LIGHTNING PROTECTION OF THATCHED ROOFED STRUCTURES

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in engineering.

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Declaration

I declare that this Research Report is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this ____ day of ____________ 20___

____

Fernando Hausse Chachaia

Dedication

I dedicate this work to my daughter and my two sons Evelina, Sandro and Fernando Jr., who are always in my mind. I also dedicate it to my wife Paulina for her courage and patience through all this time, and finally I dedicate it to the memory of my father and mother, Hausse Chachaia and Evelina Joao, who in life taught me throughout my childhood how to keep a sense of pragmatism and perseverance in every issue.

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Abstract

This work describes the design of external lightning protection system for thatched roofed structures. Lightning is a natural phenomenon that has an unpredictable strike location. Therefore in creating an external LPS, it is possible to create a path for the discharge that minimizes its harmful effects to a structure. There are many international documents and standards that describe methods of providing lightning protection. It has traditionally been accepted practice to install lightning protection masts near a thatched structure. However in solving one problem a number of others may have been created. This work explores alternative lightning protection designs for thatched roofed structures. Tests were performed in a laboratory environment to determine the level at which that will ignite from a direct strike to thatch material. These tests were performed using a combination impulse generator. It was found that thatch started to smoke at 10 kA. And ignition of the thatch occurred at 20 kA with a charge of 45 C.

1 Introduction

Lightning has higher destructive effect when the structure is not protected. In order to minimize damage in investments, protection against lightning is required and extends life of structures. Therefore protection is needed to avoid deaths of people who are living and working in thatched roofed structures in the instant that lightning hits the structure.

The main aim of this research is to design a system for protecting thatched roofed structures. No device can stop lightning formation. However, it is possible to create a path for the discharge that minimizes its harmful effects on the structure.

The design and installation of LPS must comply with IEC, BS and other relevant standards for protection against lightning if it is to be effective.

The lightning protection system established from these standards must shield a thatched roofed building, its occupants and equipment from the adverse effects associated with a lightning strike. These effects could otherwise result in fire, structural damage and electrical interference. To perform correctly, the protection system must capture the lightning, lead it safely downwards and then disperse the energy in the ground.

1.1 Research Report Overview

This research report is organized in the following way:

Chapter 1 and 2 provide the introduction and background to the topic.

Chapter 3 covers the theoretical analysis of the nature of lightning. The formation, mechanism and parameters of lightning are described in this chapter.

Chapter 4 presents the main direct effects of lightning. on thatched roofed structures.

Chapter 5 covers the assessment of the risks of the damage caused by lightning. Principles and equations to calculate the risk of damage due to lightning are given in this chapter.

Chapter 6 presents a review of different methods of lightning protection. The protective angle method, the rolling sphere method and the mesh method are discussed in this chapter.

Chapter 7 presents the components of the lightning protection system. Components such as air termination, down conductors, bonding conductors, earth-termination and surge protection devices are described.

Chapter 8 covers the lightning protection systems for thatched roofed structures. For lightning protection systems, one method is commonly used for protecting thatched roofed structures, - the mast method. There are however other methods. In this chapter we look at two methods, the mast and conductors above the roof.

Chapter 9 covers the high voltage test. The description and the results of the test are presented in this chapter.

Chapter 10 includes the overall conclusions of this research report and the recommendations for additional measures for protecting thatched roofs.

2 Background

In South Africa most of the rural communities' houses and a whole lot of up-market developments are thatched. A thatched roof is constructed with soft material, such as straw, reed, grass or coconut leaves. This material is highly flammable. According to the South African Code thatch is particularly prone to ignite because it is liable to become fluffy at surface and, if moist [1], methane and other flammable gases can be formed.

Particular attention must be paid to the protection of thatched roofs. South African Standard and other Standards, such as the British standard provide guide for the lightning protection of thatched roofed dwelling.

The design of lightning protection for thatched roofed dwellings must be considered in order to provide paths for dangerous lightning currents to the ground, to avoid sparking as far as possible and to avoid secondary direct contact between the hot lightning channel and the roof cover.

The protection of thatched roofed structures against lightning is provided by lightning masts. They do this by providing a preferential point of strike and conductive paths for lightning currents to follow. This diverts the currents away from the structure and not through it.

To review the engineering models involved in the conventional approach to lightning protection, the attachment of the leader to the struck object is often described using the so-called electro-geometrical theory [2], the core of which is the concept of a "striking distance". This concept obscures some of significant physics but allows the development of relatively simple and useful techniques for designing conventional lightning protection systems [2].

3 Nature of lightning

To provide a good lightning protection system for thatched roofed structure it is important to understand the nature of lightning.

3.1 Formation of lightning

It is generally accepted that lightning is created by a separation of electric charges due to air turbulence, although they can occur in other atmospheric conditions. The charges separation is thought to be due to the complex processes of freezing and melting and by movements of raindrops, snowflakes and ice crystals involving collisions and splintering. Clouds containing moisture rise and cool as they do so [2, 3]. If the rate of the rise is gradual, then mist and rainfall normally result. However, if the rate of the rise is above a certain level, the cooling effect will be accelerated. This may cause larger raindrops or even freezing. Typically, most positive charges accumulate at the top of the cumulonimbus clouds, leaving the lower regions negative, although there may be a small positive region near the base, as shown in Figure 3-1 [2, 3].

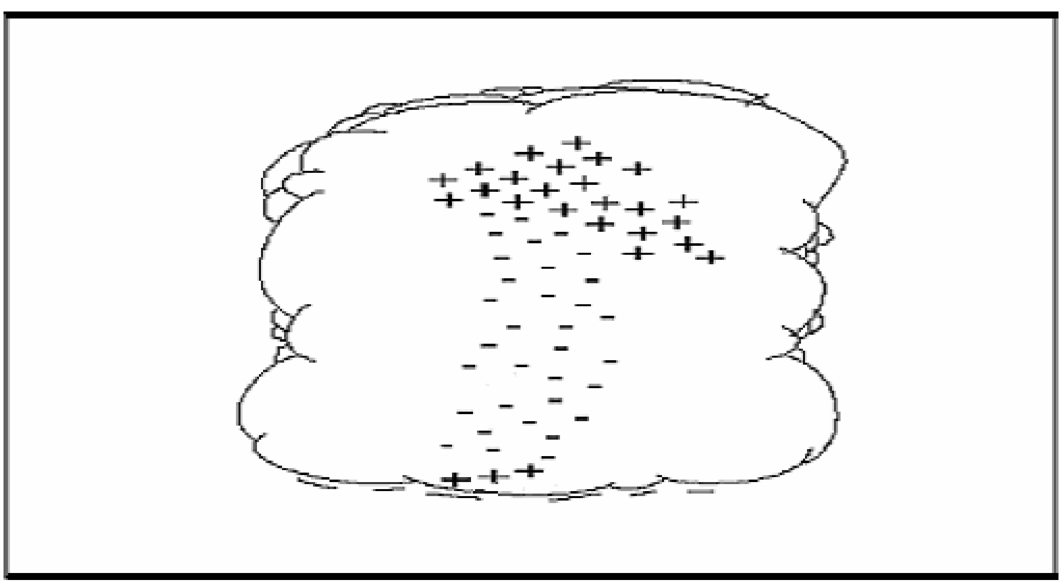

Figure 3-1: Charge in typical cumulonimbus cloud

3.2 Cloud-to-ground flashes

3.2.1 Discharge process

For cloud-to-cloud lightning the initiating and terminating charge regions are both in a thundercloud and can cause electrical interference and sometimes significant damage, while for cloud-to-ground lightning the initiating charge region is in a thundercloud and the terminating charge region is on the ground and it is the ground strikes which are generally the most destructive [3, 4]. As the potential difference between the cloud base and the underlying air/ground plane exceeds the breakdown value of the air in the immediate vicinity, the air becomes ionized and a down-stroke begins travelling at about 2 meters per micro-second. It follows a haphazard path, generally downwards, made up of small steps [2, 3].

3.2.2 Negative flash to the ground

There is some debate about the way in which the steps are produced and the point at which the actual arc commences, but eventually the negatively charged downwards leader will approach the ground as shown in Figure 3.2 [3, 5].

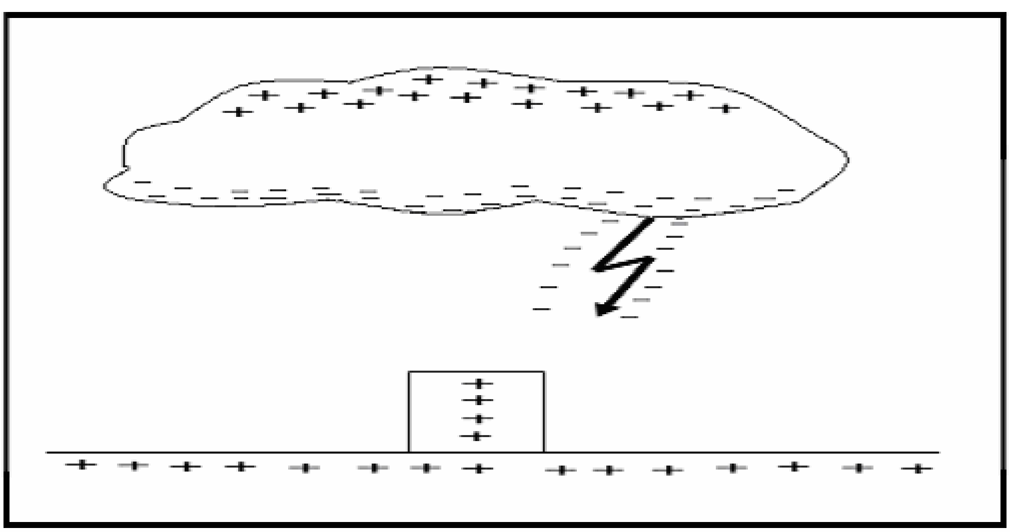

Figure 3-2: Negative downward leaders

3.2.3 Positive flash to the ground

Positive flashes to the ground pose a special problem since they do not strike the highest point (or any air termination system provided for the purpose). They generally occur less frequently than negative flashes, however in certain geographic locations there may be more positive flashes to ground. Present standards have assumed an average of around 10% positive flashes to ground [3, 5]. Normally they consist of one stroke only. They have slower rise times than negative flashes, with high peak current and charge transfer; the duration is longer than a single stroke of a negative flash but usually shorter than a complete negative flash [3, 5]. The stroke may be followed by a continuous current. The Figure 3.3 shows the positive flash to ground [2, 5].

