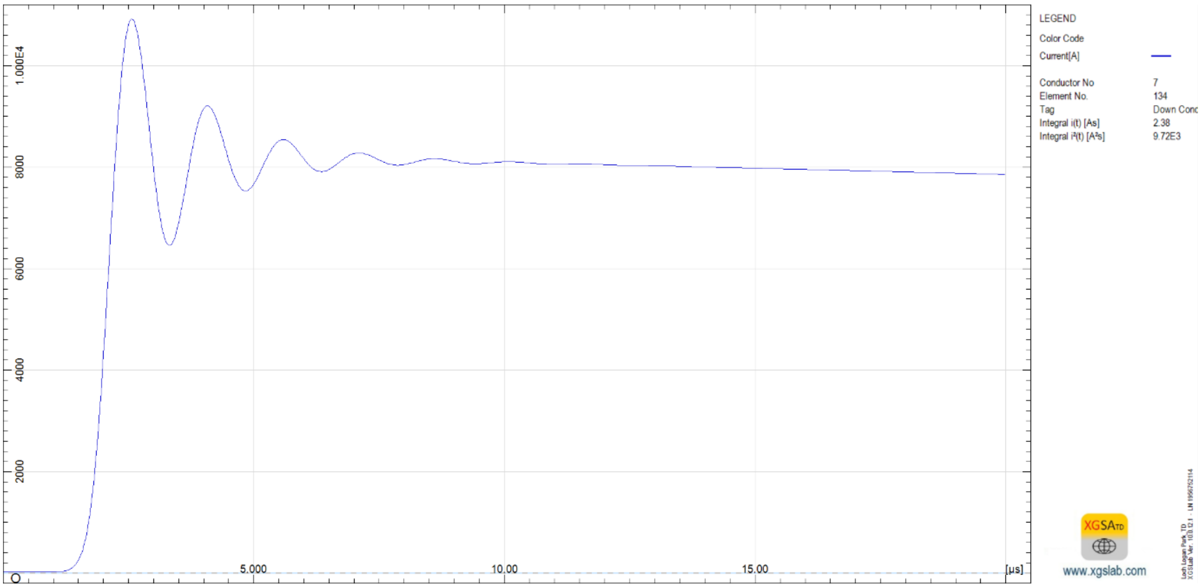

Figure D: Loch Logan Park building 6th down-conductor current distribution

ANNEXURE C: LOCH LOGAN PARK BUILDING POTENTIAL DISTRIBUTION

The potential distribution values measured over the LPS for the Loch Logan Park building during a direct lightning strike are depicted in figures E and F.

