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ELEN4000 – EIE DESIGN

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Design of an external lightning protection system for a clinic in Mbabane, Eswatini.

ABSTRACT

This paper presents a comprehensive External Lightning Protection System (ELPS) design for an off-grid clinic located in Mbabane, Eswatini. The clinic's remote setting, sensitive medical equipment, and the well-being of its occupants necessitate a meticulous approach to lightning protection. The design process encompasses risk assessment, air terminal placement using the rolling sphere method, optimal down conductor sizing, and efficient earthing system design. The risk assessment aims to identify vulnerabilities, guiding the strategic placement of air terminals to divert lightning strikes. Down conductor sizing ensures controlled current flow, and the earthing system disperses energy into the ground. The tailored approach is applied to three distinct structures: the clinic building, substation, and parking lot. The post-installation risk assessment demonstrates significant risk reduction, emphasizing the system's effectiveness in safeguarding life and services. The design's sustainability, reliability, and maintenance aspects are highlighted, along with its social, economic, and environmental impacts. Recommendations include optimized air terminal height and corrosion prevention. This paper showcases the proactive approach taken to ensure safety, innovation, and sustainability in lightning protection design for critical infrastructures.

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1. INTRODUCTION

In the effort to secure the safety and reliability of an off-grid clinic situated in Mbabane, Eswatini, a comprehensive External Lightning Protection System (ELPS) design is imperative. The clinic's remote location, the vulnerability of its medical equipment, and the well-being of its occupants underscore the necessity of such a system. The design process involves a meticulous risk assessment, the strategic placement of air terminals using the rolling sphere method, the calculation of proper down conductor sizes, and the creation of an efficient earthing system. The risk assessment serves as the foundation of the design, identifying potential vulnerabilities and consequences of lightning strikes. This assessment guides the overall strategy, ensuring that the ELPS addresses critical areas effectively. The air termination system, designed through the rolling sphere method, guarantees that air terminals are positioned to divert lightning strikes away from vulnerable sections, including the flat roof and solar panels. By calculating the minimum required cross-sectional area, the down conductor design is tailored to efficiently channel lightning current to the ground without causing harm to the building or occupants. Additionally, the earthing system design employs the soil's resistivity to create a low-resistance pathway for the lightning's energy, effectively dispersing it into the ground.

2. CLINIC LAYOUT AND ENVIRONMENTAL DESCRIPTION

The clinic, nestled in the heart of Mbabane, Eswatini, stands as a beacon of medical care and resilience in a vibrant urban landscape. Comprising three distinct structures, this healthcare facility embodies a commitment to serving the community with compassion and excellence. The main clinic building, characterized by its sleek design and flat roof, is adorned with solar panels and ventilators that testify to its eco-conscious approach to healthcare delivery. With a height of seven meters, it reaches out toward the sky, and these elevated elements make it both innovative and susceptible to the natural forces that surround it.

Adjacent to the main clinic, is the substation with the energy of electrical distribution, ensuring uninterrupted power supply. The parking lot, accommodating the flow of vehicles and visitors, provides a vital gateway to care. Amidst this dynamic environment, a thoughtful lightning protection system is imperative to safeguard the clinic, its equipment, and its occupants. As the clinic operates off the grid, harnessing the power of solar energy, the vulnerability to lightning-induced surges is a paramount concern. Addressing the unique challenges presented by the clinic's design, its rooftop assets, and the prevailing environmental conditions, the lightning protection system design must strike a balance between innovation, sustainability, and uncompromising safety.

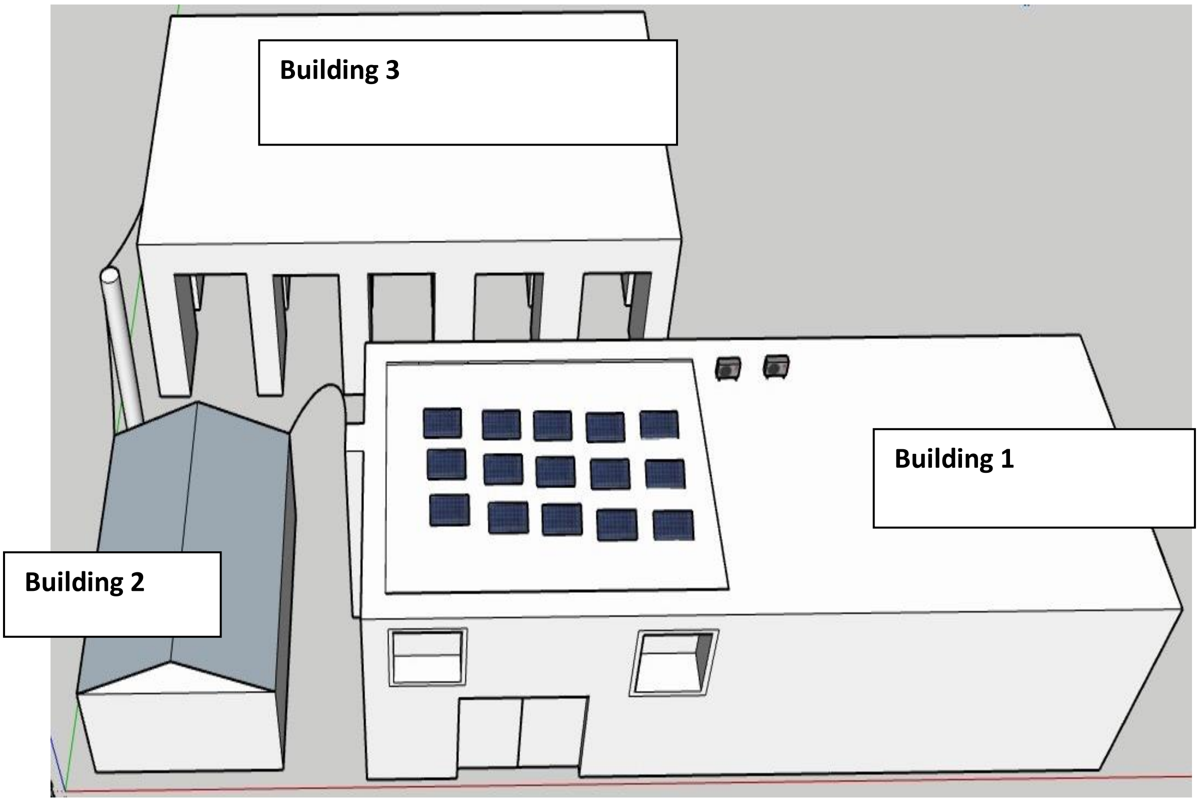

Figure 1: Clinic Layout

3. LIGHTNING HAZARDS TO THE CLINIC

i. Lightning Phenomenon:

- Natural electrical discharge due to charge imbalances between ground and atmosphere.
- Thunderclouds induce opposite charges on buildings.
- Stepped leader develops from cloud to ground, creating ionized path.

ii. Main Lightning Strike:

- Stepped leader connects with upward leader from structures.
- Intense lightning bolt with high currents moves upward.
- Heat generated leads to shock waves known as thunder.
- This can stress building materials, causing damage.

iii. Voltage Dangers:

- Step voltage: voltage difference between feet on ground.
- Touch voltage: voltage difference between person/object and ground.
- Lightning-induced currents cause step and touch voltages.
- Risk of electric shock when exposed to differing potentials.

iv. Factors Influencing Risk:

- Lightning strike magnitude, proximity, path, and nearby conductive materials.

- Soil conductivity affects current spread and voltage formation.

v. **Direct Strike Effects:**

- Lightning induces voltages in conductive materials.
- Increases touch and step voltage hazards.
- Frequency of lightning strikes impacts risk levels.

4. RISK ASSESSMENT

Risk evaluation involves analysing the geographical situation of the clinic, frequency of lightning strikes, the height of the building, and its distance from delicate equipment. Grasping these variables enables us to customize our plans to reduce threats to both people's safety and the clinic's crucial functions. A risk assessment was conducted to ascertain the degree of risk associated with the clinic's structures and the overall premises. This assessment was then compared against an established values for tolerable risk, using computed risk values that correspond to specific categories of potential loss [1]. The predefined tolerable risk values are outlined in table 4 of the SANS62305-2 document [13].

R1- Risk of loss of human life

R2- Risk of loss of service to the public

R3- Risk of loss of cultural heritage

R4- Risk of loss of economic value

Identifying risk components:

- Each primary risk is composed of several risk components. A risk component relates to a different relationship between source damage and the type of damage.
- Risk components R_A, R_B, R_C, R_M, R_U, R_V, R_W and R_z are all attributed to lightning flashes either to or near the structure or the service lines supplying the structure [17]. They involve injuries caused by electric shock, physical damage caused by dangerous sparking and failure of the internal system. The risk components are defined on Appendix B.
- The risk components can be evaluated using equation 1.

$$R_X = N_X \times P_X \times L_X \quad (1)$$

Where:

N_X is the annual number of dangerous events.