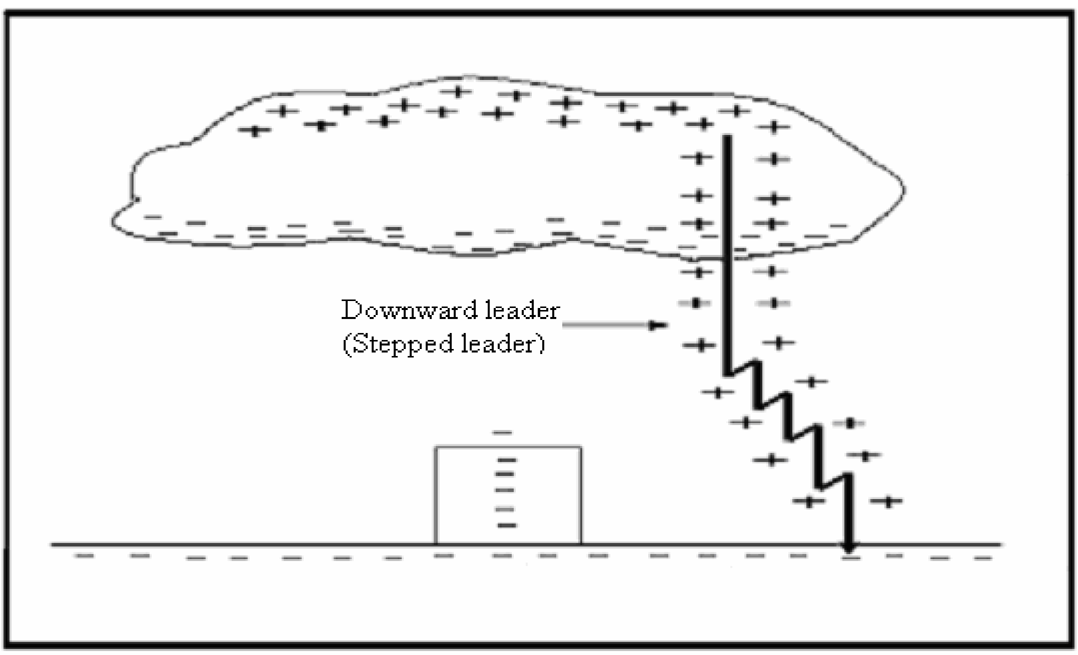

Figure 3-3: Positive downward leaders

3.2.4 Final stage of lightning

Positive charges will, in turn, be induced on the ground surface and, in particular on any high structures. If the potential is sufficiently high at the ground (or on a high structure), then ionisation of the air commences and an upward positively charged leader, will be created as shown in Figure 3-4 [5]. Eventually the negative and positive charged leaders will meet, often via a seemingly haphazard route, and the lightning discharge will be experienced, which is normally negative.

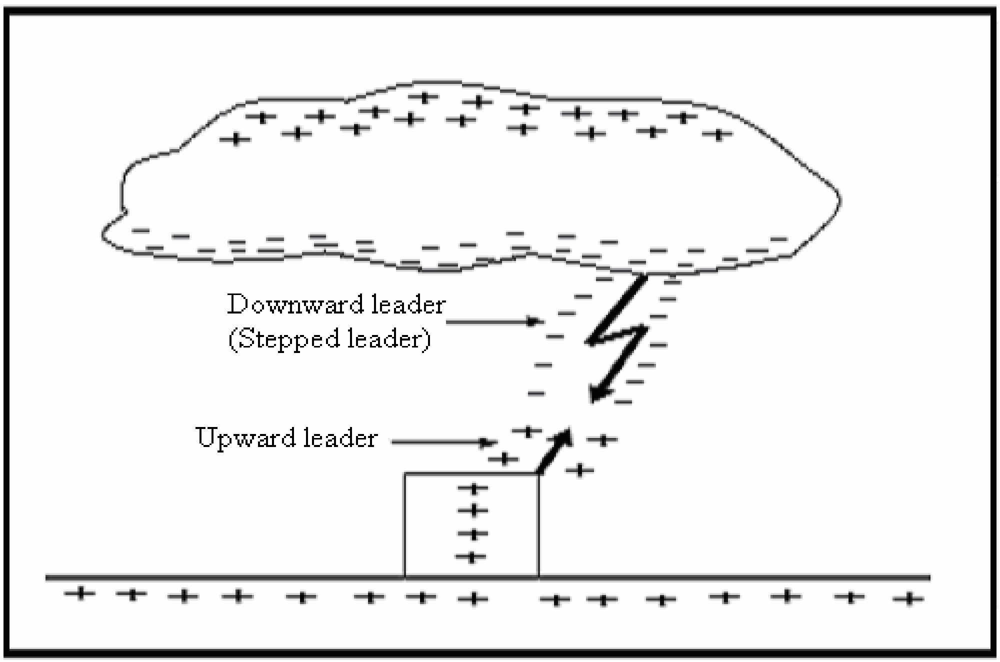

Figure 3-4: Downward and upward leaders

The amount of lightning activity is not the same in South Africa ranging from the extreme (Mpumalamga) to the nominal (Southem Cape), it varies according to many factors, including geographical location, height etc [5]. The energy associated with the discharge also varies. It is necessary to consider these factors and others, in deciding whether a lightning protection system is required and the form it should take.

3.3 Lightning currents and related parameters

When an object on the ground, be this a thatched roofed structure or any other structure, is struck by lightning the stresses to which it is subjected are determined by the current discharged into it and is best described in terms of associated current waveform. From the point of view of lightning protection this current represents the most important single parameter of the lightning discharge. The measurements of the stroke currents on the ground have shown that the high current is characterized by a fast rise to crest (1 to 10 μs) followed by a longer decay time of 50 to 1000 μs to half-time [2, 5].

3.3.1 The peak lightning current

The peak current related to the lightning stroke has amplitudes between 2 kA and 200 kA, (1 % of strokes exceed 200 kA) and are assumed statistical lognormal distributions as shown in Table 3-1 [2] and Figure 3-6 [2]. The time that the lightning stroke reaches the peak value is about 10 μs [2, 5].

Table 3-1: The experimental statistical distribution of lightning strikes as a function of their amplitude

Percentage of lightning stroke		The peak lightning current [kA]
1	Of the strokes exceed	200
5	Of the strokes exceed	100
10	Of the strokes exceed	80
20	Of the strokes exceed	50
50	Of the strokes exceed	28
60	Of the strokes exceed	20
90	Of the strokes exceed	8
99	Of the strokes exceed	3

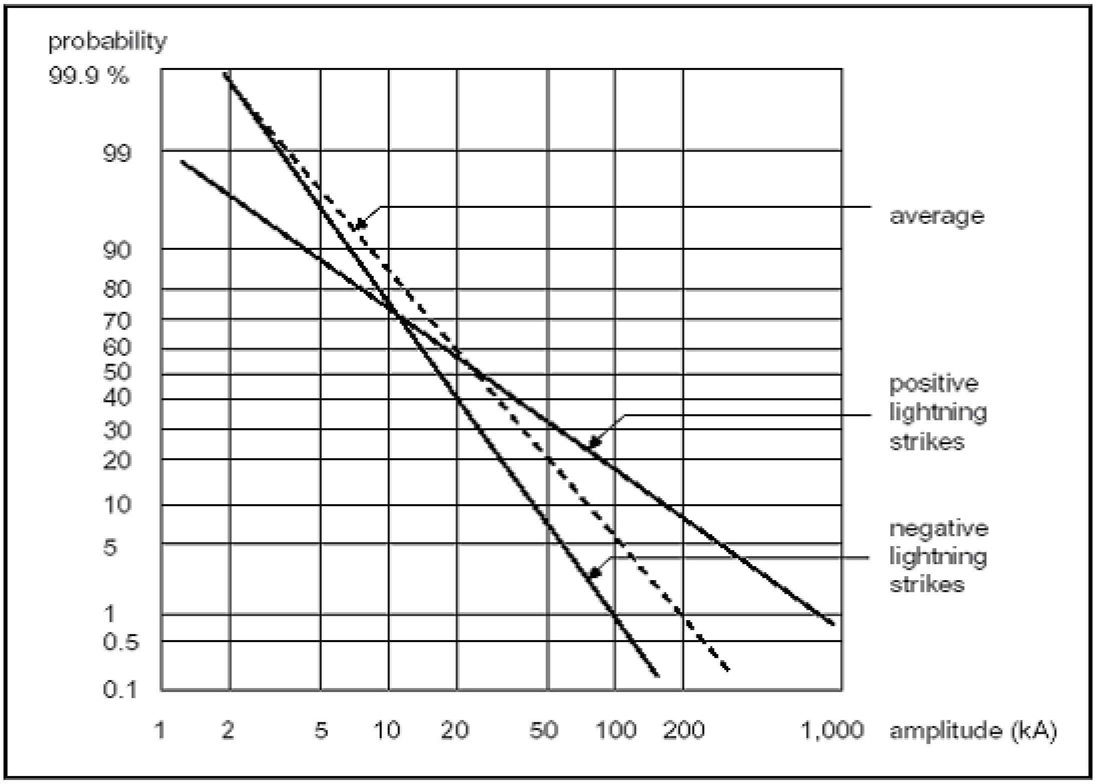

Figure 3-5: Experimental statistical distribution of positive and negative lightning strokes as a function of their amplitude [2]

3.3.2 The rate of rise of the lightning current

The rate of rise of the current, $\frac{di}{dt}$, is important when calculating voltdrops across inductive components of lightning protection systems, and for calculating induced voltages due to adjacent lightning strikes.

The probabilities of the maximum rate of rise of the current of a negative lightning stroke and positive lightning stroke are illustrated in Figure 3-7 [2].