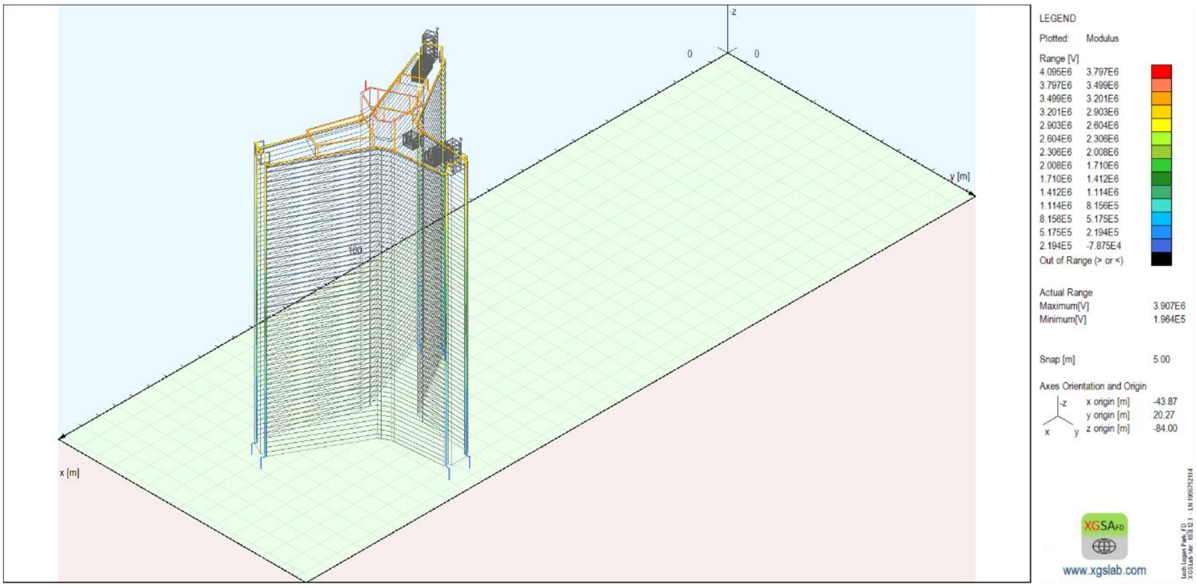

Figure E: Loch Logan Park building LPS potential distribution – 3D view

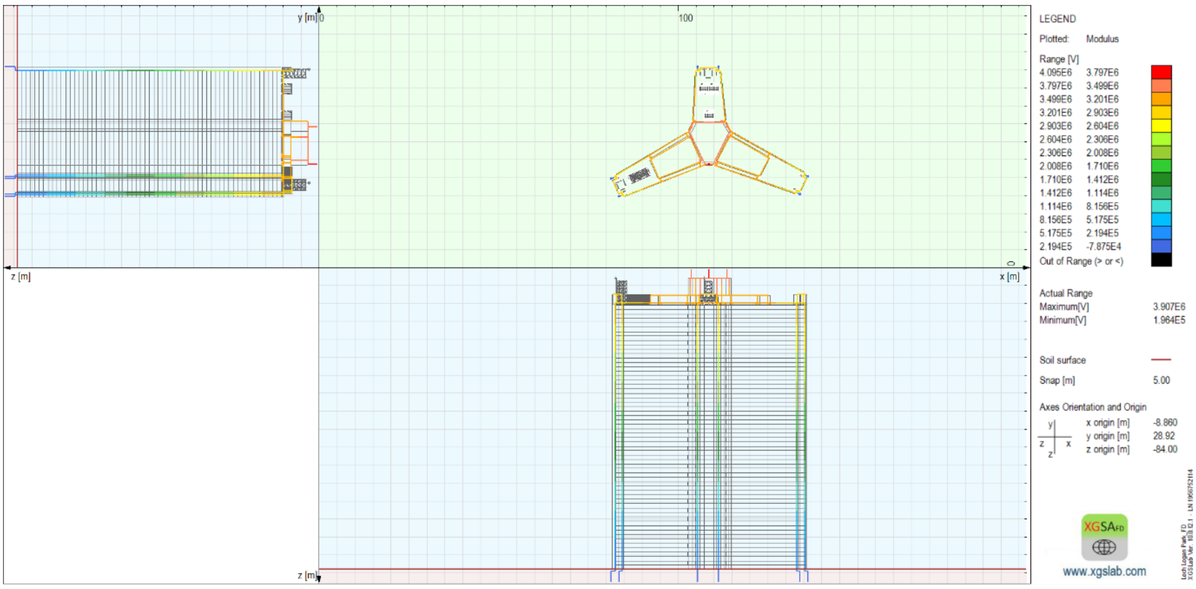

Figure F: Loch Logan Park building LPS potential distribution – 2D view

ANNEXURE D: FREE STATE PROVINCIAL GOVERNMENT BUILDING CURRENT DISTRIBUTION

Figure G depicts the waveform and current value measured at the Free State Provincial Government building's 1st down-conductor during a direct lightning strike. In contrast, Figure H depicts the waveform at the 2nd down-conductor.

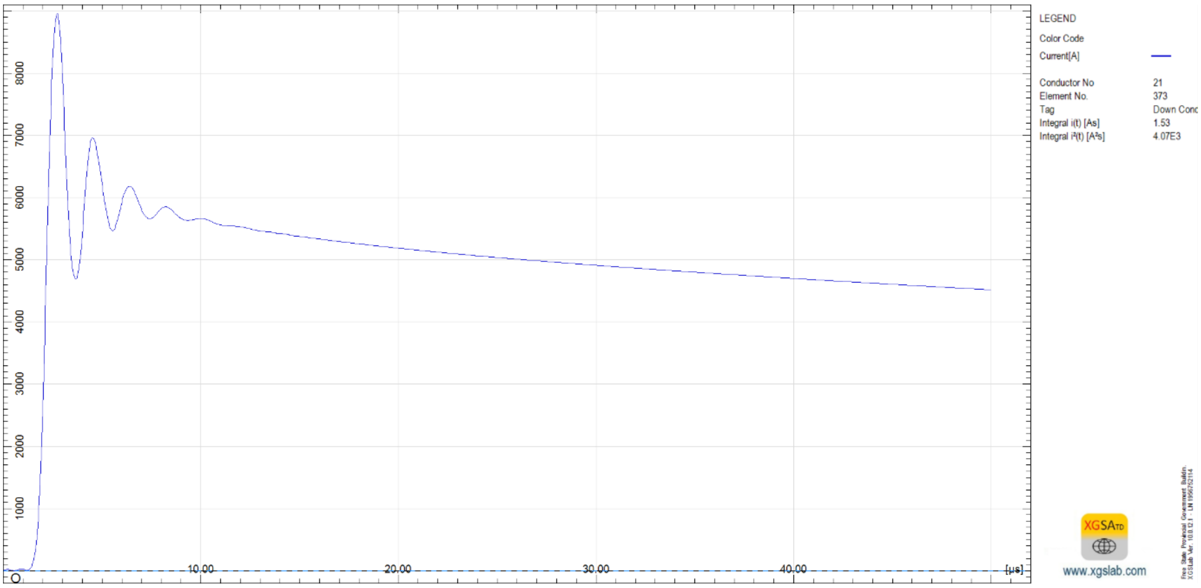

Figure G: Free State Provincial Government building 1st down-conductor current distribution

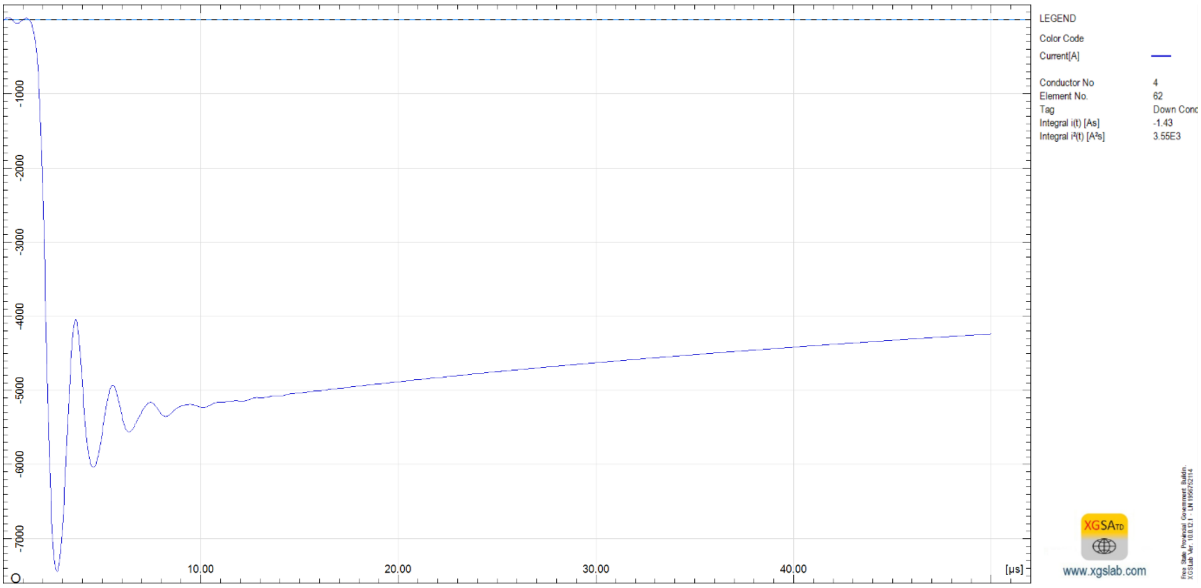

Figure H: Free State Provincial Government building 2nd down-conductor current distribution

Figure I depicts the waveform and current value measured at the Free State Provincial Government building's 4th down-conductor during a direct lightning strike. In contrast, Figure J depicts the waveform at the 5th down-conductor.