P_X is the probability of damage to the structure.

L_X is the amount of loss to a structure.

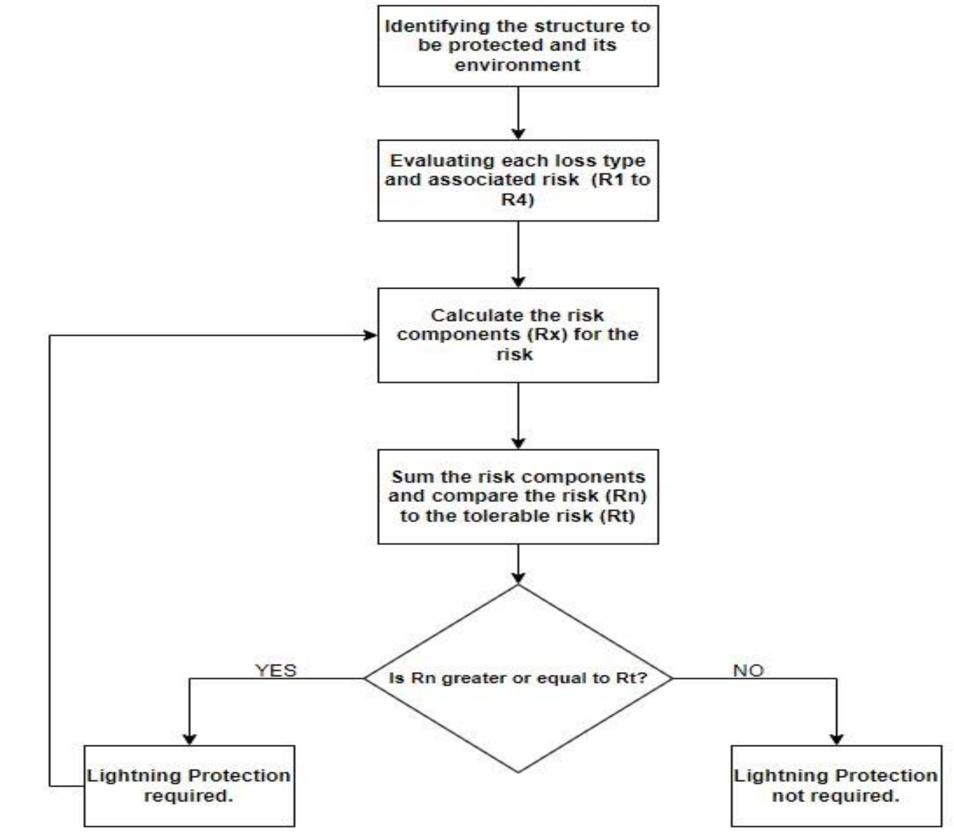

Figure 2: Flowchart of risk assessment general process

A risk assessment is performed for each building in Figure 1 and is represented in the form of a table.

Risk assessment for Building 1 (Clinic main building)

Building 1 is the main clinic with patient and workers are mostly present, and the solar panels are place on the roof as well as 2 air-conditioners. It also has overhead lines going to the parking lot (for lights) and the substation. The loss of human life (L1), loss of public service (L2), loss of cultural heritage (L3) and loss of economic value (L4) are considered for this evaluation [13]. Considering low voltage power lines to distribute energy between buildings with parameters stated on SANS62305-2 [13]. Appendix B includes calculations and assumptions for the risk assessment for each building.

Table 1: Summary of the risks of the building

	Risk components (10^{-6})								Total Risk (10^{-6})
	R_A	R_B	R_C	R_M	R_U	R_V	R_W	R_z	
RISK 1	35.5	0.8875			8.35	0.20875			44.946
RISK 2		0.8875				0.20875			1.096
RISK 3		0.8875				0.20875			1.096
RISK 4		0.8875	0.8875	103800		0.20875	167	167	104135.98

Table 1 tabulates the risk assessment results performed for building 1. From table 1, measures should be taken to reduce R_A which is the component related to injury to living beings by electric shock (step and touch voltage).

Risk Assessment for building 2.

Table 2: Summary of the risk assessment for building 2.

	Risk components (10^{-6})								Total Risk (10^{-6})
	R_A	R_B	R_C	R_M	R_U	R_V	R_W	R_z	
RISK 1	7.24	0.181			14.4	0.36			22.181
RISK 2		0.181				0.36			0.541
RISK 3		0.181				0.36			0.541
RISK 4		0.181	0.181	96000		0.36	288	288	96576.722

Table 2 tabulate the risk assessment results for building 2. For a substation reducing R4 which is the risk related to loss of economic value which can damage expensive electrical equipment is very crucial.

Risk Assessment for building 3.

Table 3: Summary of the risk assessment for building 3.

	Risk components (10^{-6})								Total Risk(10^{-6})
	R_A	R_B	R_C	R_M	R_U	R_V	R_W	R_z	
RISK 1	12	0.3			9.64	0.214			22.154
RISK 2		0.3				0.214			0.514

RISK 3		0.3				0.214			0.514
RISK 4		0.3	0.3	98400		0.241	192.8	192.8	98786.64

Table 3 tabulate the risk assessment results for building 3. For the parking lot measures should be taken to reduce R_U and R_M which are components relating indirect lightning strikes to injuring people and damaging cars.

5. RISK MANAGEMENT

Table 4: Comparing the risk assessment results with the tolerable risk values.

	Risk		Tolerable Risk R_T (y^{-1})	Comment
Building 1	R1	44.946×10^{-6}	10^{-5}	Class I LPS required.
	R2	1.096×10^{-6}	10^{-3}	
	R3	1.096×10^{-6}	10^{-4}	
	R4	104135.98×10^{-6}	10^{-3}	
Building 2	R1	22.181×10^{-6}	10^{-5}	Class I LPS required.
	R2	0.541×10^{-6}	10^{-3}	
	R3	0.541×10^{-6}	10^{-4}	
	R4	96576.722×10^{-6}	10^{-3}	
Building 3	R1	22.154×10^{-6}	10^{-5}	Class I LPS required.
	R2	0.514×10^{-6}	10^{-3}	
	R3	0.514×10^{-6}	10^{-4}	
	R4	98786.64×10^{-6}	10^{-3}	

Table 4 tabulate the comparison between the tolerable risk and the total risk to determine whether an LPS is required or not.

Risk managing:

- To diminish the risk of lightning-related effects, it is recommended to implement a lightning protection system (LPS) for R_B, thereby lowering the $P_B$factor from 1 to a value that corresponds to the LPS class.
- For building 2, characterized by a heightened explosion risk, the introduction of an automated alarm or extinguishing system can decrease the value of r_p from its initial value of 1 (no fire provision) to 0.02 for class I LPS.
- To minimize the likelihood P_{TA} of structural damage resulting from a discharge, it is advised to set up an equipotential bonding system, achieved through connecting grounding systems. This functions as an extra precautionary step.
- To mitigate losses from physical damage, particularly those arising from fire-related consequences r_p, a priority action involves the installation of automated preventive measures like fixed extinguishing systems and automatic alarms.

- To lower the probability P_C of a discharge causing disruptions in internal systems, the installation of protective devices against transient overvoltage, as outlined in SANS62305-2, is crucial. These devices should be strategically coordinated to offer safeguarding below the specified impulse voltage for the particular category of equipment and materials intended for installation.

6. DESIGN ANALYSIS

6.1. Building 1 (Clinic)

i. Air termination

Dimensions of the clinic = 60 × 20 × 7 m

A non-isolated type LPS is selected over the isolated type because of its reliability and can protect the equipment on the roof including solar panels and air conditioning units. A rolling sphere was applied to the building exposing points vulnerable to lightning strikes and vertical air rod are to be placed in such a way that the sphere only touches the air terminations [19]. The radius of the rolling sphere for a class I LPS is determined from table 2 from SANS62305-3 which is 20m.