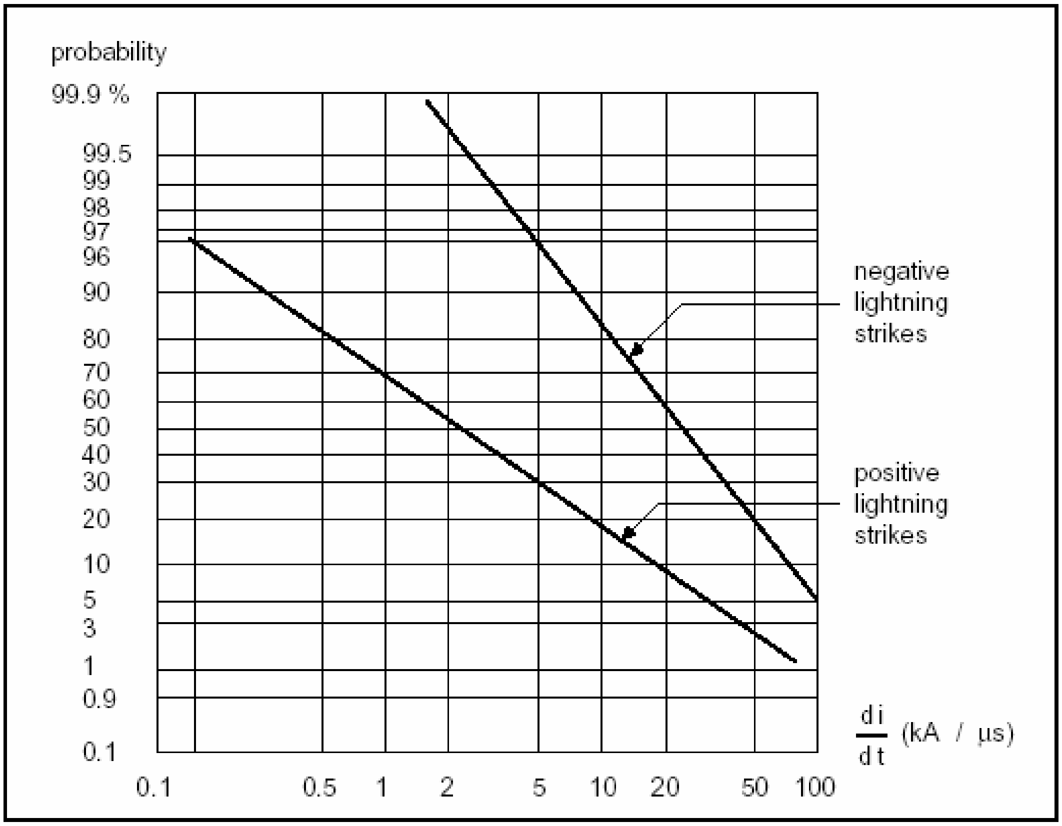

Figure 3-6: Experimental statistical distribution of positive and negative lightning strokes as a function of front steepness [2]

3.3.3 Lightning current waveform

The standard lightning is comprised of current waveform components which present the important characteristics of natural lightning flashes and is approximated by a double exponential waveform. The waveform parameters defined in SABS IEC 61024-1-1 (1993) are shown in Figure 3-8 [2, 5]. The lightning current waveform is described in terms of the time to crest, t_{cr}, and the time to half value, t_d, so that a 8/20 μs waveform has a time to crest of 8 μs and time to half value of 20 μs.

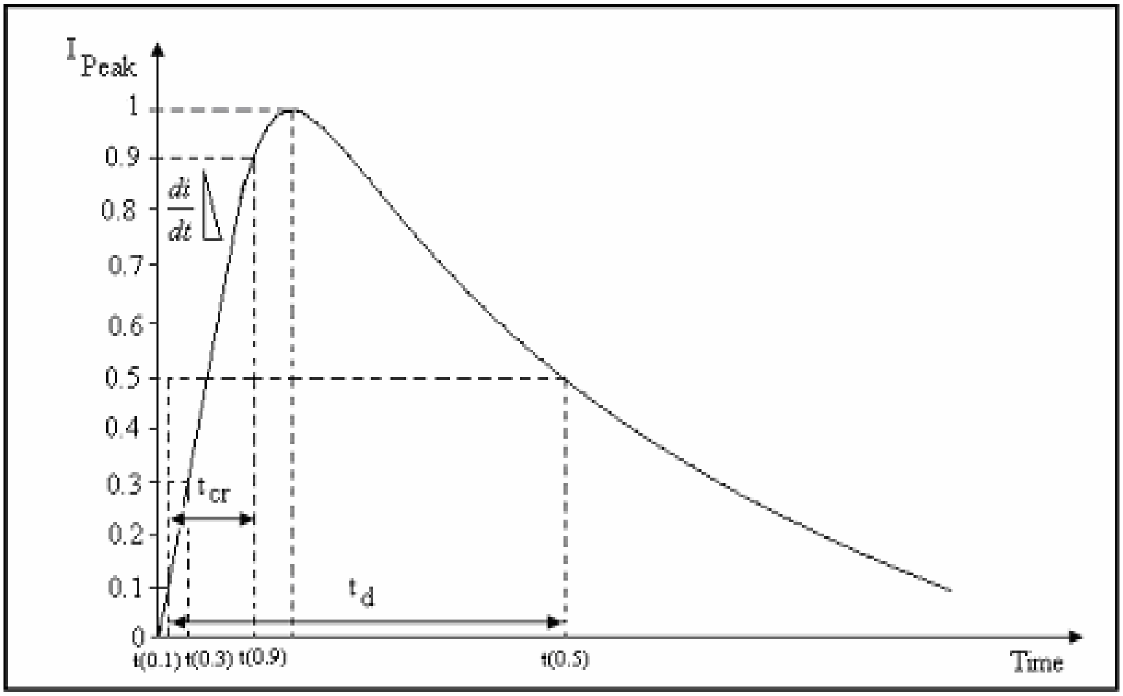

Figure 3-7: Double exponential current waveform

These values in Table 3-2 [2] should be compared with the standard waveforms used for testing electrical equipment.

Table 3-2: The lightning values

Current	2000 to 200,000 A
Voltage	100 to 1,000,000 kV
Duration	70 to 200 μs
Electrical discharge in the cloud	20 to 50 C
Energy	4 to 10 kWh
Time to crest (voltage)	1.2 μs
Time to half value (voltage)	50 μs
Time to crest (current)	8 μs
Time to half value (current)	20 μs
$\frac{di(t)}{dt}$	5.5 kA/ μs

3.3.4 Subsequent strokes

The subsequent strokes in the flash tend to have a higher rate of rise of current but lower peak amplitudes than the initial stroke and they can therefore be significant for induced voltages in wiring, where the inductively coupled voltages are proportional to the rate of change of the lightning current [2, 5].

The first stroke within a flash usually has the largest peak current (typically three times that of subsequent strokes), therefore when describing the peak current of a flash we usually imply that of the first stroke [2, 5].

Near the end of some of the strokes in a negative flash, there is often a lower level current of a few kA persisting for several milliseconds as illustrated in Figure 3-9 [5].

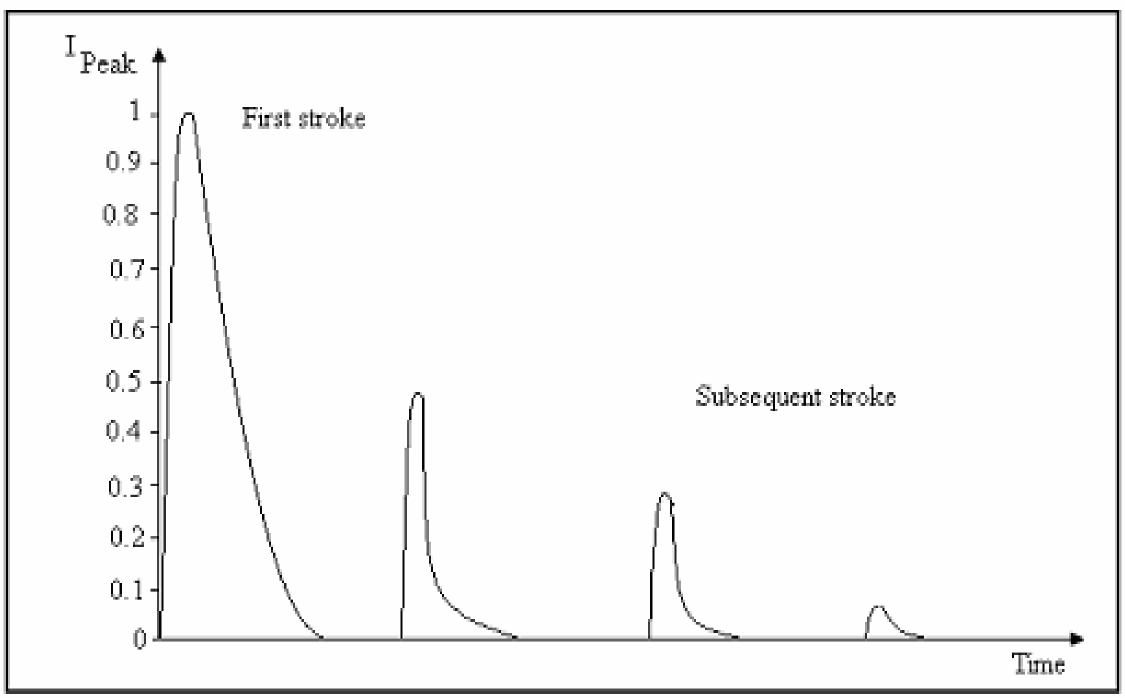

Figure 3-8: Lightning flash current waveforms

4 Effects of lightning

The effects of lightning can result in fire damage for thatched roofed structures if the protective measures are not taking into account. To provide these protective measures it is important to analyse these effects. This chapter discusses the main effects of direct lightning strike on structures.

4.1 Direct effects

These are caused by current transfer via direct attachment. They will be considered individually [2, 6]:

4.1.1 Thermal effects

When a lightning current pulse flows through a conductor of resistance R, heat is generated. Practically the whole of this heat is devoted to raising the temperature, since no significant portion of the heat can flow to the structure during the very short duration of the pulse [6].

In the construction process of thatch, wire mesh is used to reinforce and secure the bundles of thatch. If lightning current flows through the wire mesh, the thermal effect may occur and it can cause a fire for thatch. To minimize the thermal effects the metal-coated insulating sheets are used in the preparation of thatch [1, 6].

The conductor which may carry the lightning current therefore need to be designed with a cross-sectional area large enough to keep the temperature rise well below a critical value such as the ignition point or melting point of the material. The design also needs to account for the fact that rapidly changing currents in the lightning pulse tend to concentrate at the surface of the conductor (skin effect) [6].

4.1.2 Mechanical effects

The conductors which form a LPS for thatched roof should have a cross-sectional area large enough so that can carry lightning current without melting or fusing explosively. If the conductor is subjected to melt especially in contact with thatch, the thatch can ignite [6].

4.1.3 Sparking effects

The most dangerous effects for thatch are sparking effects. These effects in the presence of thatch can cause fire risk. Voltage and thermal sparking may occur either separately or together. Voltage sparking is the result of dielectric breakdown including tracking or flashover across dielectric surfaces. It could arise inductively in a loop, bend or from the resistive drop in a high resistance material, especially at joints [2, 6].

Thermal sparking consists of burning fragments of melted material thrown out from hot spots such as high resistance contacts having a high current concentration, or at acute changes of geometry. The temperatures of both types of spark are high and are potential sources of fire or explosion [2, 6].

5 Assessment of risk of damage due to lightning

The procedure for calculating the risk is well described in the standards, such as SABS 0313 (1999), SABS IEC 61662-1 (1995) and IEC 62305-2, Ed.1. The result of this calculation determines the need of a lightning protection system and its protection level.

The risk assessment compares the expected lightning strike with the probability of lightning strike on the structure. The rate of these two factors indicates the need of a lightning protection system and its degree of security (protection level) [7, 8]. This value depends on several factors, such as the type of structure and its contents, although sometimes other considerations could be taken into account in order to improve the protection level over the risk calculations [7].