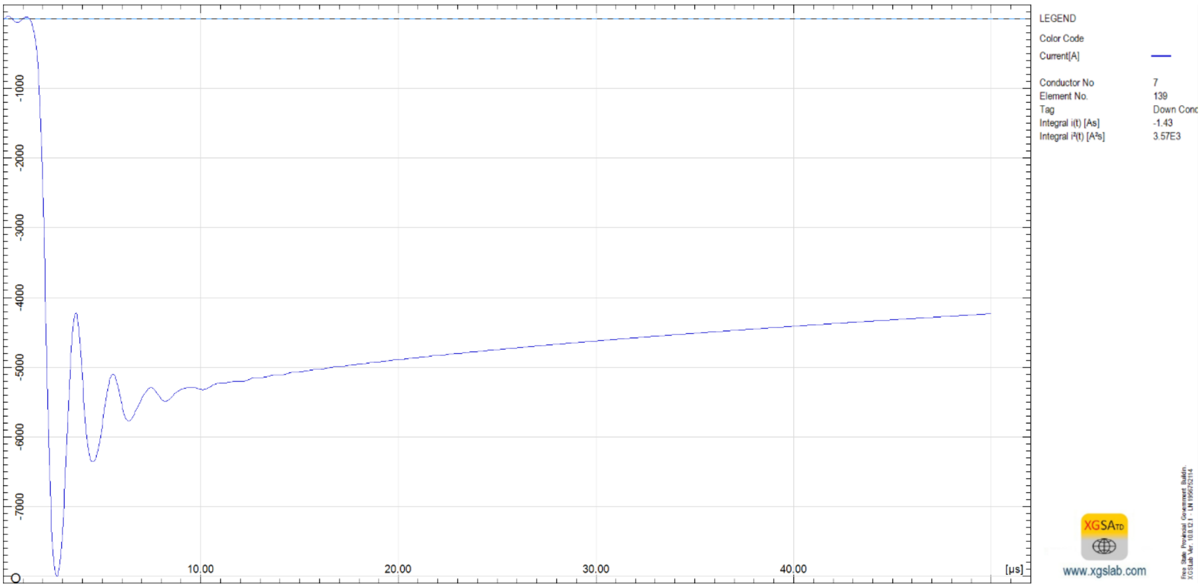

Figure I: Free State Provincial Government building 4th down-conductor current distribution

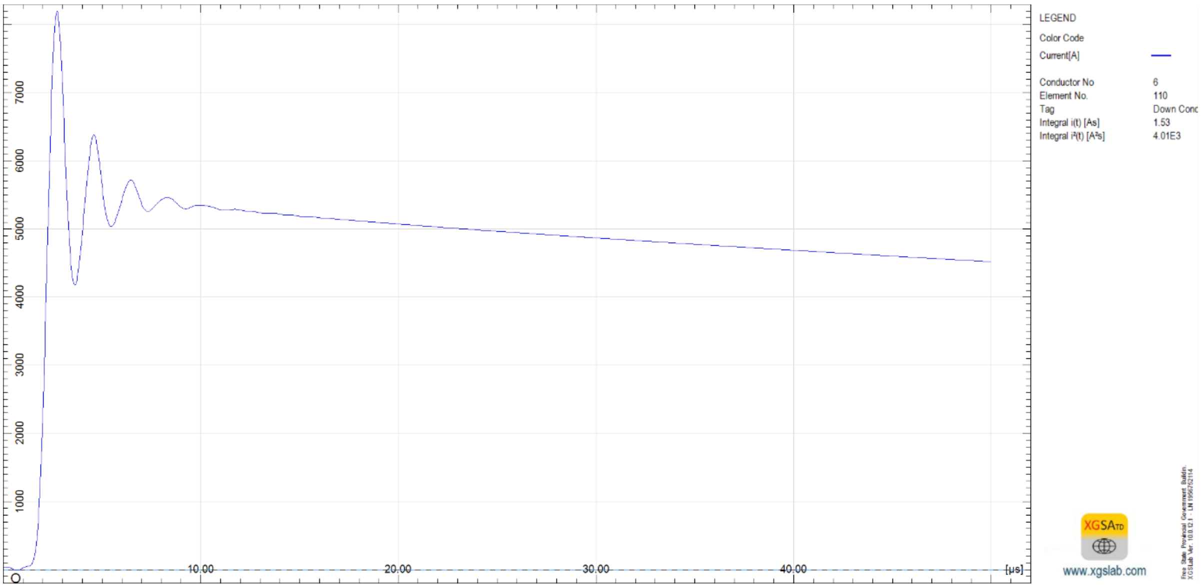

Figure J: Free State Provincial Government building 5th down-conductor current distribution

Figure K depicts the waveform and current value measured at the Free State Provincial Government building's 6th down-conductor during a direct lightning strike. In contrast, Figure L depicts the waveform at the 7th down-conductor.

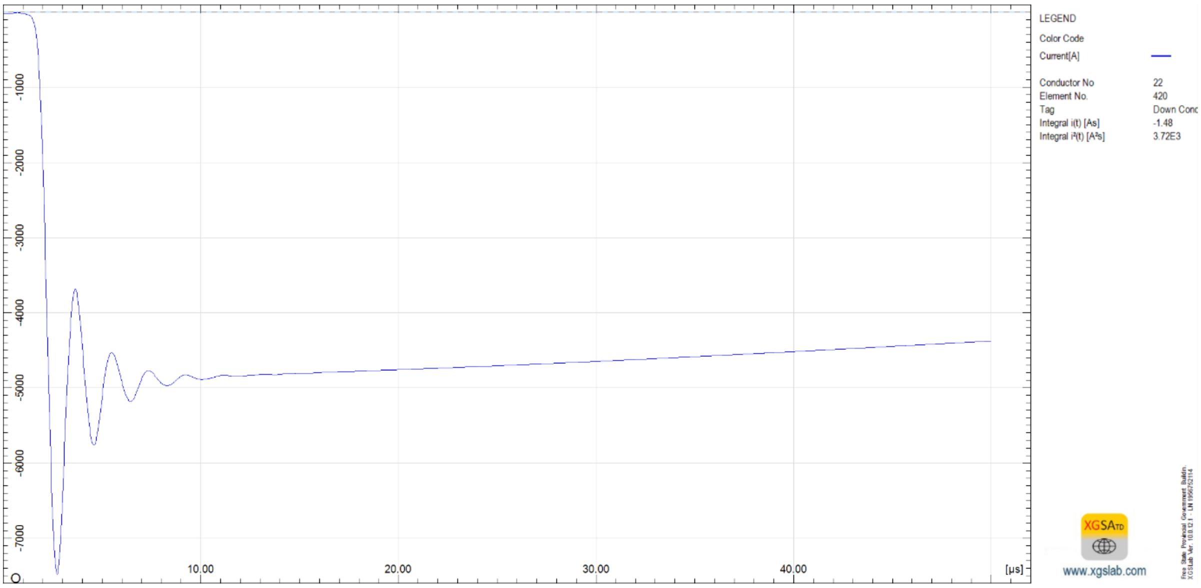

Figure K: Free State Provincial Government building 6th down-conductor current distribution