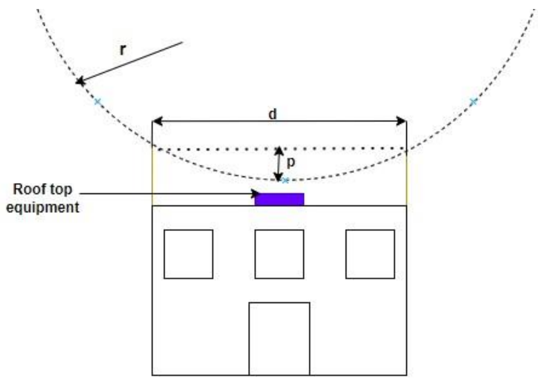

Figure 3: penetration depth [19]

According to SANS 62305-3, for buildings under 60m in height, the risk of lightning flashes to the sides of the building is low [14]. Therefore, protection is not required for the vertical sides directly below the protected area. Since the material on the roof has a height range of 50 - 70 cm, the required rod height is assumed to be 1.0m long. The distance between rods is then calculated as 10.27 m (which is the longest distance). As the rods are also used to protect solar panels and air conditioning units, the sphere's penetration distance documented in Figure 3 is also calculated using equation E36. The penetration distance is determined using the longest distance of the equipment that the rods are protecting (equation 2), which is typically the diagonal distance. According to Appendix C, the calculation reveals that the solar panels occupy a length of 8.528 m and a width of 5.724 m.

$$p = r - \sqrt{r^2 - (\frac{d}{2})^2} \tag{2}$$

$$p = 20 - \sqrt{(20)^2 - (\frac{10.27}{2})^2}$$

$$p = 0.67\ m$$

Rods with a height of 2m are suitable for this air termination design. Rods that are 2m long will ensure that the solar panels (with a height of 0.524m) and air conditioning units (0.8m) are protected, because the rod's height minus the penetration distance is greater than the height of the equipment being protected. To protect the solar panels, 4 rods are required, labelled as ABCD in Figure 4. To protect the 2 air conditioning units, only 2 air rods of 2m each are needed. For the remaining part of the roof, which is flat and doesn't have any equipment, a mesh was used.

Mesh size for LPL 1 according to SANS62305-2 is 5m × 5m.

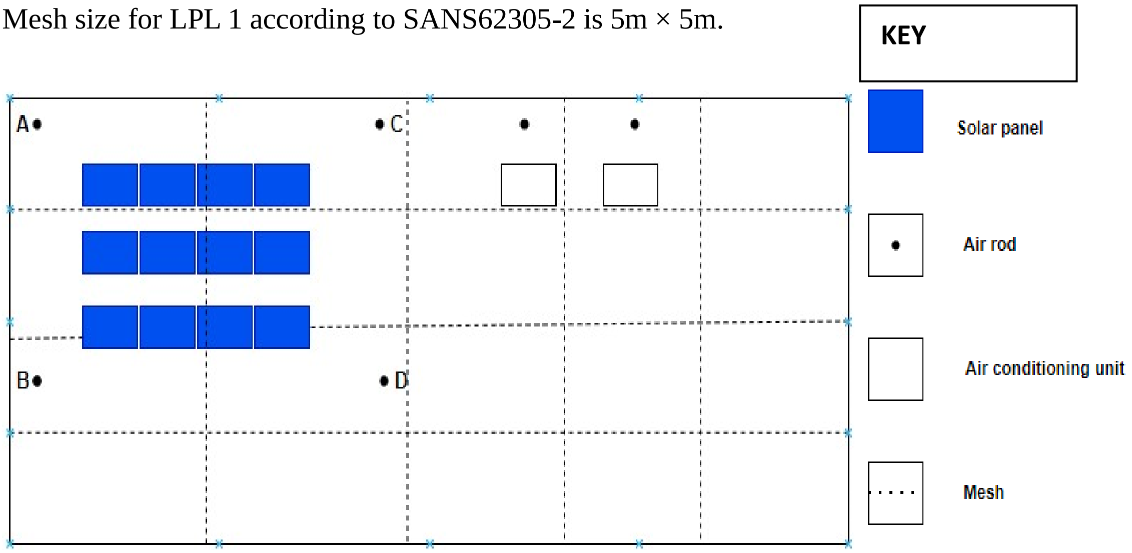

Figure 4: Top view of the building with LPS

ii. Down conductors

The number of down conductors is determined based on the size and geometry of the structure being protected. A higher number of down conductors ensures that lightning currents are evenly distributed, reducing the concentration of energy in any one path [1].

The number of down conductors N:

$$N = \frac{2\ (L+W)}{Distance\ between\ Conductors} \tag{3}$$

Proper spacing between down conductors is crucial to prevent crowding and to maintain even current distribution. The distance between conductors is determined by the LPS class shown on table 4 on SANS62305-3. The distance between conductors for Class I is 10m.

$$N = \frac{2\,(60+20)}{10} = 16 \text{ conductors}$$

It is recommended to connect aerials and metal masses on the roof of the building to the conducting network, in order to ensure correct equipotential bonding of the system, as recommended in current standards. The type of material used for the down conductor system is copper because it is an excellent conductor with high corrosion resistance, and it is widely used in lightning protection systems because of its longevity.

iii. Earth termination

The purpose of earthing termination is to provide a low-resistance path for lightning currents to travel from the lightning protection system components (such as air terminals and down conductors) into the ground. The number of grounding electrodes and their placement depend on factors such as soil resistivity, building size, and the desired grounding resistance [6]. The size and material of grounding conductors should be chosen to minimize resistance and ensure efficient current flow [7]. The depth at which grounding electrodes are buried affects their performance [7].

a. SUITABLE EARTHING SYSTEM METHOD FOR BUILDING 1

- ***Type A Earthing System***

Earth electrodes need to be set up at the bottom of every downward conductor. A minimum of 2 electrodes must be used [7]. The minimum total length of electrode l_1 for each down conductor is determined by the soil resistivity and the lightning protection class. With this information, the corresponding l_1 value is determined using Figure 3 in SANS 62305-3.

For a soil resistivity of 2000Ω.m, $l_1$is 50m.

l_1 = 50 m (horizontal electrodes)

$0.5l_1$= 25m (vertical electrodes)

Number of electrodes required for 14 down conductors: assuming that the length of each electrode is 2.4m.

$$Number\ of\ vertical\ electrode = \frac{25}{2.4} \approx 11\ electrodes$$

- ***Type B Earthing System***

A ring conductor is dependent on the total area of the building being protected, the lightning protection class and the soil resistivity. The ring conductors requires a mean radius r_e that is greater than or equal to l_1. According to SANS62305- 3 the ring conductor should be installed approximately 1m away from the building and buried at least 0.5m [6].

$r_e = 50m$

Installing a ring electrode 1m away from a building with a perimeter of 160m will require 168m of conductor.

The area of the ring is 1364 m^2 (62×22 m).

The mean radius of the ring $r_e = \sqrt{\frac{Area\ of\ the\ building}{\pi}}$ (4)

$r_e = 19.54$m

Comparing r_e and l_1, r_e is less than l_1 meaning that additional electrodes are required.

The length of the additional electrodes $l_e = \frac{(l_1 - r_e)}{2}$ (5)

$l_e = \frac{(50 - 19.54)}{2} = 15.23\ m$

The total length of the earth electrodes L_e required is the sum of the minimum length of the vertical earth electrode and the length of the additional electrodes.

$L_e = 25 + 15.23\ m = 40.23\ m$

Assuming earth electrode of length 2.4m are used the number of electrodes required is approximately 17.

$Number\ of\ vertical\ electrode = \frac{40.23}{2.4} \approx 17\ electrodes$

For this earthing system design Type B is selected because of its good corrosion resistance, low electrical resistance between the electrode and the earth, and potential of the earth's surface decreases as the distance from the earth electrode increases [6]. According to SANS62305-3 for building with extensive electronic systems (in our case solar panels and air conditioning units) type B earthing is preferable. The required earth electrode resistance of 10 Ω or less from the soil resistivity of 2000 Ω. To obtain less than 10Ω resistance for the system each down conductor will need to be connected to an electrode of 160Ω or less [7].

$$R_e = \frac{2\rho_E}{3d} \quad (6)$$

$$R_e = \frac{2\times2000}{3\times1.13\sqrt{1364}} = 31.94\ \Omega$$

Installing 17 × 2.4m electrodes with a diameter of 14.2mm at each down conductor will be sufficient to obtain less than 10Ω resistance for the system.

iv. Bonding

The equipotential system within the clinic should be installed using bonding conductors. All metallic components including electrical systems and other conductive parts need to be connected to the bonding network [1]. The equipotential bonding network should be bonded to the grounding system.

6.2. Building 2 (substation)

i. Air termination

The method used for the air termination design of building 2 (substation) is the mesh method. According to SANSA62305-3 for slopped flat roof building the mesh method is recommended for buildings with sensitive equipment like data centres or laboratories, the mesh system helps distribute the lightning current more evenly reducing the risk of induced surges. The building requires a class II lightning protection system, this means that the mesh width is 10×10m according to SANS62305-3 [13]. This enhances the overall dissipation of lightning energy by providing multiple paths for the lightning current to follow. This helps prevent the concentration of lightning energy on specific points, reducing the risk of damage.

ii. Down conductors

The number of down conductors N for building 3 is approximately 3 down conductors required with the distance of 10 m between conductors for class II LPS. The building requires at least 3 down conductors of length 5m to direct the lightning current safely to the earthing system.

iii. Earth termination

Type A earthing promotes equipotential bonding. This helps minimize potential differences within the substation, reducing the risk of side-flashes and arcing. $l_1$is 30m for class II lightning protection system.

l_1 = 30 m (horizontal electrodes)

$0.5l_1$= 15m (vertical electrodes)

Number of electrodes required for 3 down conductors, assuming that the length of each electrode is 2.4m.

$$Number\ of\ vertical\ electrode = \frac{15}{2.4} \approx 6\ electrodes$$

To obtain less than 10Ω resistance for the system each down conductor will need to be connected to an electrode of 30Ω or less for 3 down conductors.

$$R_e = \frac{\rho_E}{2\pi L}\left[\ln\left(\frac{8L}{D}\right) - 1\right] \tag{7}$$

Where D is the diameter of the rod (m) and L is the length of the electrode(m).