Standards of practice for lightning protection consider that lightning protection is needed in the following cases [7, 8]:

- Large concentrations of persons
- Need of continuity in production or public services
- Areas with high lightning density
- Very high or isolated buildings
- Buildings containing explosive or inflammable materials
- Buildings containing irreplaceable heritage
- Buildings or structures whose risk index, calculated according to the standard, determine the need for a lightning protection system with a certain protection level

5.1 Risk calculation and determination of protection level

The SABS 0313 provides an equation to determine the expected annual frequency of direct lightning flashes to a structure, N_d. The following equation is used:

$$N_d = N_g \times A_e \times C_e \times 10^{-6} \tag{5-1}$$

N_g is the average ground lightning flash density in square kilometre per year, concerning the particular area where the structure is located. This value can be obtained statistically from an isokeraunic map. In South Africa, the value of N_g is given from Table 13-1 in Appendices. C_e is the environmental coefficient which describes the particular location of the structure and is given in Table 13-2 Appendices.

5.1.1 Calculation of the equivalent collection area, A_e

The equivalent collection area A_e is given in Figure 5-1 and is calculated as follows [1, 5]:

$$A_e = LW + 6H\,(L + W) + 9\pi H^2 \tag{5-2}$$

The equivalent collection area, A_e, of the structure in square kilometres is defined as the measure of the ground surface and a straight line with a 1:3 slope which passes from the upper parts of the structure as shown in Figure 5-1 [1, 5]. This area has the same expected annual frequency of direct lightning flashes, N_d as the structure.

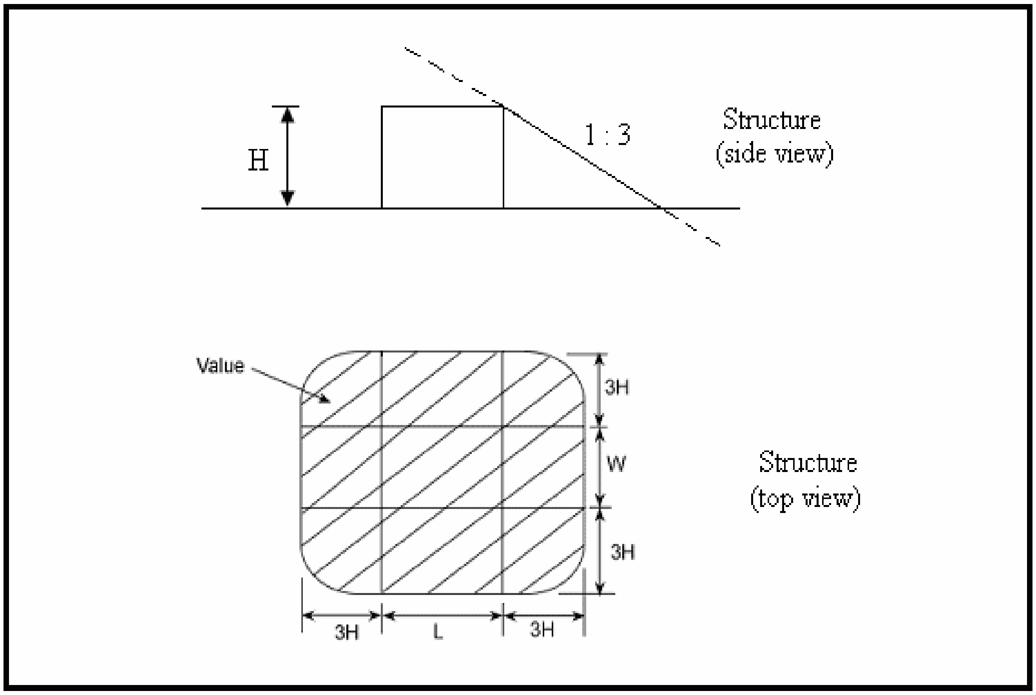

Figure 5-1: The equivalent collection area of a structure

5.1.2 Calculation of LPS efficiency, *E*

The estimation of LPS efficiency is achieved after analysing the risk of damage. This analysis takes into account appropriate factors such as [1, 9]:

- Type of construction;
- Presence of flammable and exposure substances;
- Measures put in place to reduce the consequential effects of lightning;
- Number of people affected by the damage;
- Type and importance of service concerned; and
- Value of goods that could suffer damage

SABS 0313 also provide an equation to determine the accepted annual frequency of lightning flashes, N_c, as follows:

$$N_c = a \times b \times c \tag{5-3}$$

a is the Factor that depends on the type of the structure, b is the Factor which depends on the contents of the structure, c is the Factor which takes into account the consequential losses. The factors a, b and c are determined from Tables 13-3, 13-4, 13-5 respectively in Appendices

With these values, the efficiency, E and the protection levels are calculated as follows [1]:

$$E = 1 - \frac{N_c}{N_d} \tag{5-4}$$

Table 5-1: The efficiency, E and its related protection level

Calculated efficiency, E	Corresponding protection level
$E > 0{,}98$	Level I + additional measures
$0{,}95 < E \leq 0{,}98$	Level I
$0.90 < E \leq 0.95$	Level II
$0.80 < E \leq 0.90$	Level III
$0 < E \leq 0.80$	Level IV

When the calculated efficiency of the LPS, E is equal to zero no protection measure is needed [8, 9].

The need for lightning protection system is determined from the comparison between the value of the accepted annual frequency of direct lightning flashes (N_c) and the expected annual frequency of direct lightning flashes to the structure (N_d) as follows [9]:

If N_d is less than or equal to N_c, the LPS is not needed.

If N_d exceeds N_c, an LPS of efficiency, E calculated in equation 5-4 can be installed and the proper protection level can then be selected according to Table 5-1 [5, 9].

5.1.3 Expected number of direct strike

As described in section 5.1, the relationship between expected annual frequency of direct lightning flashes to a structure (N_d) and lightning ground flash density (N_g) is defined by the equation 5-1. Table 13-1 in Appendices gives the lightning ground flash density in South Africa.

Considering the cone of protection (Figure 8-1 and Figure 8-2), we can estimate the effective area of a structure projected over the ground surface, the area of attraction increases as the height of the mast increases. For a mast height H, a circle of radius 3H produces a protection cone for the structure that will intercept a lightning flash. Thus, assuming a thatched roofed building of 10m x 6m, with a height of 9m, the effective area is shown in Figure 5-1. Using equation 5-2, the calculated area is equal to 3200 m^2 = 0.0032 km^2.

Applying the lightning ground flash density of Table 13-1 in Appendices for Johannesburg, we obtain an estimated interception rate for the following different cases according to the environmental coefficient given on Table 13-2 in appendices as follows:

1) A structure amongst other buildings and trees of the same or greater height

$N_d = 7.5 \times 0.0032 \times 0.25 = 0.006$ Flashes per year

2) A structure surrounded by smaller buildings

$N_d = 7.5 \times 0.0032 \times 0.50 = 0.012$ Flashes per year

3) Isolated structure or no buildings within a distance of 3H

$N_d = 7.5 \times 0.0032 \times 1.0 = 0.024$ Flashes per year

4) Isolated structure on a hill

$N_d = 7.5 \times 0.0032 \times 2.0 = 0.048$ Flashes per year

For each of the above cases the calculated flashes per year are related to the area covered by the assumed building and its associated cones. The building will be expected to intercept a lightning flash once every hundred and sixty seven years for case 1 once every eighty three years for case 2 once every forty two years for case 3 and once every twenty one years for case 4.

The lightning flash interception rate of the building can be understood as the flash interception rate of the installed LPS for the structure, since the LPS is designed for protecting the structure.

5.1.4 Estimated efficiencies of an LPS and its related levels of protection

From equation 5-3 and Tables 13-3, 13-4, 13-5 in Appendices, the estimated and accepted annual frequency of direct lightning strikes (N_c), is equal to 10^{-3} Flashes per year. Therefore, the estimated efficiencies of an LPS and its related levels of protection for each case are the following:

1) 83% $(0.80 < E \leq 0.90)$ -Level III

2) 92% $(0.90 < E \leq 0.95)$ -Level II

3) 96% $(0.95 < E \leq 0.98)$ -Level I

4) 98% $(0.95 < E \leq 0.98)$ -Level I

The obtained levels of protection justify the need of LPS in order to protect the thatched roofed structures, its occupants and equipment from lightning flashes.

Taking into account that thatched roofed structures are prone to ignite, the cases 2, 3 and 4 above are considered in the designing of lightning protection system in this work, implying that protection level of I and II is necessary for thatched roofed structure.

6 Methods of lightning protection

The methods of lightning protection are well described using the zone of protection concepts for a structure. The zone of protection is the space within the volume to be protected and where the lightning protection air termination is located. Air termination can have different forms such as [1, 5]:

- Rods;
- Stretched wires; and
- Meshed conductors.

In order to place the air termination in a proper position on the building to be protected, the following methods can be used [1, 5]:

- The protective angle method;
- The rolling sphere method; and
- The mesh method

6.1 The protective angle method

The structure to be protected lies within an imaginary cone ABC with the highest point of the structure providing protection as shown in Figure 6-1 [1]. Table 6-3 [1] provides the recommended values for the cone angle, α (in degrees).

Table 6-1: Protective angle according to the protection level

Protection level	Height of air termination, h_t [m]			
	20	**30**	**45**	**60**
	Angle, α [in degrees]			
I	25	-	-	-
II	35	25	-	-
III	45	35	25	-
IV	55	45	35	25

The protection angle method is suitable for simple buildings. If the height is larger than the rolling sphere radius, R, the protection angle method can not be used [10, 11].

The zone of protection offered by an air termination system is considered to be 45º for heights up to 20m [11]. Above this height, the zone of protection is determined by the rolling sphere method.