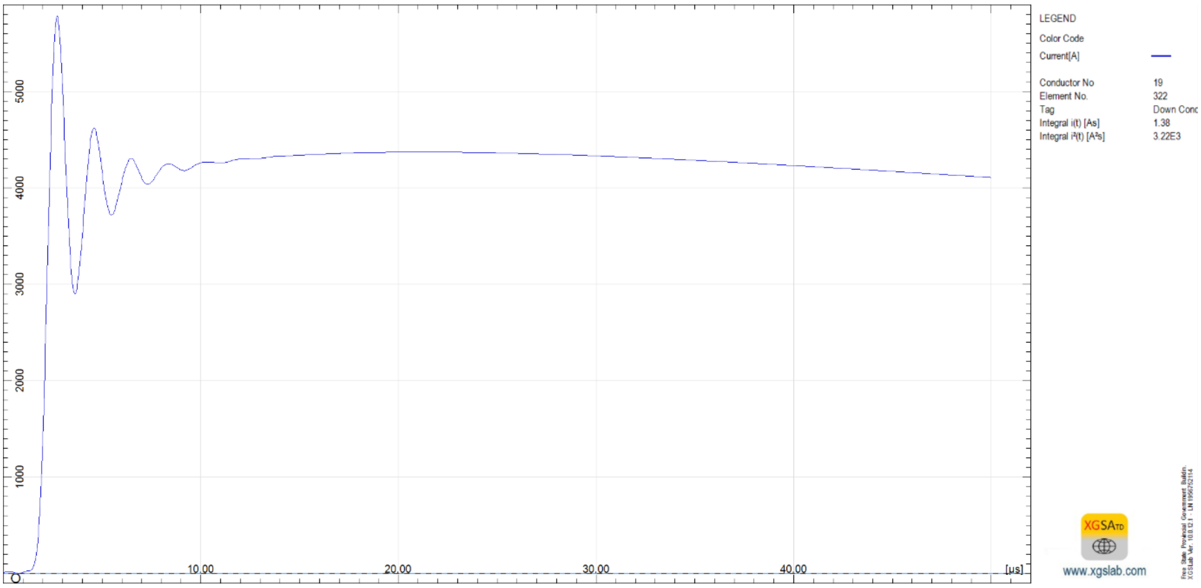

Figure L: Free State Provincial Government building 7th down-conductor current distribution

Figure M depicts the waveform and current value measured at the Free State Provincial Government building's 9th down-conductor during a direct lightning strike. In contrast, Figure N depicts the waveform at the 10th down-conductor.

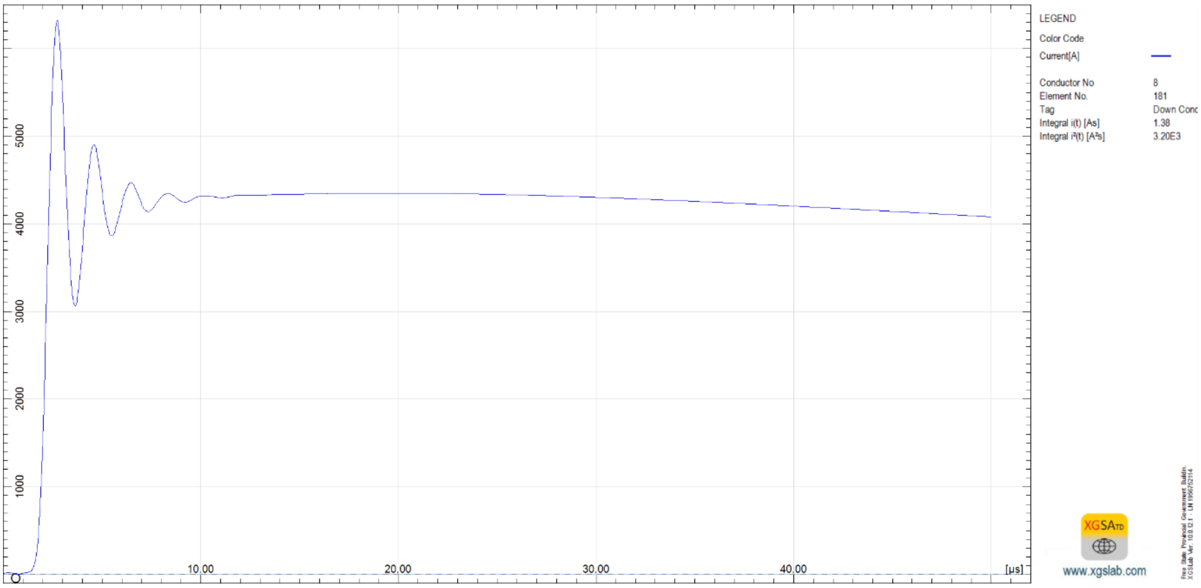

Figure M: Free State Provincial Government building 9th down-conductor current distribution