If electrodes of length 2.4 m which has a standard 5/8" diameter are used R_e is approximately 823.55 Ω [1]. The electrode resistance would not be able to meet the system requirement of at least 30Ω or less to obtain less than 10Ω earth resistance [7].

iv. Bonding

Installing an equipotential bonding system similar to that of the clinic. Bond all metallic parts within the substation to create uniform potentials.

6.3. Building 3 (Parking lot)

i. Air termination

According to Table 2 of SANS 62305-3, a Class I LPS requires a mesh with dimensions of 5×5 meters [14]. The mesh method is suitable for the protection of flat roofs. A mesh system provides uniform protective coverage over the entire flat roof parking lot, ensuring that the entire area is equally covered and reducing the risk of lightning strikes to vehicles, structures, and people throughout the parking lot. There are no exposed rods that require regular inspection for damage or corrosion.

ii. Down conductors

The number of down conductors, N, required for building 3 is approximately 3, with a distance of 10 meters between conductors for Class II LPS [14]. The building requires at least 3 down conductors, each with a length of 5 meters, to safely direct the lightning current to the grounding system.

iii. Earth termination

Parking lots are often open spaces with limited protection from natural elements. Type A earthing can provide effective lightning protection for vehicles and occupants, minimizing the risk of damage from direct lightning strikes. The earth electrode is to be installed at 0.5m above the ground to minimize electrical coupling effects in the earth [8].

l_1 is 30m for class II lighnting protection system.

l_1 = 30 m (horizontal electrodes)

$0.5l_1$= 15m (vertical electrodes)

Number of electrodes required for 3 down conductors: assuming that the length of each electrode is 2.4m.

$$Number\ of\ vertical\ electrode = \frac{15}{2.4} \approx 6\ electrodes$$

iv. Bonding

Install an equipotential bonding system for the parking lot metallic components. Bond the lightning protection system's components to the equipotential bonding network. Establishing a common grounding point as the one on figure 5 for all the buildings to connect the grounding electrodes of the buildings, ensuring that their potentials remain equal during electrical events [15]. By creating a network of interconnected conductors, equipotential bonding helps equalize potentials, thereby reducing the risk of touch and step voltages.

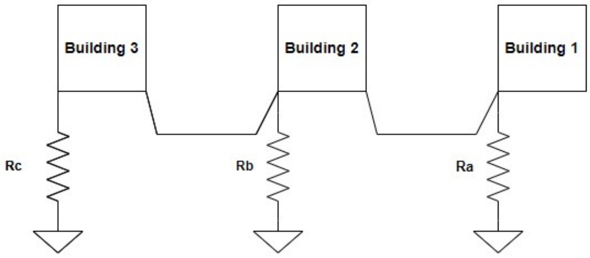

Figure 5: Common grounding point [15]

7. ANALYSIS OF DESIGN OUTCOME

Table 5: Risk Assessment after installing LPS.

		Tolerable Risk	Total Risk	
			Before installing LPS	After installing LPS
Building 1	R1	10^{-5}	44.946×10^{-6}	1.74×10^{-7}
Building 2	R1	10^{-5}	22.181×10^{-6}	1.10×10^{-8}
Building 3	R1	10^{-5}	22.154×10^{-6}	1.10×10^{-8}

Table 5 tabulates the post installation results for each building's R1 value. We can see that R1 for all the 3 building was successfully reduced after installing the LPS and now the risk value of R1 is less than the tolerable risk value.

8. SUSTAINABILITY, RELIABILITY AND MAINTANACE OF THE DESIGN

The use of high-quality, corrosion-resistant materials, especially copper, contributes to the system's longevity and minimizes the need for replacements. Copper, known for its durability and recyclability, reduces the demand for new raw materials and lessens the environmental burden [6]. The design adheres to recognized lightning protection standards, ensuring that the system's components and layout are well-vetted and proven to work effectively. The mesh method chosen for specific structures, like the substation and parking lot, ensures even current distribution and enhances protection against induced surges. This comprehensive approach to reliability is crucial in healthcare settings, where uninterrupted services are paramount. The choice of copper components helps minimize maintenance requirements due to their resistance to corrosion.

9. SOCIAL, ECONOMIC AND ENVIRONMENTAL IMPACTS

9.1. SOCIAL IMPACTS

The primary social impact of an ELPS is enhanced occupant safety. Lightning strikes can cause injuries or fatalities and can disrupt critical operations in buildings. An effective ELPS reduces the risk of electric shock, fires, and structural damage, ensuring a safer environment for occupants, including patients, staff, and visitors. Implementing an ELPS demonstrates a commitment to safety and public welfare. This enhances public confidence in the facility's ability to provide secure and reliable services, particularly for healthcare facilities where patient well-being is a priority [10]. An ELPS can minimize potential emergency response requirements due to lightning-related incidents. This reduces the burden on emergency services and healthcare staff, allowing them to focus on other critical tasks [9]. Proper ELPS design and signage can raise awareness about lightning safety, promoting safer behaviour during thunderstorms. Overreliance on the ELPS might lead to complacency during lightning events, potentially exposing individuals to risks.

9.2. ECONOMIC IMPACTS

Designing and installing an ELPS requires an initial investment. However, this investment is often outweighed by the potential costs of lightning-induced damage, equipment replacement, business interruption, and insurance claims [11]. The economic impact is therefore positive in the long run. The durability of copper, the primary material used in the ELPS, aligns with its longevity and resistance to corrosion [12]. This translates to fewer replacements, reduced maintenance costs, and prolonged equipment life. Moreover, insurance companies recognize the reduced risk of lightning-related claims, leading to potential reductions in insurance premiums. Thus, the ELPS design becomes not just a protective measure but also a smart investment in the clinic's long-term financial resilience. Insurance companies recognize the reduced risk of lightning-related claims, which can result in cost savings over time.

9.3. ENVIRONMENTAL IMPACTS

The use of copper in the ELPS design poses both positive and negative environmental impacts. On the positive side, copper is highly recyclable, minimizing the demand for new material extraction and reducing environmental stress. Its durability also means fewer replacements, contributing to reduced waste. Additionally, copper's superior conductivity aids in efficiently dissipating lightning energy, decreasing the risk of environmental harm from lightning-induced fires. However, the mining and production of copper have environmental costs, including energy consumption and emissions. Thus, a careful balance must be struck between the benefits of copper's performance and its environmental footprint. By responsibly sourcing materials, considering energy-efficient manufacturing, and prioritizing longevity, the ELPS design can mitigate these impacts.

10. RECOMMENDATIONS

The height of air terminals should be proportionate to the building's height and surrounding structures. Incorrectly sized air terminals can affect the system's ability to attract lightning strikes. Place down conductors near main openings to provide a safe path for lightning currents to follow [7]. This helps prevent side flashes and reduces the risk of lightning entering the building. Apply corrosion-resistant coatings to grounding electrodes and bonding conductors, these coatings act as a barrier against corrosive agents [18].

11. CONCLUSION

In conclusion, the comprehensive design of the External Lightning Protection System (ELPS) for the off-grid clinic in Mbabane, Eswatini, has successfully addressed the critical challenges posed by the clinic's remote location, sensitive medical equipment, and the safety of its occupants. The meticulous risk assessment laid the foundation for a targeted approach, ensuring that potential vulnerabilities were identified and accounted for. The strategic placement of air terminals using the rolling sphere method ensured that lightning strikes were diverted away from key areas such as the flat roof and solar panels. The calculation of proper down conductor sizes guaranteed efficient channelling of lightning current without causing harm to the clinic's structure or occupants. Additionally, the design of an effective earthing system dispersed lightning's energy into the ground, minimizing potential damage. The sustainability, reliability, and maintenance of the design were emphasized through the choice of durable materials, adherence to standards, and routine inspections. The social, economic, and environmental impacts of the ELPS were also highlighted, showing how the system enhances safety, offers economic benefits over time, and contributes to environmental responsibility.