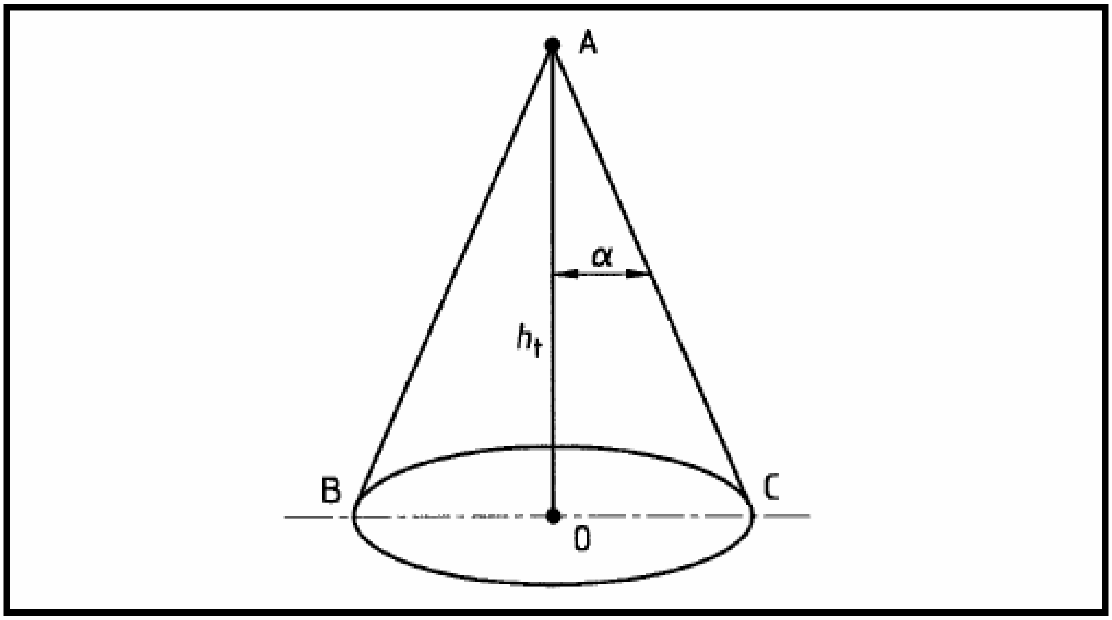

Figure 6-1: An imaginary cone formed from protective angle [1]

6.2 The rolling sphere method

The rolling sphere method is used when we are dealing with complex structures. When the use of the protective angle method is excluded, the rolling sphere method is used to identify the protected volume of the structure [1, 11].

This involves rolling an imaginary sphere of radius given in Table 6-2 [10] over a structure. The areas touched by the sphere are deemed to require protection as shown in Figure 6-2 [11]. On tall structures, this can obviously include the sides of the building.

Table 6-2: Rolling sphere radius

Protection level	Radius of the sphere
I	20
II	30
III	45
IV	60

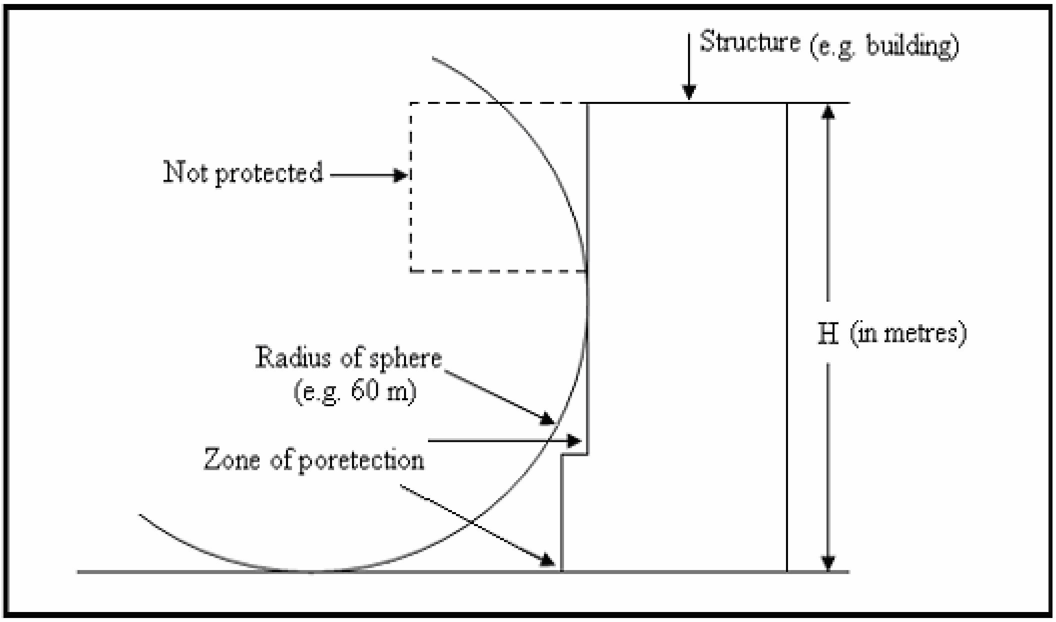

Figure 6-2: Rolling sphere [11]

If two parallel horizontal LPS air terminations are placed above the horizontal reference plane as shown in Figure 6-3 [1], the penetration distance *p* of the rolling sphere below the level of the air terminations is calculated as follows [1]:

$$p = R - \sqrt{R^2 - \left(\frac{d}{2}\right)^2} \qquad (6\text{-}1)$$

p is the penetration distance of rolling sphere, R is the radius of rolling sphere and d is the distance separating two air terminations.

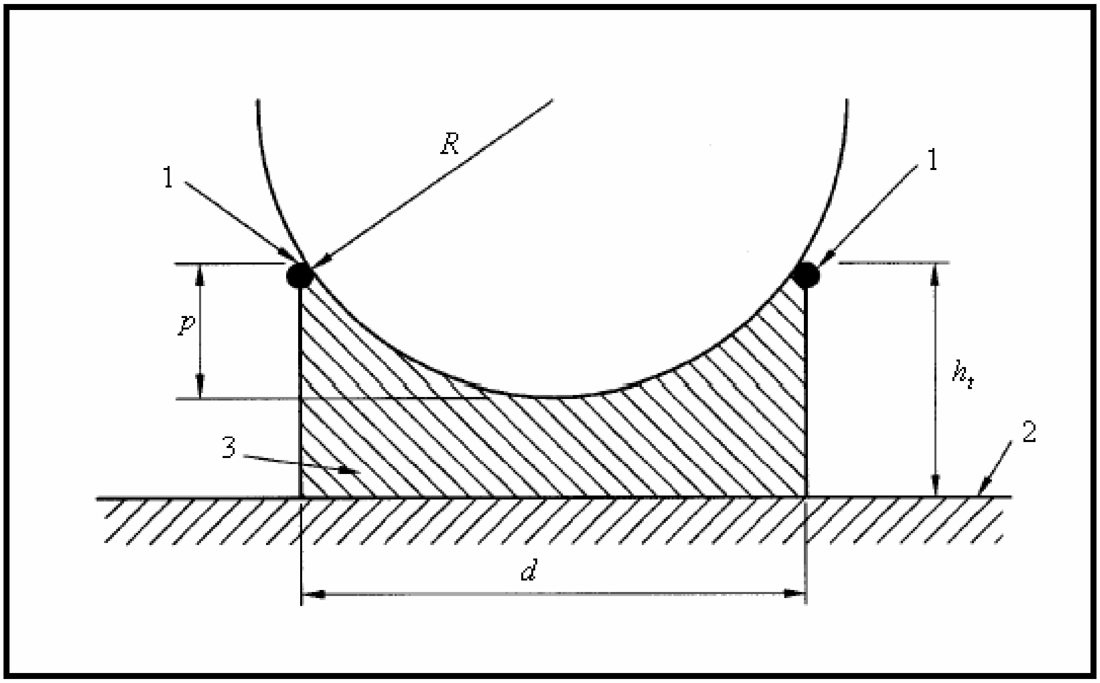

Figure 6-3: Space protected by two air terminations [1]

1- Two air – terminations, 2- horizontal reference plane, 3- whole protected area, h_t - physical height of the air-termination above the reference plane. This height is given in Table 6-1.

6.3 The mesh method

The mesh method is suitable for protecting flat surfaces. BS 6651 recommends that on high risk structures such as explosive factories and thatched roofs, no part of the roof should be more than 2.5m from an air termination conductor. This is generally achieved by applying a 5m x 10m mesh to the roof [11].

However, for most structures, a mesh of 10m x 20m is considered sufficient, giving a maximum distance from any part of the roof to the nearest conductor of 5m. All metal structures on the roof would be interconnected using this mesh [11].

The recommended sizes for the mesh according to their protection level are listed in Table 6-3 [5, 10].

Table 6-3: Recommended size for mesh

Protection level	Mesh size [m]
I	5
II	10
III	10
IV	20

7 Components of lightning protection system (LPS)

In the design of LPS for thatched roofed structures is based on the concepts of a protective angle and rolling sphere methods, which are applied to the structure to ensure that all exposed areas are protected by the system. The lightning protection system must be designed to provide sufficiently low impedance so that the lightning energy will follow the required route. This requires an integrated design and use of materials with sufficiently low impedance. The various components of the lightning protection system for thatched roofed structures are as follows [5, 11]:

- Air terminations
- Down conductors
- Bonding conductors
- Earth termination

7.1 Air terminations

In general air terminations consist of a vertical rods, stretched wires and meshed conductors on the roof and top edges of a structure. The conductors typically form a mesh of 10 m by 20 m, smaller on high risk buildings. Metal projections, including rods, are connected to this [11].

For thatched roofed structures, air terminations consist of the highest point of the mast, stretched wires and meshed conductors on the roof and top edges of a structure.

BS 6651 requires that all parts of the roof are within 5m of a conductor of the air termination. This distance is reduced to 2.5 m in high risk buildings. Rods, if used, are positioned near those locations where a strike is most likely (for example roof peaks, building corners etc).

7.2 Down conductors

For thatched roofed structures down conductors are the masts and are required to provide a low impedance path down the structure, in a manner which minimises potential differences and induced current.

The mast must be located at least one metre a way from the thatched roofed structure. This will avoid the flash-side that can occur between the mast and metal objects in the structure [5].

In general the down conductors would be symmetrically positioned around the building in such a way that the average value of the distance between them is more than the values indicated in Table 7-1 [10], ideally including the corners. Sensitive electronic equipment should not be positioned within the building, near to these down paths as there is a risk of inductive interference. Currents would flow in all paths, but the largest would flow in the path nearest to the point of impact.

Table 7-1: Average distance between down conductors

Protection level	Average distance [m]
I	10
II	15
III	20
IV	25

Each down conductor should be taken to an earth termination and interconnected via a horizontal ring conductor installed near ground level. A test clamp is often fitted to enable the continuity of pairs of down conductors to be checked at ground level and provide a means of isolating the earth electrode [12].

7.3 Bonding conductors

In the case of large thatched roofed structures and thatched roofed structures involving a group of closely spaced houses, the lightning protection system requires more than one mast. In this case bonding conductors are necessary for interconnecting the masts.

The metalwork (such as central heating ducts, pipes etc.) in the thatched roofed structures must be connected to the bonding bar using bonding conductors. Bonding bars are constructed and installed in a way that allows easy access for inspection [1].

The bonding bar should be connected to the earth termination system. For large structures, more than one bonding bar could be provided and interconnected [12]. This is to ensure that a side-flash does not occur. As the current flows into conductors, a potential would be created [13]. If metalwork is not bonded, this can initially be at a potential nearer to that of earth and thus can offer a more desirable path to ground [13].

The bonding bars should be placed above ground at vertical intervals not exceeding 20 m for structures of more than 20 m in height [9, 12]. Bonding bars should be connected to the horizontal ring which bonds the down conductors.

If the whole lightning current or substantial part of it flows through a bonding connection, the minimum dimension for cross-sections of bonding conductors are given in Table 7-2 [10].