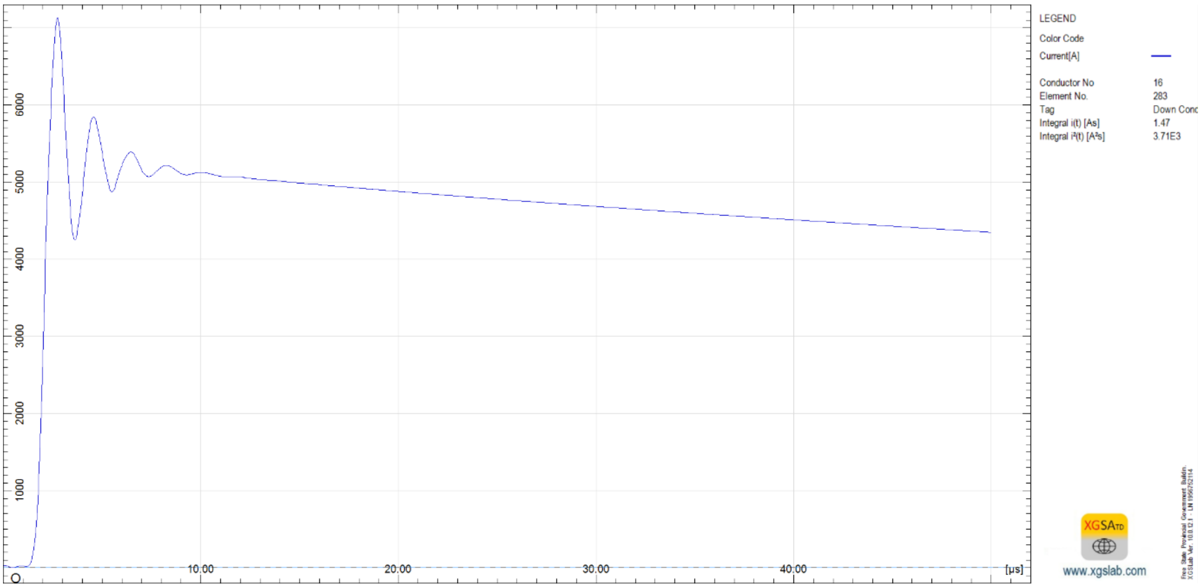

Figure N: Free State Provincial Government building 10th down-conductor current distribution

ANNEXURE E: FREE STATE PROVINCIAL GOVERNMENT BUILDING POTENTIAL DISTRIBUTION

The potential distribution values measured over the LPS for the Free State Provincial Government building during a direct lightning strike are depicted in figures O and P.

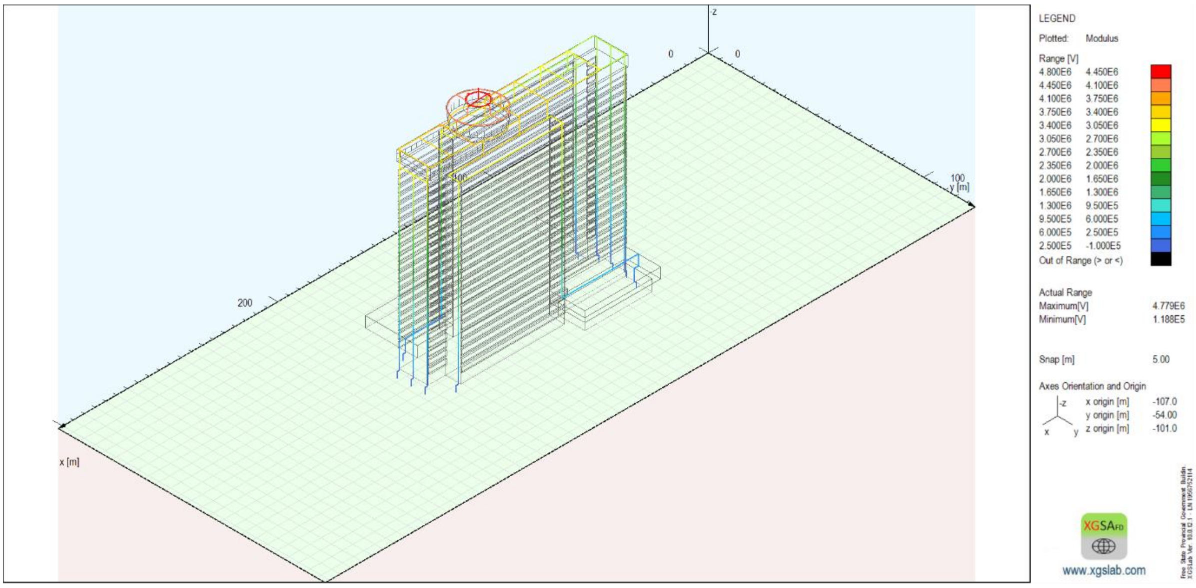

Figure O: Free State Provincial Government building LPS potential distribution – 3D view

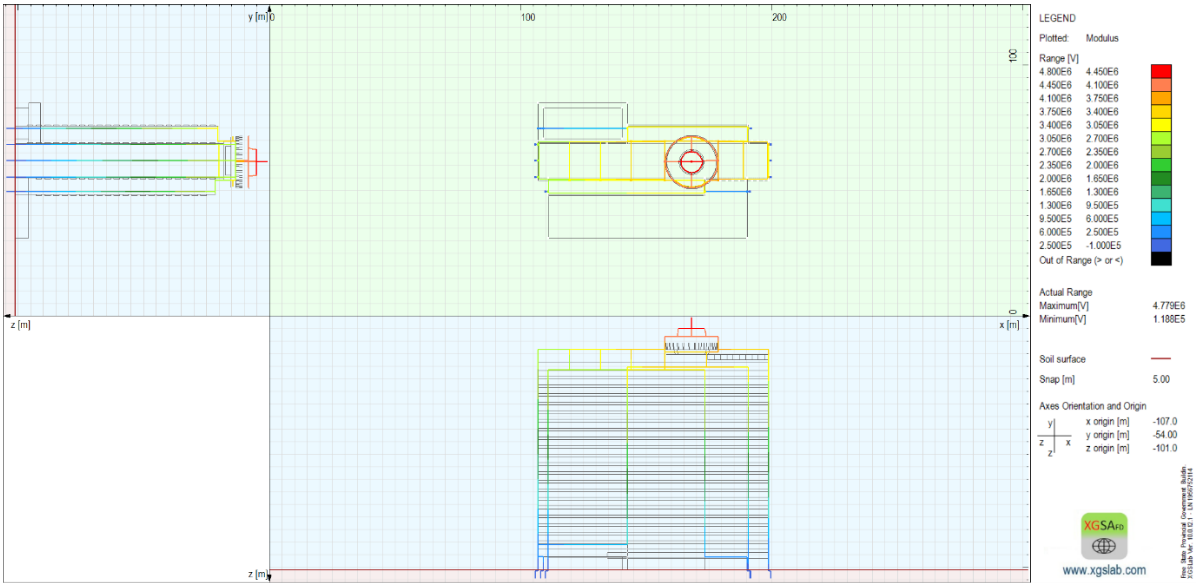

Figure P: Free State Provincial Government building LPS potential distribution – 2D view

ANNEXURE F: BOET TROSKIE HALL BUILDING CURRENT DISTRIBUTION

Figure Q depicts the waveform and current value measured at the Boet Troskie Hall building's 2nd down-conductor during a direct lightning strike. In contrast, Figure R depicts the waveform at the 3rd down-conductor.