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APPENDIX A

Non-technical report

Lightning Protection Design for Off-Grid Clinic in Mbabane, Eswatini

Introduction

In the pursuit of ensuring safety and reliability for an off-grid clinic situated in Mbabane, Eswatini, the design of a robust External Lightning Protection System (ELPS) becomes imperative. The clinic's unique location, housing valuable medical equipment, and catering to the well-being of its occupants underscore the necessity of such a system. The design process involves meticulous risk assessment, strategic placement of air terminals, calculation of optimal down conductor sizes, and an efficient earthing system. This report outlines the key design elements and their impact on safeguarding the clinic's assets and occupants.

Challenges and Clinic Overview

Nestled in Mbabane, the clinic is a symbol of medical care and resilience. Comprising multiple structures, it caters to the community's healthcare needs. The main clinic building, characterized by its modern design and solar panels, stands at 7 meters high, making it both innovative and susceptible to natural forces. The substation ensures uninterrupted power supply, while the parking lot serves as a vital entry point. Lightning-induced surges pose a significant concern due to the clinic's reliance on solar energy and sensitive equipment.

Lightning Hazards and Risk Assessment

The report delves into the nature of lightning and its potential impact on the clinic. Lightning's stepped leader connecting with structures and generating intense currents can lead to damage and electric shock. The risk assessment examines variables such as geographical location, frequency of lightning strikes, building height, and proximity to equipment. This evaluation aids in customizing lightning protection measures to mitigate risks to both occupants and the clinic's operations.

Design Strategies

The report explores the design strategies implemented for each building structure. The main clinic's air terminal placement, determined by the rolling sphere method, diverts lightning strikes away from critical areas. The selection of down conductor sizes ensures controlled lightning current flow. The earthing system design disperses energy into the ground, preventing damage. The substation's mesh method evenly distributes lightning current, and the parking lot benefits from both mesh and type A earthing systems.

Outcome and Impact

The design's success is measured through a post-installation risk assessment, revealing substantial reductions in risk levels, aligning with tolerable values. This underscores the effectiveness of the ELPS in safeguarding life and services. The report emphasizes the design's sustainability, reliability, and maintenance, achieved through durable materials and adherence to standards. It delves into the social, economic, and environmental implications, highlighting how the ELPS enhances safety, offers long-term economic benefits, and promotes environmental responsibility.

Conclusion

In conclusion, the report showcases the significance of a well-designed ELPS for the off-grid clinic in Mbabane. By striking a balance between innovation, safety, and sustainability, the clinic's assets and occupants are protected from lightning-related risks. Future implementations should consider optimized air terminal height and corrosion prevention for further enhancement. This proactive approach exemplifies the clinic's commitment to safety, innovation, and resilience in the face of natural forces.

APPENDIX B

Building 1 Risk Assessment

Table 1A: Characteristics of the structure and its environment

Parameters	Comment	Symbol	Value
Dimensions		L ×W× H	60 ×20 × 7
Location factor	Objects of smaller around	C_D	0.5
Environment	rural	C_E	1
LPS	none	P_B	1
People present inside or outside	yes	n_t	50
Lightning flash density	1/km^2/year	N_G	12

Collection Area

a. Collection area of the building A_D

$$A_D = L \times W + 6H(L + W) + \pi(3H)^2 \quad \text{(E1)}$$

$$A_D = 60 \times 20 + 6(7)(60 + 20) + \pi(3 \times 7)^2$$

$$A_D = 5945.44 \text{ m}^2$$

b. Collection area of the power line $A_{L(P)}$

$$A_{L(P)} = 40 \times L_L \quad \text{(E2)}$$

L_L is the length of the power line which is approximated to 10m.

$$A_{L(P)} = 40 \times 10$$

$$A_{L(P)} = 400\, m^2$$

c. Collection area near the power line $A_{l(P)}$

$$A_{l(P)} = 4000 \times L_L \quad \text{(E3)}$$

$$A_{l(P)} = 4000 \times 10$$

$A_{l(P)} = 40000\, m^2$

d. Collection area of the adjacent structure A_{DJ} (building 2)

$A_{DJ} = L \times W + 6H(L + W) + \pi(3H)^2$ (E4)

$A_{DJ} = 5 \times 4 + 6(5)(5 + 4) + \pi(3 \times 5)^2$

$A_{DJ} = 996.86\, m^2$

e. Collection area of flashes striking near the structure A_M

$A_M = 2 \times 500(L + W) + \pi \times 500^2$ (E5)

$A_M = 865398.16\, m^2$

Number of dangerous events

a. Annual number of events to structure N_D

$N_D = N_G \times A_D \times C_D \times 10^{-6}$ (E6)

$N_D = 12 \times 5945.44 \times 1 \times 10^{-6}$

$N_D = 0.071$

b. Annual number of events to the power line $N_{L(P)}$

$N_{L(P)} = N_G \times A_{L(p)} \times C_{L(P)} \times C_{E(P)} \times C_{T(P)} \times 10^{-6}$ (E7)

$N_{L(P)} = 12 \times 400 \times 1 \times 1 \times 1 \times 10^{-6}$

$N_{L(P)} = 0.0048$

c. Annual number of events near the power line $N_{l(P)}$

$N_{l(P)} = N_G \times A_{l(p)} \times C_{I(P)} \times C_{E(P)} \times C_{T(P)} \times 10^{-6}$

$N_{l(P)} = 12 \times 40000 \times 1 \times 1 \times 1 \times 10^{-6}$

$N_{l(P)} = 0.48$

d. Annual number of events to the structure at the end of the power line $N_{DJ(P)}$

$N_{DJ(P)} = N_G \times A_{DJ} \times C_{DJ} \times C_{T(P)} \times 10^{-6}$ (E8)

$N_{DJ(P)} = 12 \times 996.86 \times 1 \times 1 \times 10^{-6}$

$N_{DJ(P)} = 0.0119$

e. Annual number of dangerous events near a structure

$N_M = N_G \times A_M \times 10^{-6}$

$N_M = 12 \times 865398.16 \times 10^{-6}$

$N_M = 10.38$

Probability of damage

a. Probability that a flash to a structure will cause injury to living beings by electric shock P_A

$P_A = P_{TA} \times P_B$ (E9)

P_{TA} and P_B are determined using SANS 62305-2 Table B.1 and Table B.3.

$P_A = 1 \times 1 = 1$

b. Probability that a flash to a line will cause injury to living beings by electric shock P_U

$P_U = P_{TU} \times P_{EB} \times P_{LD} \times C_{LD}$ (E10)

$P_U = 1 \times 1 \times 1 \times 1 = 1$

c. Probability that a flash to a line will cause physical damage P_v

$P_V = P_{EB} \times P_{LD} \times C_{LD}$ (E11)

$P_V = 1 \times 1 \times 1 = 1$

d. Probability that a direct flash to a structure will cause internal system failure P_C

$P_C = P_{SD} \times C_{LD}$ (E12)

$P_C = 1 \times 1 = 1$

e. Probability that a flash near a structure will cause internal system failure P_M

$P_M = P_{SPD} \times P_{MS}$ (E13)

$P_M = 1 \times 1 = 1$

f. Probability that a flash to the power line will cause internal system failure P_w

$P_W = P_{SPD} \times P_{LD} \times C_{LD}$

$P_W = 1 \times 1 \times 1 = 1$

g. Probability that a flash near the power line will cause internal system failure P_z

$$P_z = P_{SPD} \times P_{LI} \times C_{LI} \tag{E14}$$

$P_z = 1 \times 1 \times 1 = 1$

EXPECTED ANNUAL LOSS OF HUMAN LIFE

L_T – Losses due to injuries by electric shock inside or outside the building

L_F – Losses due to physical damage

a. Loss by injury to living beings L_A

$$L_A = r_t \times L_T \times \frac{n_z}{n_t} \times \frac{t_z}{8760} \tag{E15}$$

$L_A = 0.01 \times 0.1 \times 1 \times \frac{4380}{8760} = 0.0005$

b. Loss of structure by physical damage (flashes to structure) L_B

$$L_B = r_p \times r_f \times h_Z \times L_F \times \frac{n_z}{n_t} \times \frac{t_z}{8760} \tag{E16}$$

- r_p the reduction factor as a function of provisions taken to reduce the consequences of fire in the case of a clinic is assumed to 0.5 because clinics must ensure the safety of occupants and a fire extinguisher should always be present as well as safe escape routes.
- r_f the reduction factor as a function of risk and fire or explosion of the structure for zone 2 which is outside the building is 0.001.
- t_z is the time in hours per year for which the persons are present in the zone, 4380 hours per year is assumed.