Table 7-2: Minimum dimensions for bonding conductors

Protection level	Material	Cross section [mm^2]
I to IV	Cu	16
	Al	25
	Fe	50

7.4 Earth termination

The mast protecting thatched roofed structure can be used at below ground as earth termination. For thatched roofed structures involving a group of closely spaced houses, the earth termination can consist of a ring of buried copper which encircles the structure. As we know from the section 7.2 the down conductors for thatched roofed structures are the masts, Each mast must have separate earth electrode termination and these are normally looped together to form a ring, with horizontal electrodes being used The impedance of the termination is required to be a maximum of 10 Ω [11]. The most common terminations are driven rods and these are required to be at least 1.5 m long with a minimum of 9m being used for each system [11].

The ring helps to provide potential equalisation at ground level, in addition to potential grounding. The latter helps reduce the touch voltage which could be experienced by a person in contact with the mast during a lightning discharge. The external ring earth electrode should be used preferably buried at a depth of at least 0.5 m but not closer to 1 m from the walls [1, 10].

Embedded earth electrodes shall be installed in such a way as to allow inspection during construction. The embedded depth and type of the earth electrodes shall be such as to minimize the effects of corrosion, soil drying and freezing and thereby stabilize the equivalent earth resistance [10, 12]. It is recommended that the first metre of vertical earth electrode should not be regarded as being effective under frost conditions.

The earth electrode design may be influenced by the soil conditions. The treatment of soil resistivity can have corrosive effects on the earth electrode. The relationship between the soil resistivity and corrosiveness is given in table 7-3 [12].

Table 7-3: Soil resistivity and corrosiveness

Corrosiveness	Soil resistivity [Ω.m]
very severe	0 – 10
moderate to severe	10 – 100
Mild	100 – 1000
probably not corrosive	> 1000

8 Lightning protection system for thatched roofs

The discussion in chapters 6 and 7 gives some guidance on the lightning protection system for a thatched roofed structure. There are two basic approaches to providing sufficient protection for thatched roofs, that of lightning masts or a meshed conductor system on the roof.

8.1 Lightning mast

According to SABS 0313, the lightning mast must be located at least 1 metre away from the house, with sufficient height to provide an effective cone of protection. For small structures one mast should be sufficient to form the cone of protection as shown in Figure 8-1. In the case of large structures and structures involving a group of closely spaced houses, a minimum of two masts are recommended, with four being even more effective. Figure 8-2 shows the implementation use of the two masts. The height of the mast and its relative angles of protection are given on Table 6-1.

According to the estimated efficiencies in section 5.1.4, the lightning protection system for thatched roofed structures is considered in this work taking into account the risk levels (levels of protection) I and II. According to Table 6-1, the protective angles for these levels of protection are 25^0 and 35^0 as shown in Figure 8-1.

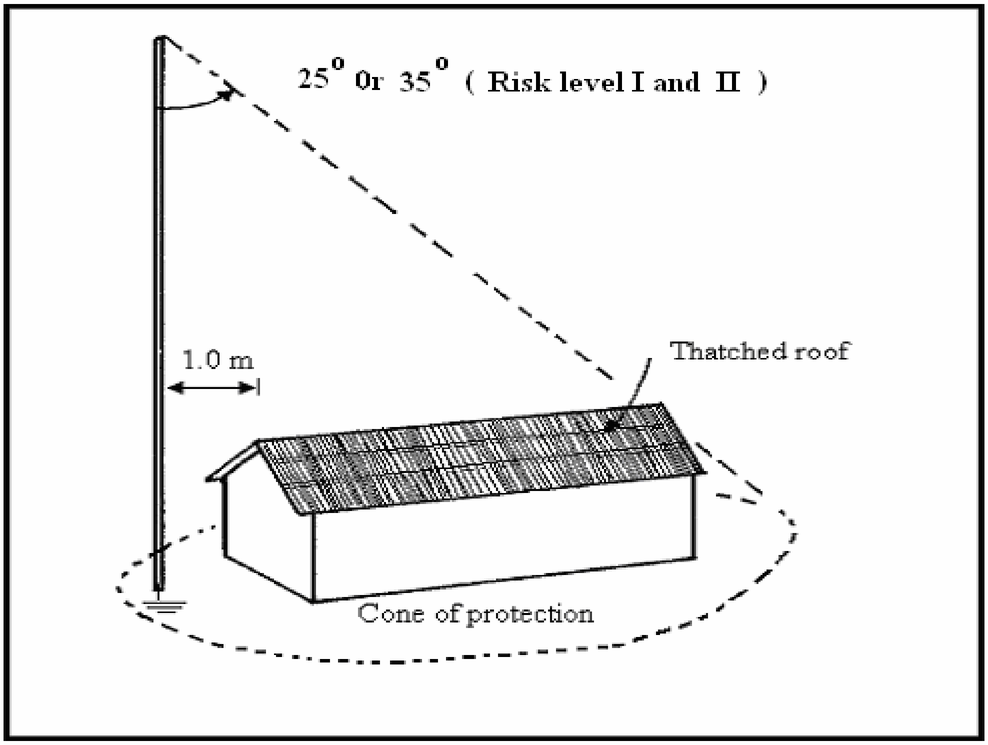

Figure 8-1: Lightning protection system using one mast

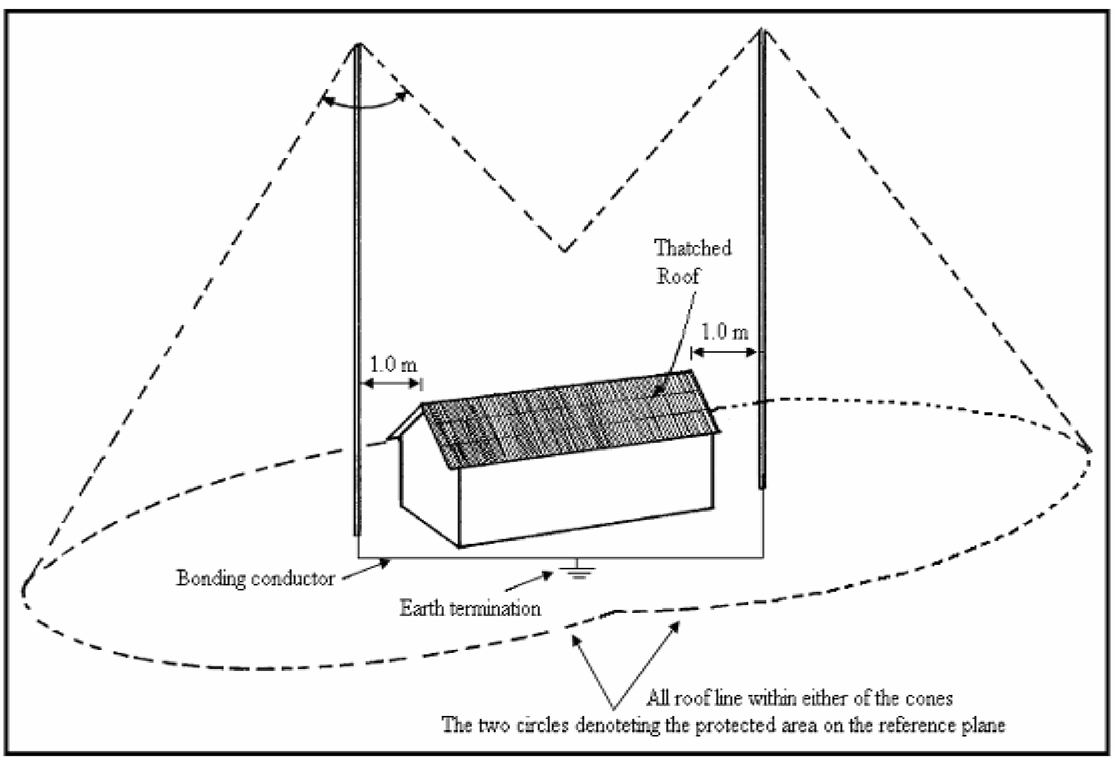

Figure 8-2: Lightning protection system using two masts

In order to provide effective protection for thatched roofs, the zone of protection provided by the mast must include gables ends, chimneys, antennas, vent pipes and any other metal objects. Telephone wires, overhead service connections to the power system, or other overhead metal wires or pipes must not enter the structure through or close to the thatch. The power system and communication system must enter the building from bellow ground level.

8.2 Lightning conductors above the roof

Protecting thatched roofs against lightning using a conductor system above the roof is considered in this work as an alternative method for the method described in paragraph 8.1 above. A possibly more effective protection can be expected from a lattice of lightning conductors strung some distance above the roof. As described in section 6.3.

Since the thatch is prone to ignite, the side-flash becomes a problem. This should be avoided by considering the recommended size of the mesh on the roof given on Table 6-3 and the down conductor for the mesh conductors have to be routed far enough away from the thatched roof

8.3 Protection of equipment inside the thatched roofed structure

In order to complete a lightning protection system design, potential equalization is a fundamental basis for the realization of internal lightning protection, that is the lightning over-voltage protection for the electrical and also the electronic data transmission facilities and devices in a thatched roofed structure. In the event of a lightning stroke, the potential of all installations in the affected building (including live conductors in the electrical systems with arrestors) will be increased to a value equivalent to that arising in the earthing system and no dangerous over-voltages will be generated in the system.

The protection of electronic equipment against potential differences and static charge build up will be provided by interconnecting all non-current carrying metal objects to a bonding bar that is effectively connected to the earth electrode system.

9 High voltage laboratory tests

The tests aim to verify the resistibility of thatch to ignite when hit by lightning. These tests provide a mechanism to determine the behaviour of thatch when side-flash occurs and from this appropriate protection measures can be implemented

The lightning current test is performed according to SABS IEC 1312-1:1995 and SABS IEC 60-1:1989 standards. These standards specify the tolerance parameters for the different exponential current impulses as shown on Table 9-1 and give a guideline on how a lightning current impulse is obtained for test purposes. The tolerances defined below are for the testing of surge protective devices and as no test standard is available for thatch these parameters will be adopted for this work.

Table 9-1: Standard exponential impulse current according to SABS IEC 60-1

Waveform	Time to crest	Time to half value	Value for peak
1/20	1µs ±10%	20 µs ±10%	±10%
4/10	4µs ±10%	10 µs ±10%	±10%
8/20	8µs ±10%	20 µs ±10%	±10%
30/80	30µs ±10%	80 µs ±10%	±10%

9.1 Test description

A combined impulse generator (voltage, current) and associated measuring instruments were used for the testing of old thatch and wet thatch.

Figure 13-1 in appendices shows the test and measuring system which comprises a combined impulse generator (voltage, current) ranging from $0-40\,\text{kA}$ and measuring instrument (TEKTRONIX THS 720P). With prefixed air-gap length of 10 mm, the voltage was varied through the voltage control unit until the air broke down, and then the peak current was measured. These tests are accompanied by a spark and some noise which indicate the occurrence of a flash-over within the spark gap. The tests were repeated for a fixed air-gap length of 20 mm and 30 mm.