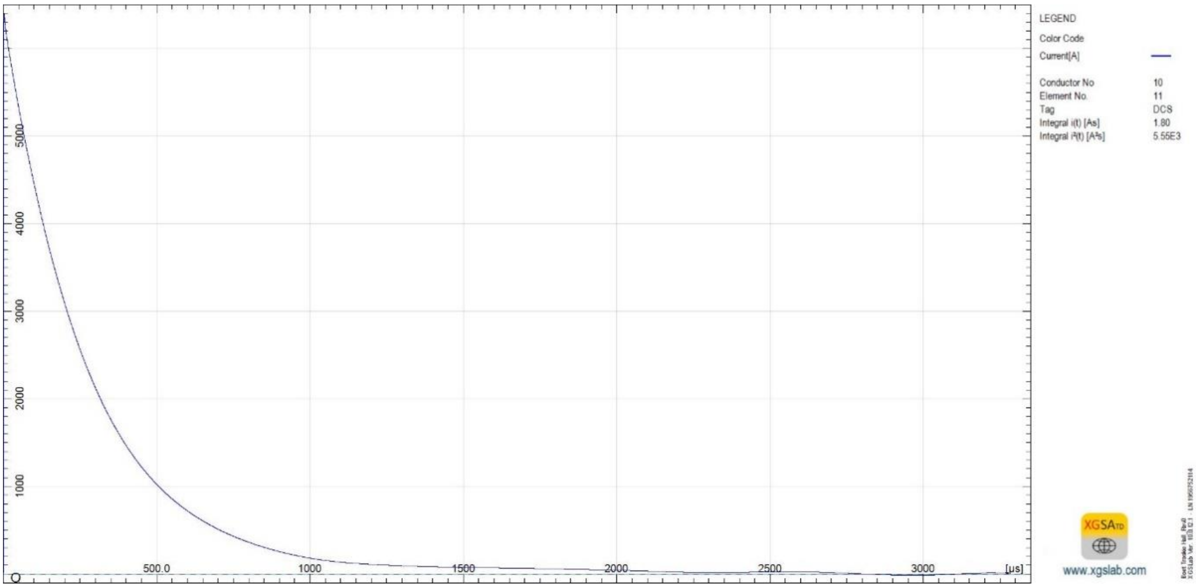

Figure Q: Boet Troskie Hall building 2nd down-conductor current distribution

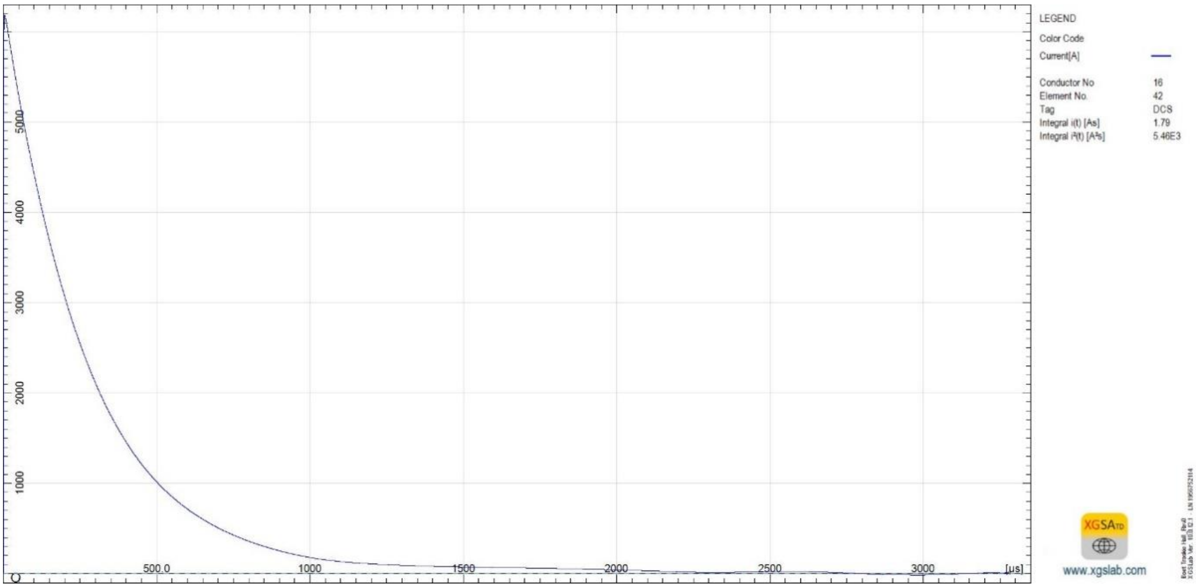

Figure R: Boet Troskie Hall building 3rd down-conductor current distribution

Figure S depicts the waveform and current value measured at the Boet Troskie Hall building's 5th down-conductor during a direct lightning strike. In contrast, Figure T depicts the waveform at the 6th down-conductor.