$L_B = 0.5 \times 0.001 \times 5 \times 0.01 \times 1 \times \frac{4380}{8760}$

$L_B = 0.0000125$

c. Loss by injury to living beings (flashes to service line) L_U

$$L_U = r_t \times L_T \times \frac{n_z}{n_t} \times \frac{t_z}{8760} \qquad \text{(E17)}$$

$L_U = 0.0005$

d. Loss by physical damage to structure (flashes to service line) L_V

$$L_V = r_p \times r_f \times h_Z \times L_F \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$$

$L_V = 0.0000125$

e. Loss by flashes near structure to internal system L_M

$$L_M = L_o \times \frac{c_s}{{c_t}^a} \qquad \text{(E18)}$$

$L_M = 10^{-2} \times 1$

$L_M = 0.01$

f. Loss by direct flashes to the power line causing internal system failure L_W

$$L_W = L_o \times \frac{c_s}{{c_t}^a} \qquad \text{(E19)}$$

$L_z = L_M = 0.01$

g. Loss by flashes near the power line to internal systems L_z

$$L_z = L_o \times \frac{c_s}{{c_t}^a} \qquad \text{(E20)}$$

$L_z = L_o \times \frac{c_s}{{c_t}^a} = L_M$

$L_z = 0.01$

RISK OF LOSS OF HUMAN LIFE (R1)

$R1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z$

- When calculating the risk of loss of human life, the risk components which are mostly responsible are R_A, R_B, R_U and R_V.

a. Risk to the structure resulting in shock to humans R_A

$$R_A = N_D \times P_A \times L_A \tag{E21}$$

$R_A = 0.071 \times 1 \times 0.0005$

$R_A = 0.0000355$

b. Risk to the structure resulting in physical damages R_B

$$R_B = N_D \times P_B \times L_B \tag{E22}$$

$R_B = 0.071 \times 1 \times 0.0000125$

$R_B = 0.0000008875$

c. Risk to the power line resulting in shock to humans $R_{U(p)}$

$$R_{U(P)} = (N_{L(P)} + N_{DJ(P)}) \times P_U \times L_U \tag{E23}$$

$R_{U(P)} = (0.0048 + 0.0119) \times 1 \times 0.0005$

$R_{U(P)} = 0.00000835$

d. Risk to the power line causing physical damage $R_{V(p)}$

$$R_{V(P)} = (N_{L(P)} + N_{DJ(P)}) \times P_V \times L_V \tag{E24}$$

$R_{V(P)} = (0.0048 + 0.0119) \times 1 \times 0.0000125$

$R_{V(P)} = 0.00000020875$

Therefore $R_1 = R_A + R_B + R_{U(P)} + R_{V(P)}$

$R_1 = 0.0000355 + 0.0000008875 + 0.00000835 + 0.00000020875$

$R_1 = 0.0000369$

RISK OF LOSS OF SERVICE TO THE PUBLIC (R2)

$$R2 = R_{B2} + R_{C2} + R_{M2} + R_{V2(P)} + R_{W2(P)} + R_{Z2(P)} \quad \text{(E25)}$$

- Determining R2 involves calculating the risk of physical damage by fire in a structure caused by direct lightning flashes to the structure (R_{B2}) and the risk of physical damage by fire caused by direct lightning flashes on the power line ($R_{V2(P)}$).
- Therefore R_{B2} and $R_{V2(P)}$ are the same values as calculated for R1.

$R2 = 0.0000008875 + 0.00000020875$

$R2 = 0.000001096$

RISK OF LOSS OF CULTURAL HERITAGE (R3)

$$R3 = R_{B3} + R_{V3(P)} \quad \text{(E27)}$$

$R3 = 0.0000008875 + 0.00000020875$

$R3 = 0.000001096$

RISK OF LOSS OF ECONOMIC VALUE (R4)

$$R4 = R_{A4} + R_{B4} + R_{C4} + R_{M4} + R_{V4(P)} + R_{W4(P)} + R_{Z4(P)} \quad \text{(E28)}$$

$$R_C = N_D \times P_C \times L_B \quad \text{(E29)}$$

$R_C = 0.071 \times 1 \times 0.0000125$

$R_C = 0.0000008875$

$$R_M = N_M \times P_M \times L_M \quad \text{(E30)}$$

$R_M = 10.38 \times 1 \times 0.01$

$R_M = 0.1038$

$$R_W = (N_{L(P)} + N_{DJ(P)}) \times P_W \times L_W \quad \text{(E31)}$$

$R_W = (0.0048 + 0.0119) \times 1 \times 0.01$

$R_W = 0.000167$

$$R_Z = (N_{L(P)} + N_{DJ(P)}) \times P_Z \times L_Z \quad \text{(E32)}$$

$R_Z = (0.0048 + 0.0119) \times 1 \times 0.01$

$R_Z = 0.000167$

Therefore $R4 = R_{B4} + R_{C4} + R_{M4} + R_{V4(P)} + R_{W4(P)} + R_{Z4(P)}$

$R4 = 0.0000008875 + 0.0000008875 + 0.1038 + 0.00000020875 + 0.000167 + 0.000167$

$R4 = 0.1041$

<u>Building 2 Risk Assessment</u>

Table 2A: Characteristics of the structure and its environment

Parameters	Comment	Symbol	Value
Dimensions		L ×W× H	10 ×5× 5
Location factor	Objects of smaller around	C_D	0.5
Environment	rural	C_E	1
LPS	none	P_B	1
People present inside	yes	n_t	5

or outside			
Lightning flash density	$1/km^2/year$	N_G	12

Collection Area

a. Collection area of the building A_D

$$A_D = L \times W + 6H(L + W) + \pi(3H)^2$$

$$A_D = 10 \times 5 + 6(5)(10 + 5) + \pi(3 \times 5)^2$$

$$A_D = 1206.85 \text{ m}^2$$

b. Collection area of the power line $A_{L(P)}$

$$A_{L(P)} = 40 \times L_L$$

L_L is the length of the power line which is approximated to 10m.

$$A_{L(P)} = 40 \times 10$$

$$A_{L(P)} = 400\, m^2$$

c. Collection area near the power line $A_{l(P)}$

$$A_{l(P)} = 4000 \times L_L$$

$$A_{l(P)} = 4000 \times 10$$

$$A_{l(P)} = 40000\, m^2$$

d. Collection area of the adjacent structure A_{DJ} (building 2)

$$A_{DJ} = L \times W + 6H(L + W) + \pi(3H)^2$$

$$A_{DJ} = 25 \times 10 + 6(5)(25 + 10) + \pi(3 \times 5)^2$$

$$A_{DJ} = 2006.858\, m^2$$

e. Collection area of flashes striking near the structure A_M

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

$A_M = 800398.16\, m^2$

Number of dangerous events

a. Annual number of events to structure N_D

$N_D = N_G \times A_D \times C_D \times 10^{-6}$

$N_D = 12 \times 1206.85 \times 1 \times 10^{-6}$

$N_D = 0.01448$

b. Annual number of events to the power line $N_{L(P)}$

$N_{L(P)} = N_G \times A_{L(p)} \times C_{L(P)} \times C_{E(P)} \times C_{T(P)} \times 10^{-6}$

$N_{L(P)} = 12 \times 400 \times 1 \times 1 \times 1 \times 10^{-6}$

$N_{L(P)} = 0.0048$

c. Annual number of events near the power line $N_{l(P)}$

$N_{l(P)} = N_G \times A_{l(p)} \times C_{I(P)} \times C_{E(P)} \times C_{T(P)} \times 10^{-6}$

$N_{l(P)} = 12 \times 40000 \times 1 \times 1 \times 1 \times 10^{-6}$

$N_{l(P)} = 0.48$

d. Annual number of events to the structure at the end of the power line $N_{DJ(P)}$

$N_{DJ(P)} = N_G \times A_{DJ} \times C_{DJ} \times C_{T(P)} \times 10^{-6}$

$N_{DJ(P)} = 12 \times 2006.858 \times 1 \times 1 \times 10^{-6}$

$N_{DJ(P)} = 0.024$

e. Annual number of dangerous events near a structure

$N_M = N_G \times A_M \times 10^{-6}$

$N_M = 12 \times 800398.16 \times 10^{-6}$

$N_M = 9.60$

Probability of damage

a. Probability that a flash to a structure will cause injury to living beings by electric shock P_A

$P_A = P_{TA} \times P_B$

P_{TA} and P_B are determined using SANS 62305-2 Table B.1 and Table B.3.