The experimental test setup is shown in Figure 13-1 in appendices. The results of these measurements are shown on Tables 9-2, 9-3 and 9-4 below. Figures 9-1, 9-2 and 9-3 show the impulse current waveforms.

9.2 Discussions of results

The test showed that the old thatch can easily ignite compared to the wet thatch. Some parts of the old thatch started to smoke when the current was increased up to 10 kA. At 32 kA the noise and the spark became more intense. Because of safety issues, the test with 32 kA to 40 kA was made without thatch in order to avoid fire since the high voltage laboratory at the School of Electrical and Information Engineering in the University of the Witwatersrand, Johannesburg is not designed for fire tests. The wet thatch was subjected to the same conditions as the old thatch, it did not burn but the area affected by the spark dried up.

During the test, it was also observed that when the airgap is small the spark and the noise are more intense than when the airgap is big. With an air-gap of 10 mm the thatch started to smoke at 10 kA with related impulse charge of 20 C. With an air-gap of 20 mm and 30 mm a current higher than 10 kA would be needed in order for the thatch to ignite. This can be seen in the result measurements on Tables 9-2, 9-3 and 9-4

Four peak current tests using an air-gap of 10mm were carried out. The four peak current tests and their respective results are shown on Table 9-2 and Figure 9-1 below.

Table 9-2: Parameters from test with 10 mm of airgap

Parameters	Measured parameters			
	1	**2**	**3**	**4**
Peak current [kA]	5	8	10	20
Peak rate-of-rise [kA/µs]	0.58	0.69	1.2	3.5
Time to crest [µs]	1.1	1.3	1.6	3.2
Time to half value [µs]	2.3	2.8	3.2	7.5
Impulse charge [C]	6.5	12	20	45
Sparking	No	No	Yes	Yes
Smoking	No	No	Yes	Yes
Ignition	No	No	No	Yes

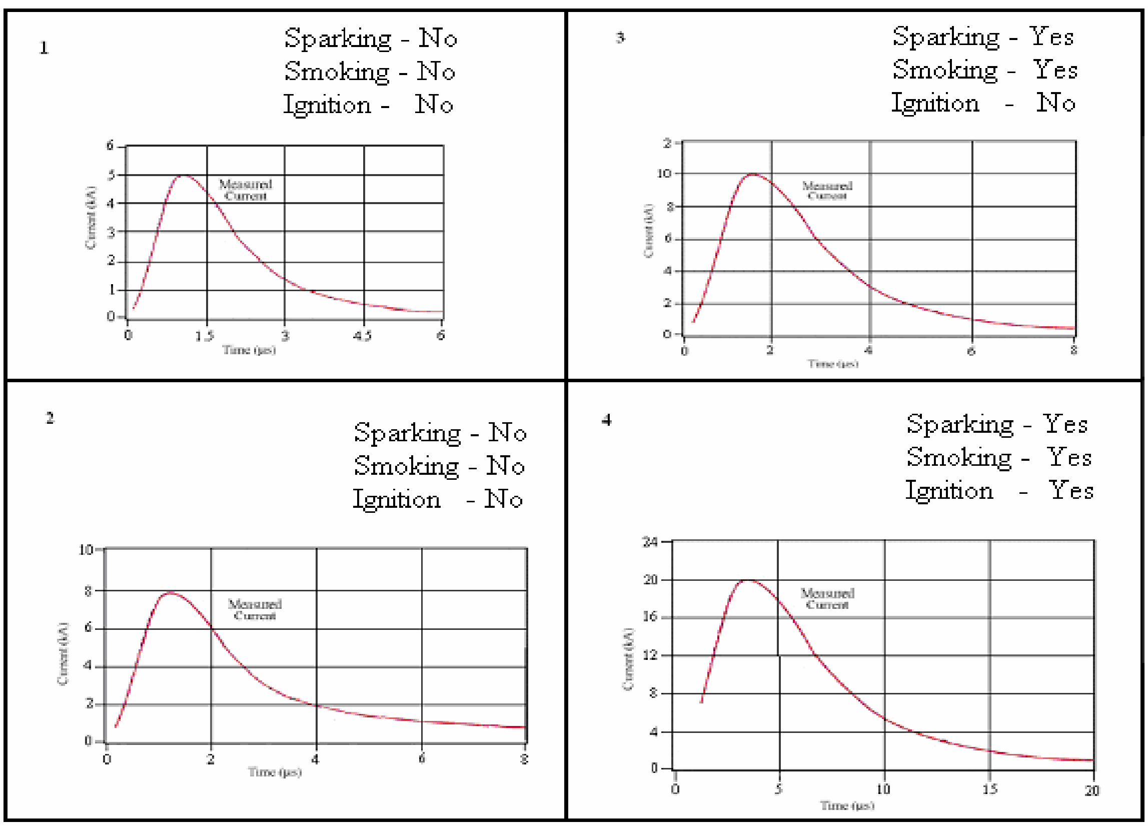

Figure 9-1: Impulse current waveforms from measurements with 10 mm of airgap

The measured impulse current waveforms are within the tolerance defined in Table 9-1, therefore these results are acceptable.

With air-gaps of 20 mm and 30 mm, four peak current tests were carried out for each air-gap. The results of the tests are presented on Tables 9-3 and 9-4 below. Figures 9-2 and 9-3 show the impulse current waveforms. As well as with tests performed at a gap length of 10 mm the new results are also within the acceptable tolerance as described in Table 9-1.

Table 9-3: Parameters from test with 20 mm of airgap

Parameters	**Measured parameters**			
	1	**2**	**3**	**4**
Peak current [kA]	20	25	30	35
Peak rate-of-rise [kA/μs]	1.2	3	4.5	5.6
Time to crest [μs]	9.8	11.6	14.5	21.6
Time to half value [μs]	18.5	32.5	46.7	49.8
Impulse charge [C]	80	110	160	186
Sparking	Yes	Yes	Yes	Yes
Smoking	Yes	Yes	Yes	x
Ignition	Yes	Yes	Yes	x

x – the test was done without thatch

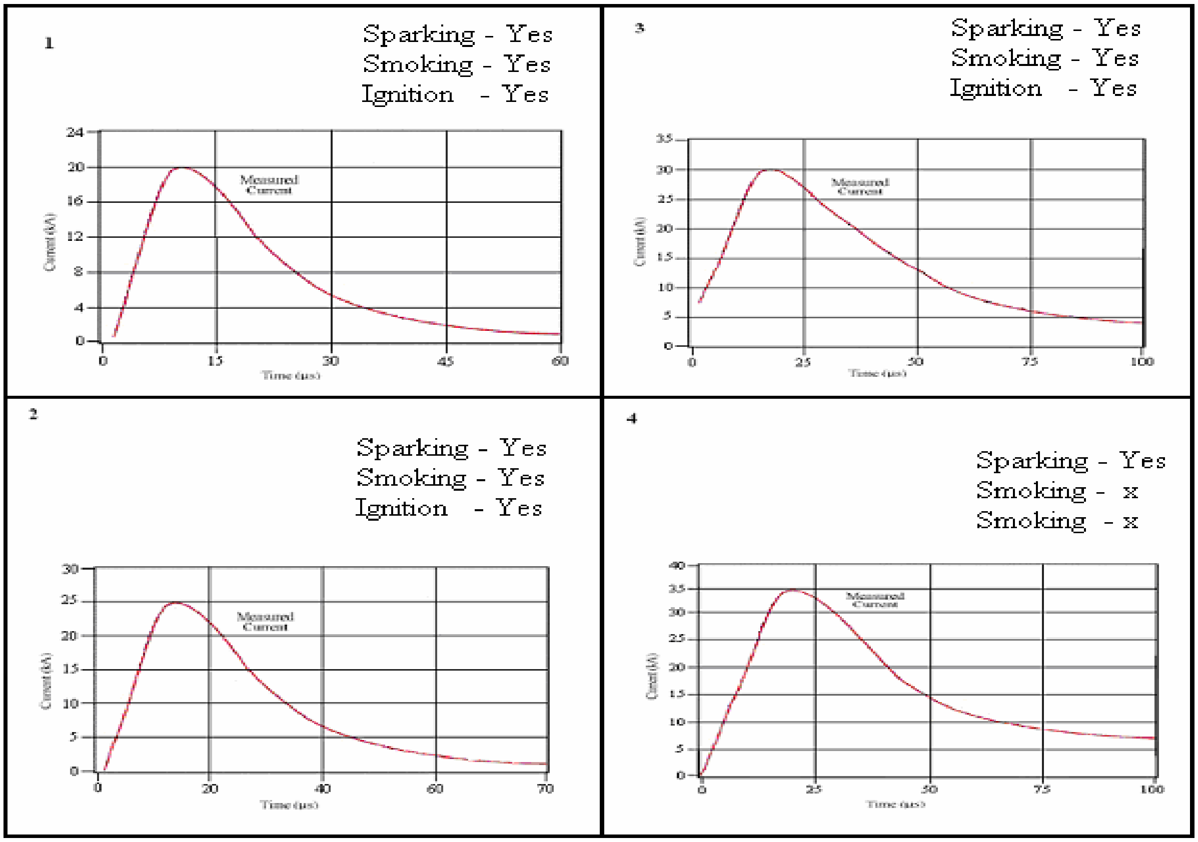

Figure 9-2: Impulse current waveforms from measurements with 20 mm of airgap

Table 9-4: Parameters from test with 30 mm of airgap

Parameters	**Measured Parameters**			
	1	**2**	**3**	**4**
Peak current [kA]	25	30	36	39
Peak rate-of-rise [kA/µs]	1.5	2.5	3.2	4.3
Time to crest [µs]	24.7	25.1	43	46.1
Time to half value [µs]	75.5	83.4	98.1	120
Impulse charge [C]	86	109	150	287
Sparking	N	Yes	Yes	Yes
Smoking	N	Yes	x	x
Ignition	N	N	x	x