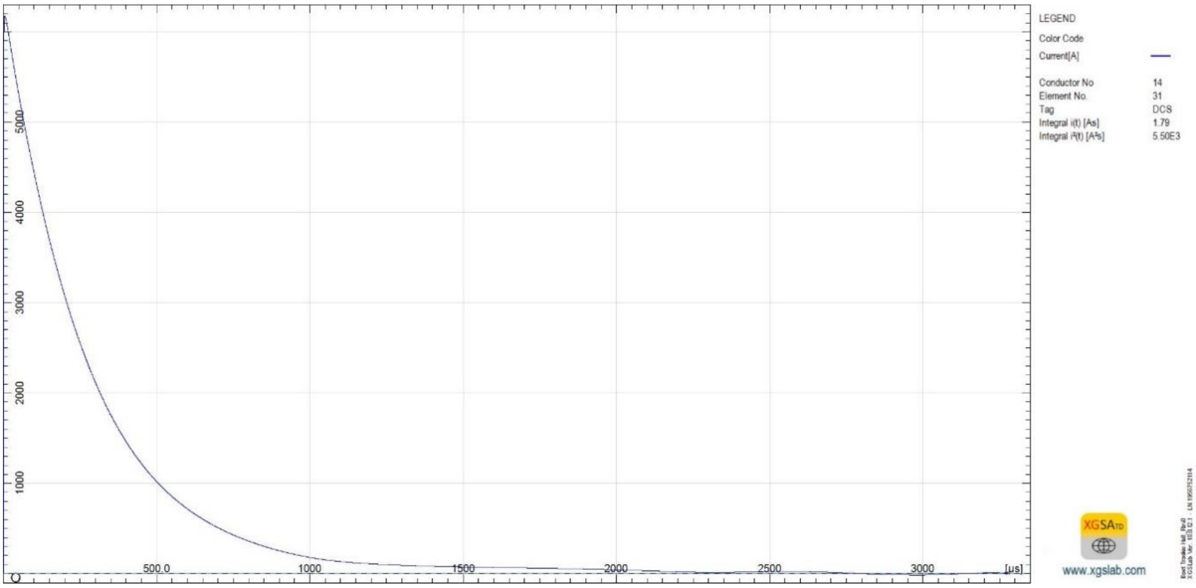

Figure S: Boet Troskie Hall building 5th down-conductor current distribution

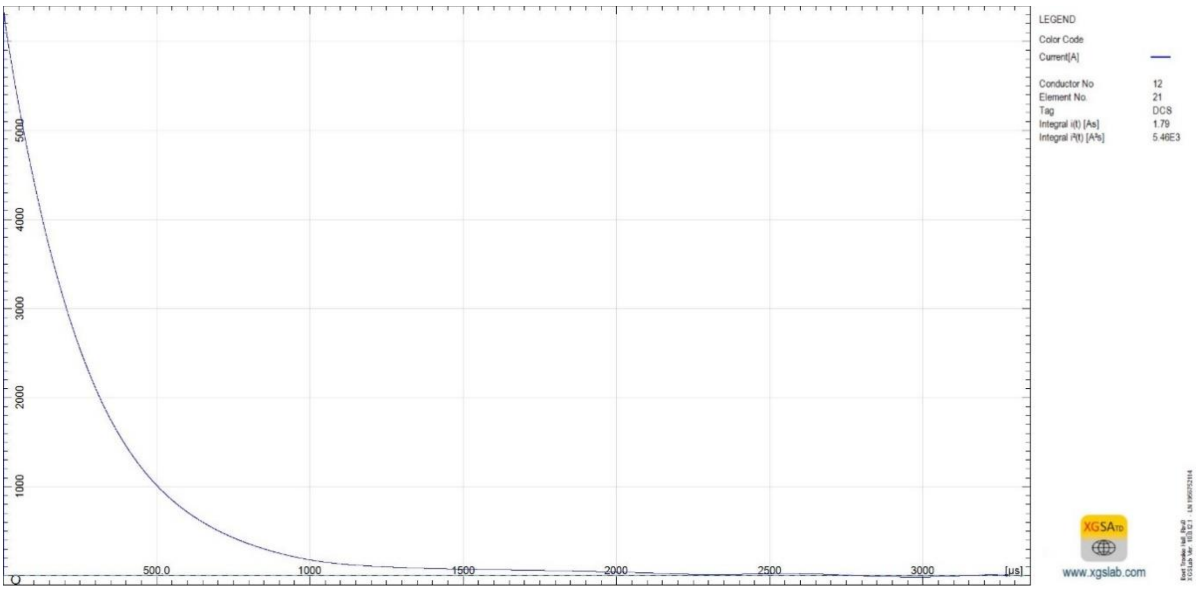

Figure T: Boet Troskie Hall building 6th down-conductor current distribution

Figure U depicts the waveform and current value measured at the Boet Troskie Hall building's 7th down-conductor during a direct lightning strike. In contrast, Figure V depicts the waveform at the 8th down-conductor.