$P_A = 1 \times 1 = 1$

b. Probability that a flash to a line will cause injury to living beings by electric shock P_U

$P_U = P_{TU} \times P_{EB} \times P_{LD} \times C_{LD}$

$P_U = 1 \times 1 \times 1 \times 1 = 1$

c. Probability that a flash to a line will cause physical damage P_v

$P_V = P_{EB} \times P_{LD} \times C_{LD}$

$P_V = 1 \times 1 \times 1 = 1$

d. Probability that a direct flash to a structure will cause internal system failure P_C

$P_C = P_{SD} \times C_{LD}$

$P_C = 1 \times 1 = 1$

e. Probability that a flash near a structure will cause internal system failure P_M

$P_M = P_{SPD} \times P_{MS}$

$P_M = 1 \times 1 = 1$

f. Probability that a flash to the power line will cause internal system failure P_w

$P_W = P_{SPD} \times P_{LD} \times C_{LD}$

$P_W = 1 \times 1 \times 1 = 1$

g. Probability that a flash near the power line will cause internal system failure P_z

$P_z = P_{SPD} \times P_{LI} \times C_{LI}$

$P_z = 1 \times 1 \times 1 = 1$

EXPECTED ANNUAL LOSS OF HUMAN LIFE

a. Loss by injury to living beings L_A

$L_A = r_t \times L_T \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_A = 0.01 \times 0.1 \times 1 \times \frac{4380}{8760}$ = 0.0005

b. Loss of structure by physical damage (flashes to structure) L_B

$L_B = r_p \times r_f \times h_Z \times L_F \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_B = 0.5 \times 0.001 \times 5 \times 0.01 \times 1 \times \frac{4380}{8760}$

$L_B =$ 0.0000125

c. Loss by injury to living beings (flashes to service line) L_U

$L_U = r_t \times L_T \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_U =$ 0.0005

d. Loss by physical damage to structure (flashes to service line) L_V

$L_V = r_p \times r_f \times h_Z \times L_F \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_V = 0.0000125$

e. Loss by flashes near structure to internal system L_M

$L_M = L_o \times \frac{c_s}{{c_t}^a}$

$L_M = 10^{-2} \times 1$

$L_M = 0.01$

f. Loss by direct flashes to the power line causing internal system failure L_W

$L_W = L_o \times \frac{c_s}{{c_t}^a}$

L_z= L_M = 0.01

g. Loss by flashes near the power line to internal systems L_z

$L_z = L_o \times \frac{c_s}{{c_t}^a}$

$L_z = L_o \times \frac{c_s}{{c_t}^a}$ = L_M

$L_z = 0.01$

<u>RISK OF LOSS OF HUMAN LIFE (R1)</u>

$R1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z$

a. Risk to the structure resulting in shock to humans R_A

$R_A = N_D \times P_A \times L_A$

$R_A = 0.01448 \times 1 \times 0.0005$

$R_A = 0.00000724$

b. Risk to the structure resulting in physical damages R_B

$R_B = N_D \times P_B \times L_B$

$R_B = 0.01448 \times 1 \times 0.0000125$

$R_B = 0.000000181$

c. Risk to the power line resulting in shock to humans $R_{U(p)}$

$R_{U(P)} = (N_{L(P)} + N_{DJ(P)}) \times P_U \times L_U$

$R_{U(P)} = (0.0048 + 0.024\ ) \times 1 \times 0.0005$

$R_{U(P)} = 0.0000144$

d. Risk to the power line causing physical damage $R_{V(p)}$

$R_{V(P)} = (N_{L(P)} + N_{DJ(P)}) \times P_V \times L_V$

$R_{V(P)} = (0.0048 + 0.024\ ) \times 1 \times 0.0000125$

$R_{V(P)} = 0.00000036$

Therefore $R_1 = \ R_A + R_B + R_{U(P)} + R_{V(P)}$

$R_1 = 0.00000724 + 0.000000181 + 0.0000144\ + 0.00000036$

$R_1 = \ \ 0.000022181$

RISK OF LOSS OF SERVICE TO THE PUBLIC (R2)

$R2 = \ \ R_{B2} + R_{C2} + R_{M2} + R_{V2(P)} + R_{W2(P)} + R_{Z2(P)}$

$R2 = 0.000000181 + \ 0.00000036$

$R2 = 0.000000541$

RISK OF LOSS OF CULTURAL HERITAGE (R3)

$R3 = \ \ R_{B3} + R_{V3(P)}$

$R3 = \ 0.000000181 + \ 0.00000036$

$R3 = 0.000003781$

RISK OF LOSS OF ECONOMIC VALUE (R4)

$R4 = R_{A4} + \ \ R_{B4} + R_{C4} + R_{M4} + R_{V4(P)} + R_{W4(P)} + R_{Z4(P)}$

$R_C = N_D \times P_C \times L_B$

$R_C = 0.01448 \ \times 1 \times 0.0000125$

$R_C = 0.000000181$

$R_M = N_M \times P_M \times L_M$

$R_M = 9.60 \ \times 1 \times 0.01$

$R_M = 0.096$

$R_W = (N_{L(P)} + N_{DJ(P)}) \times P_W \times L_W$

$R_W = \ (0.0048 + 0.024) \times 1 \times 0.01$

$R_W = \ 0.000288$

$R_Z = (N_{L(P)} + N_{DJ(P)}) \times P_Z \times L_Z$

$R_Z = (0.0048 + 0.024) \times 1 \times 0.01$

$R_Z = 0.000288$

Therefore $R4 = R_{B4} + R_{C4} + R_{M4} + R_{V4(P)} + R_{W4(P)} + R_{Z4(P)}$

$R4 = 0.000000181 + 0.000000181 + 0.096 + 0.00000036 \ + 0.000288 \ + 0.000288$

$R4 = 0.0965$

Building 3 Risk Assessment

Table 3A: Characteristics of the structure and its environment

Parameters	Comment	Symbol	Value
Dimensions		$L \times W \times H$	$25 \times 10 \times 5$
Location factor	Objects of smaller or same height around	C_D	0.5
Environment	rural	C_E	1
LPS	none	P_B	1
People present inside or outside	yes	n_t	50
Lightning flash density	1/km^2/year	N_G	12

Collection Area

a. Collection area of the building A_D

$$A_D = L \times W + 6H(L + W) + \pi(3H)^2$$

$$A_D = 25 \times 10 + 6(5)(25 + 10) + \pi(3 \times 5)^2$$

$$A_D = 2006.858 \text{ m}^2$$

b. Collection area of the power line $A_{L(P)}$

$$A_{L(P)} = 40 \times L_L$$

L_L is the length of the power line which is approximated to 10m.

$$A_{L(P)} = 40 \times 10$$

$$A_{L(P)} = 400\, m^2$$

c. Collection area near the power line $A_{l(P)}$

$$A_{l(P)} = 4000 \times L_L$$

$$A_{l(P)} = 4000 \times 10$$

$A_{l(P)} = 40000\, m^2$

d. Collection area of the adjacent structure A_{DJ} (building 2)

$A_{DJ} = L \times W + 6H(L + W) + \pi(3H)^2$

$A_{DJ} = 10 \times 5 + 6(5)(10 + 5) + \pi(3 \times 5)^2$

$A_{DJ} = 1206.858\, m^2$

e. Collection area of flashes striking near the structure A_M

$A_M = 2 \times 500(25 + 10) + \pi \times 500^2$

$A_M = 820398.16\, m^2$

Number of dangerous events

a. Annual number of events to structure N_D

$N_D = N_G \times A_D \times C_D \times 10^{-6}$

$N_D = 12 \times 2006.858 \times 1 \times 10^{-6}$

$N_D = 0.024$

b. Annual number of events to the power line $N_{L(P)}$

$N_{L(P)} = N_G \times A_{L(p)} \times C_{L(P)} \times C_{E(P)} \times C_{T(P)} \times 10^{-6}$

$N_{L(P)} = 12 \times 400 \times 1 \times 1 \times 1 \times 10^{-6}$

$N_{L(P)} = 0.0048$

c. Annual number of events near the power line $N_{l(P)}$

$N_{l(P)} = N_G \times A_{l(p)} \times C_{I(P)} \times C_{E(P)} \times C_{T(P)} \times 10^{-6}$

$N_{l(P)} = 12 \times 40000 \times 1 \times 1 \times 1 \times 10^{-6}$

$N_{l(P)} = 0.48$

d. Annual number of events to the structure at the end of the power line $N_{DJ(P)}$

$N_{DJ(P)} = N_G \times A_{DJ} \times C_{DJ} \times C_{T(P)} \times 10^{-6}$

$N_{DJ(P)} = 12 \times 1206.858 \times 1 \times 1 \times 10^{-6}$

$N_{DJ(P)} = 0.01448$

e. Annual number of dangerous events near a structure

$N_M = N_G \times A_M \times 10^{-6}$

$N_M = 12 \times 820398.16 \times 10^{-6}$

$N_M = 9.84$

Probability of damage

a. Probability that a flash to a structure will cause injury to living beings by electric shock P_A

$P_A = P_{TA} \times P_B$

P_{TA} and P_B are determined using SANS 62305-2 Table B.1 and Table B.3.