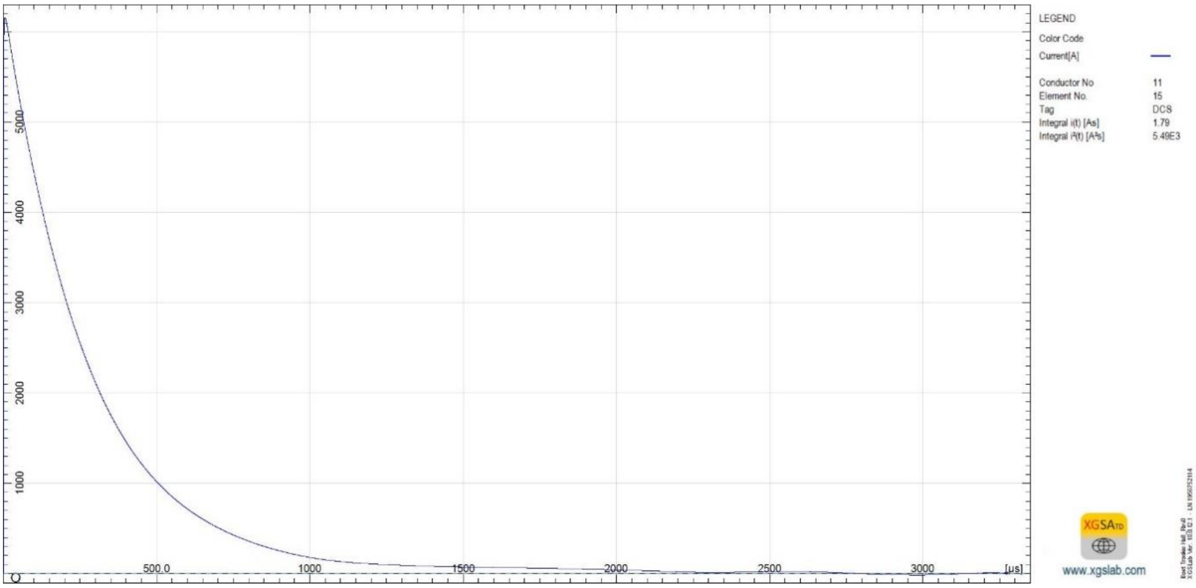

Figure U: Boet Troskie Hall building 7th down-conductor current distribution

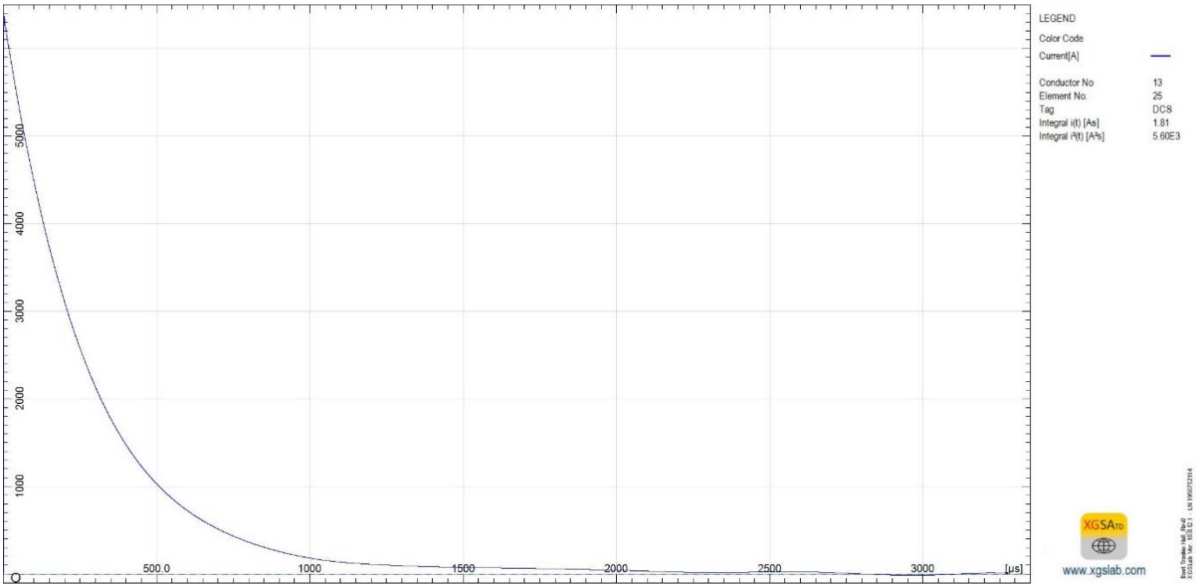

Figure V: Boet Troskie Hall building 8th down-conductor current distribution

ANNEXURE G: BOET TROSKIE HALL BUILDING POTENTIAL DISTRIBUTION

The potential distribution values measured over the LPS for the Boet Troskie Hall building during a direct lightning strike are depicted in figures W and X.

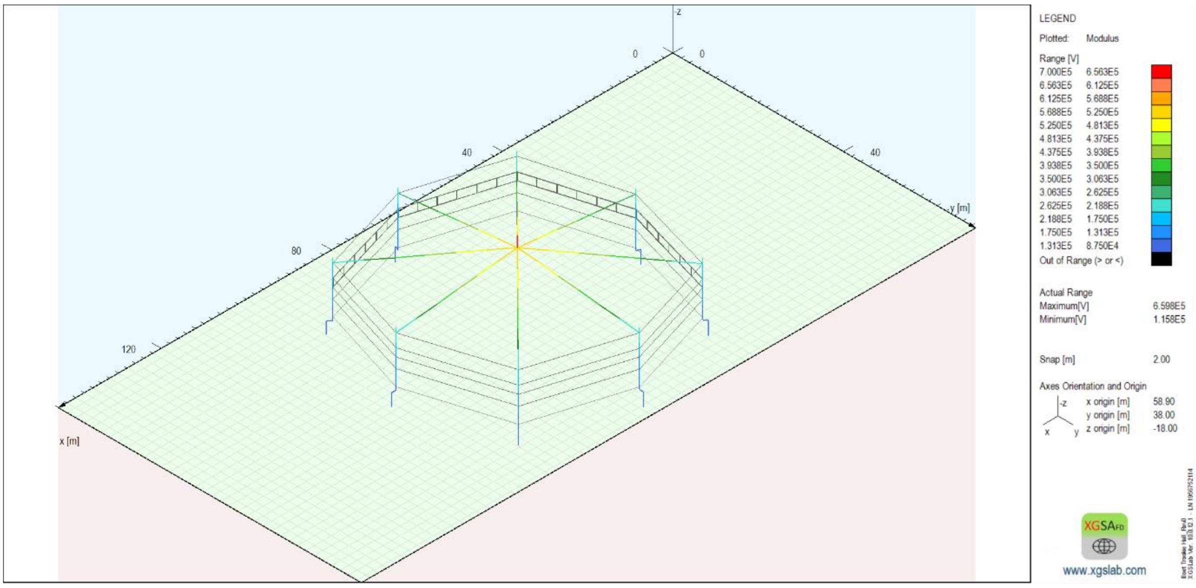

Figure W: Boet Troskie Hall building LPS potential distribution – 3D view

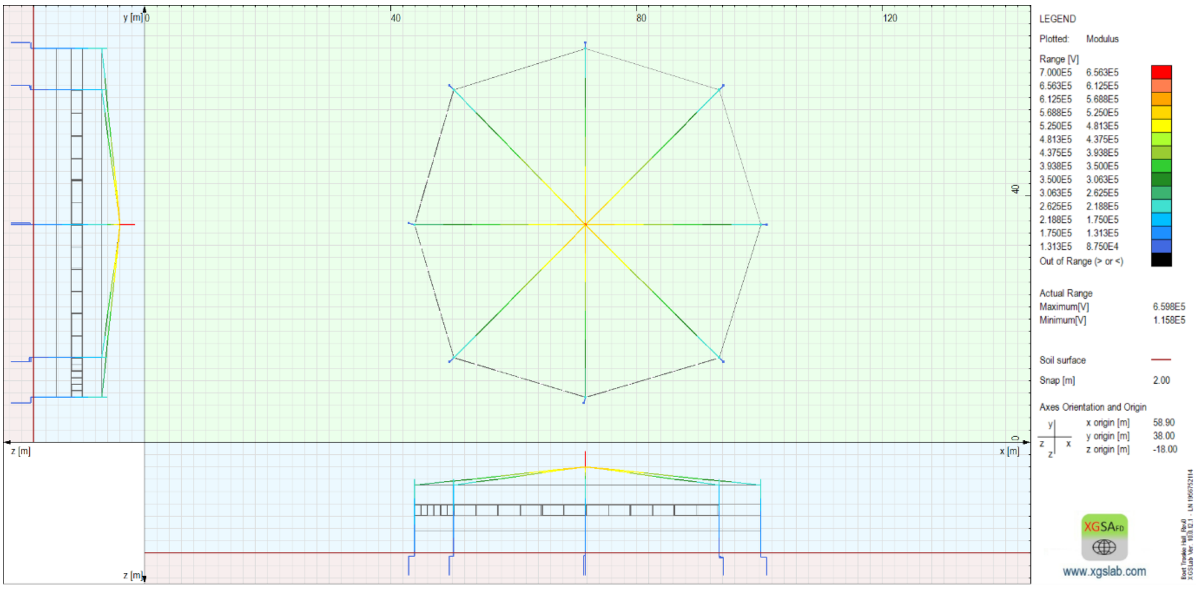

Figure X: Boet Troskie Hall building LPS potential distribution – 2D view