$P_A = 1 \times 1 = 1$

b. Probability that a flash to a line will cause injury to living beings by electric shock P_U

$P_U = P_{TU} \times P_{EB} \times P_{LD} \times C_{LD}$

$P_U = 1 \times 1 \times 1 \times 1 = 1$

c. Probability that a flash to a line will cause physical damage P_v

$P_V = P_{EB} \times P_{LD} \times C_{LD}$

$P_V = 1 \times 1 \times 1 = 1$

d. Probability that a direct flash to a structure will cause internal system failure P_C

$P_C = P_{SD} \times C_{LD}$

$P_C = 1 \times 1 = 1$

e. Probability that a flash near a structure will cause internal system failure P_M

$P_M = P_{SPD} \times P_{MS}$

$P_M = 1 \times 1 = 1$

f. Probability that a flash to the power line will cause internal system failure P_w

$P_W = P_{SPD} \times P_{LD} \times C_{LD}$

$P_W = 1 \times 1 \times 1 = 1$

g. Probability that a flash near the power line will cause internal system failure P_z

$P_z = P_{SPD} \times P_{LI} \times C_{LI}$

$P_z = 1 \times 1 \times 1 = 1$

EXPECTED ANNUAL LOSS OF HUMAN LIFE

a. Loss by injury to living beings L_A

$L_A = r_t \times L_T \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_A = 0.01 \times 0.1 \times 1 \times \frac{4380}{8760} = 0.0005$

b. Loss of structure by physical damage (flashes to structure) L_B

$L_B = r_p \times r_f \times h_Z \times L_F \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_B = 0.5 \times 0.001 \times 5 \times 0.01 \times 1 \times \frac{4380}{8760}$

$L_B = 0.0000125$

c. Loss by injury to living beings (flashes to service line) L_U

$L_U = r_t \times L_T \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$

$L_U = 0.0005$

d. Loss by physical damage to structure (flashes to service line) L_V

$$L_V = r_p \times r_f \times h_Z \times L_F \times \frac{n_z}{n_t} \times \frac{t_z}{8760}$$

$$L_V = 0.0000125$$

e. Loss by flashes near structure to internal system L_M

$$L_M = L_o \times \frac{c_s}{{c_t}^a}$$

$$L_M = 10^{-2} \times 1$$

$$L_M = 0.01$$

f. Loss by direct flashes to the power line causing internal system failure L_W

$$L_W = L_o \times \frac{c_s}{{c_t}^a}$$

L_z= L_M = 0.01

g. Loss by flashes near the power line to internal systems L_z

$$L_z = L_o \times \frac{c_s}{{c_t}^a}$$

$$L_z = L_o \times \frac{c_s}{{c_t}^a} = L_M$$

$$L_z = 0.01$$

<u>RISK OF LOSS OF HUMAN LIFE (R1)</u>

$$R1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z$$

a. Risk to the structure resulting in shock to humans R_A

$$R_A = N_D \times P_A \times L_A$$

$$R_A = 0.024 \times 1 \times 0.0005$$

$$R_A = 0.000012$$

b. Risk to the structure resulting in physical damages R_B

$R_B = N_D \times P_B \times L_B$

$R_B = 0.024 \times 1 \times 0.0000125$

$R_B = 0.0000003$

c. Risk to the power line resulting in shock to humans $R_{U(p)}$

$R_{U(P)} = (N_{L(P)} + N_{DJ(P)}) \times P_U \times L_U$

$R_{U(P)} = (0.0048 + 0.01448) \times 1 \times 0.0005$

$R_{U(P)} = 0.00000964$

d. Risk to the power line causing physical damage $R_{V(p)}$

$R_{V(P)} = (N_{L(P)} + N_{DJ(P)}) \times P_V \times L_V$

$R_{V(P)} = (0.0048 + 0.01448\ ) \times 1 \times 0.0000125$

$R_{V(P)} = 0.000000241$

Therefore $R_1 = R_A + R_B + R_{U(P)} + R_{V(P)}$

$R_1 = 0.000012 + 0.0000003 + 0.00000964 + 0.000000241$

$R_1 = 0.00002218$

<u>RISK OF LOSS OF SERVICE TO THE PUBLIC (R2)</u>

$R2 = R_{B2} + R_{C2} + R_{M2} + R_{V2(P)} + R_{W2(P)} + R_{Z2(P)}$

$R2 = 0.0000003 + \ 0.000000241$

$R2 = 0.00002218$

RISK OF LOSS OF CULTURAL HERITAGE (R3)

$R3 = \ \ R_{B3} + R_{V3(P)}$

$R3 = \ \ 0.0000003 + \ 0.000000241$

$R3 = 0.00002218$

RISK OF LOSS OF ECONOMIC VALUE (R4)

$R4 = R_{A4} + \ \ R_{B4} + R_{C4} + R_{M4} + R_{V4(P)} + R_{W4(P)} + R_{Z4(P)}$

$R_C = N_D \times P_C \times L_B$

$R_C = 0.024 \ \times 1 \times 0.0000125$

$R_C = 0.0000003$

$R_M = N_M \times P_M \times L_M$

$R_M = 9.84 \ \times 1 \times 0.01$

$R_M = 0.0984$

$R_W = (N_{L(P)} + N_{DJ(P)}) \times P_W \times L_W$

$R_W = \ (0.0048 + 0.01448) \times 1 \times 0.01$

$R_W = \ 0.0001928$

$R_Z = (N_{L(P)} + N_{DJ(P)}) \times P_Z \times L_Z$

$R_Z = (0.0048 + 0.01448) \times 1 \times 0.01$

$R_Z = 0.0001928$

Therefore $R4 = R_{B4} + R_{C4} + R_{M4} + R_{V4(P)} + R_{W4(P)} + R_{Z4(P)}$

$R4 = 0.0000003 + 0.0000003 + 0.0984 + 0.000000241 \quad + 0.0001928 \ + 0.0001928$

$R4 = 0.0987$

APPENDIX C

Clinic energy requirements.

- 5KHW a day for a clinic with 0-60 beds [2]
- The number of solar panels required will be 12 assuming that the panels used provide 415W of power.
- Assuming the use of Canadian 415W poly-crystalline with the dimensions 2132 × 1048 × 30 mm.
- Assuming that the panels are installed at an angle of 30° facing the sun to increase the efficiency.
- Using trigonometric functions,

  $sin\theta = \frac{height}{hypoteneus}$ (E33)

  the height if the panels is 0.524m.
- The panels are installed as 4 series and 3 parallel.
- The distance between the parallel panels is the 1.048m (the hypotenuse) to avoid the shadow of the other panels falling on the other panels.
- The total length (L_p) and width (W_p) the solar panels occupy on the roof is:

$L_p = Length\ of\ each\ panel\ \times 4$ (E34)

$L_p = 2.132\ \times 4$

$L_p = 8.528\ m$

$W_p = 4(Width\ of\ each\ panel) + 2(Distance\ \ between\ the\ panels\ to\ avoid\ the\ shadow)$
(E35)

$W_p = 4(0.907) + 2(\ 1.048)$

$W_p = 5.724\ m$

The diagonal distance between air rods (D_G) from figure* which is AD or BC of the solar system is calculated:

$D_G = \sqrt{{L_P}^2 + {W_P}^2}$ (E36)

$D_G = \sqrt{(8.528)^2 + (5.724)^2}$

$D_G = 10.27\ m$

APPENDIX D

MINUTES OF MEETINGS

In this Appendix minutes of the weekly meetings are provided. The meetings were held over a period of six weeks, every Friday.

Meeting 1 minutes

Date: 21 July 2023

Duration: 1 hour

Meeting lead: Dr. Hunt

Discussion:

- Introductions
- Explanation of the design question
- Resources or material to use throughout the design.

Meeting 2 minutes

Date: 28 July 2023

Duration: 1 hour

Meeting lead: Dr. Hunt

Discussion:

- Introduction to Lightning and surge protection systems.

Next meeting: 4 August 2023 at 10:00 am

Meeting 3 minutes

Date: 4 August 2023

Duration: 1 hour

Meeting lead: Dr. Hunt

Discussion:

- Presentation on each student’s progress.

Next meeting: 11 August 2023 at 10:00 am

Meeting 4 minutes

Date: 11 August 2023

Duration: 1 hour

Meeting lead: Dr. Hunt

Discussion:

- Presentations continued.

Next meeting: 18 August 2023 at 10:00 am

Meeting 5 minutes

Date: 18 August 2023

Duration: 1 hour

Meeting lead: Dr. Hunt

Discussion:

- Report writing and design questions.

Next meeting: 25 August 2023 at 10:00 am

Meeting 6 minutes

Date: 25 August 2023

Duration: 1 hour

Meeting lead: Dr. Hunt

Discussion:

- Report writing and design questions.

APPENDIX E

WORK BREAKDOWN AND TIME MANAGEMENT

Table E1: Weekly work breakdown

Week	**Task**
1	Research on external lightning protection systems.
2	Planning on how to approach the design.
3	Designing air termination system.
4	Designing the lightning protection system for the clinic.
5	Drafting design report
6	Finalizing design report for submission.

Table E2: Time Management

Activity	**Time spent (weeks)**
Research	1
Planning	1
Design	2
Calculations	1
Report writing	1