x – the test was done without thatch

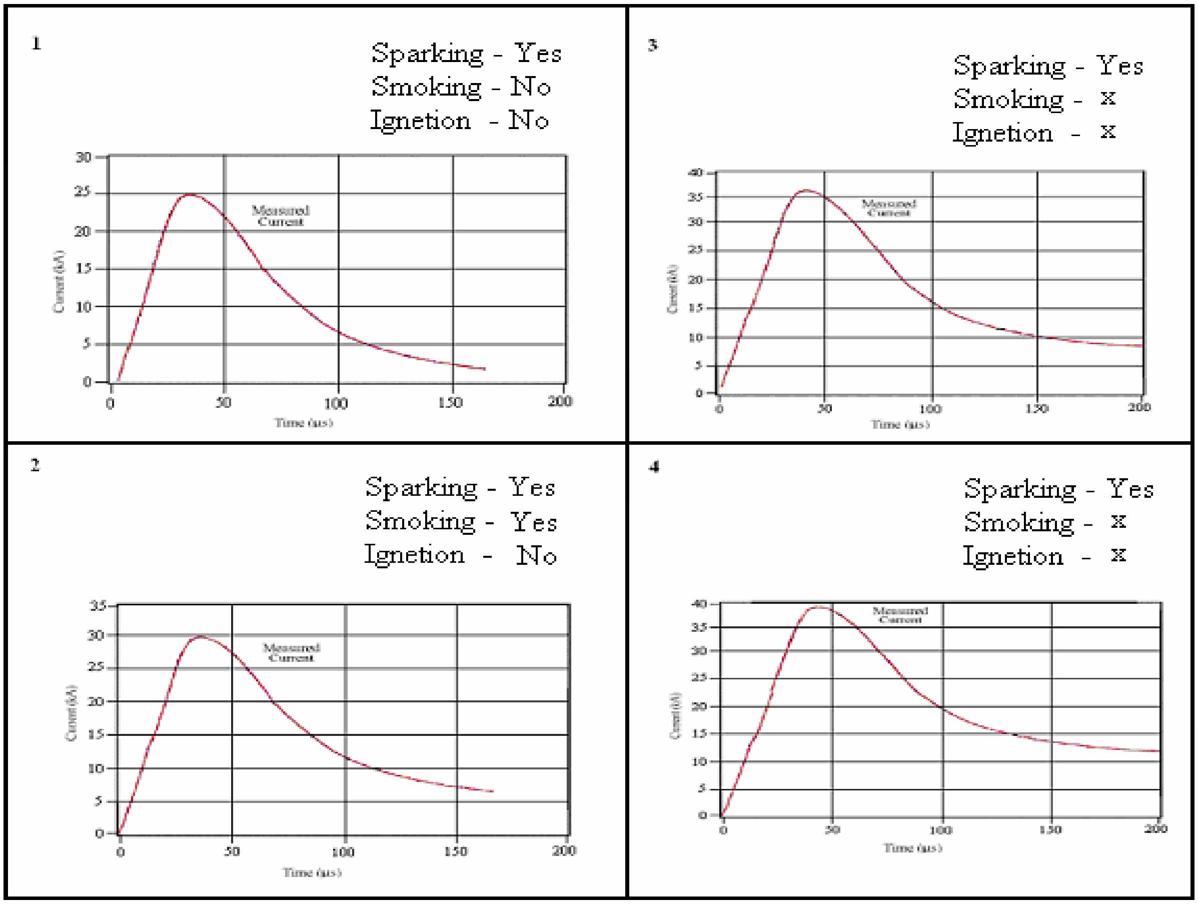

Figure 9-3: Impulse current waveforms from measurement with 30 mm of airgap

The measured parameters such as peak current amplitude, peak rate-of-rise, and time duration and impulse charge shown on Tables 9-2, 9-3 and 9-4 and waveforms in Figures 9-1, 9-2 and 9-3 are of primary importance for evaluation of the direct lightning effect in thatch. These parameters are to be applied for thatched roofed structures lightning protection design.

The waveforms in Figure 9-1, 9-2, and 9-3 are not intended to replicate a specific lightning event, but they are intended to be composite waveforms whose effects on thatch are those expected from natural lightning.

10 Conclusions and recommendations

From the literature reviews and the test results that culminate with the present research report , it is possible to cite the following conclusions and recommendations:

The results obtained from the various tests show that a lightning current of 10kA with an impulse charge of 20 C and with the waveform 1 in Figure 9-1 can be sufficient to cause the thatch to smoke. Therefore with a lightning current of 10kA, the probability of the occurrence of side-flashes is high when there are metal objects close to the thatched roof. The thatch started to ignite at peak current of 20 kA and the impulse charge of 45 C with impulse current waveform 4 in Figure 9-1.

The lightning protection system for thatched roofed structures should be designed by a qualified technician according to standards.

There is a limited amount of information on lightning protection of thatched roofed structures. This work contributes to this pool of knowledge and will provide useful information for further research.

From the test results, it is clear that thatch can ignite if side-flash occurs between metal objects. This can be avoided if the recommended clearance distances between thatch and all lightning conductor objects are considered. These conductors must be bonded to the earth termination system of the lightning protection system.

One of the main aims of this work was to test the performance of lightning protection system for thatched roofed structures, The test facilities used however is not designed for fire tests, therefore a complete structure test was not possible. Therefore only the thatch resistibility tests were performed.

From calculation of the efficiency of LPS in section 5.1.4, the protective levels that can be used for the LPS of thatched roofed structures are I and II

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12 Appendices

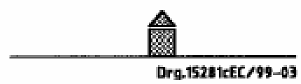
12.1 Lightning ground flash density, N_g

Table 12-1: Lightning ground flash density N_g in South Africa [1]

1	2	3	4	5	6
Town	N_g	Town	N_g	Town	N_g
Aberdeen	1,8	Gobabis	2,6	Paarl	0,2
Albertina	0,5	Golden Gate	6,4	Petrus Steyn	4,4
Alexandria	0,8	Grabouw	0,2	Pietermaritzburg	7,0
Aliwal North	5,3	Graaff-Reinet	2,5	Pietersburg	3,6
Aranos	1,6	Grahamstown	1,4	Piet Retief	11,7
Aroab	1,7	Greytown	5,5	Piketberg	0,2
Barberton	7,5	Groblersdal	5,1	Pongola	6,3
Beaufort West	1,7	Harding	5,5	Port Alfred	1,4
Belfast	7,3	Harrismith	9,4	Port Elizabeth	0,9
Benoni	7,5	Heidelberg (C)	8,0	Potchefstroom	7,0
Bergville	6,3	Heilbron	5,8	Potgietersrus	3,4
Bethal	8,6	Hermanus	0,1	Pretoria	7,5
Bethlehem	6,4	Hluhluwe	6,0	Prieska	3,0
Bethulie	3,3	Hoedspruit	2,8	Prince Albert	0,6
Bloemfontein	5,2	Humansdorp	1,1	Queenstown	5,2
Bloemhof	4,8	Irene	7,2	Reddersburg	6,4
Blyderivierspoort	4,5	Jagersfontein	2,2	Richards Bay	5,2
Boksburg	7,5	Johannesburg	7,5	Richmond (KZN)	8,0
Brakpan	7,5	Jozini	5,6	Riversdale	0,2
Brandvlei	0,9	Keetmanshoop	1,2	Roedtan	4,9
Brits	8,0	Kempton Park	7,5	Rustenburg	8,1
Bultfontein	3,6	Keiskammahoek	2,0	Sabie	3,2
Burgersdorp	3,3	Kimberley	4,8	Satara	1,5
Butterworth	0,9	King William's Town	1,1	Schweizer-Reneke	5,6
Cala	5,2	Klerksdorp	7,0	Scottburgh	3,0
Caledon	0,2	Knysna	0,4	Senekal	4,7
Calvinia	0,7	Komatipoort	2,6	Sishen	3,4
Cape Town	0,3	Kroonstad	5,8	Skukuza	2,3
Carletonville	7,5	Krugersdorp	7,0	Somerset East	0,8
Carnarvon	1,1	Kuruman	3,0	Springbok	0,6
Carolina	9,0	Ladybrand	0,4	Springs	7,5
Cathcart	1,6	Ladismith (C)	7,5	Standerton	7,6
Cedara	8,0	Ladysmith (KZN)	9,0	Stanger	3,5
Ceres	0,2	Laingsburg	0,6	Stellenbosch	0,3
Christiana	6,4	Lichtenburg	5,5	Steytlerville	1,7
Colenso	7,8	Loskop	4,3	Sutherland	0,9
Colesberg	3,0	Louis Trichardt	1,5	Swakopmund	0,5
Cradock	5,8	Lüderitz	0,4	Tarkastad	3,4
De Aar	2,5	Lydenburg	5,0	Thabazimbi	2,1
Delareyville	5,4	Machadodorp	8,7	Theunissen	5,2
Donnybrook	8,5	Mafikeng	5,6	Touws River	0,3
Doornfontein	7,3	Malmesbury	0,1	Tsumeb	4,0
Dordrecht	2,6	Mandini	3,4	Tzaneen	4,1
Douglas	4,0	Margate	1,8	Umtata	3,0
Dundee	9,2	Marikana	6,9	Uniondale	0,6
Durban	4,4	Matatiele	6,6	Upington	2,2
East London	1,6	Middelburg (C)	3,3	Utrecht	9,0
Edenvale	5,6	Middelburg (Mpumalanga)	4,6	Ventersdorp	5,6
Elliott	4,2	Molteno	1,6	Vereeniging	7,5
Empangeni	4,1	Montagu	0,2	Victoria West	1,4
Ermelo	9,0	Mooi River	6,9	Villiersdorp	0,4
Eshowe	5,3	Mossel Bay	0,5	Vredendal	0,2
Evander	8,5	Murraysburg	1,9	Vryburg	3,0
Flagstaff	4,9	Naboomspruit	6,0	Vryheid	8,9
Fort Beaufort	1,4	Nelspruit	2,7	Walvis Bay	0,2
Fraserburg	1,3	Nossop	2,2	Warmbaths	7,5
George	1,5	Noupoort	7,4	Welkom	5,0
Georgedale	5,6	Nylstroom	7,0	Willowmore	1,5
Germiston	7,5	Ohrigstad	4,2	Windhoek	2,3
Giants Castle	13,0	Oshakati	2,3	Witbank	7,5
Gobabes	0,2	Oudtshoorn	0,5	Zeerust	4,2

12.2 Determination of the environmental coefficient, C_e

Table 12-2: Environmental coefficient, C_e [1]

1	2	3
Relative location of structure	**Illustration**	C_e
Structure amongst other buildings and trees of the same or greater height		0,25
Structure surrounded by smaller buildings		0,50
Isolated structure or no buildings within a distance of 3 *h*		1,00
Isolated structure on a hill		2,00

12.3 Calculation of the accepted annual frequency of lightning flashes, N_c

Table 12-3: Factors depending on the type of structure [1]

Description	Factor
Construction of walls	a_1
Reinforced concrete interconnected metal façade	5
Interconnected prefabricated reinforced concrete parts, steel skeleton	4
Masonry, concrete without steel, not interconnected prefabricated concrete parts	0.5
Wood framework or other combustible materials	0.1

Roof construction	a_2
Steel	4
Reinforced concrete	2
Prefabricated reinforced concrete parts	0.5
Wood	0.1
Roof covering	a_3
Reinforced concrete	4
Metal sheet	2
Tile, slate	1
plastic foils, roofing felt	0.5
Thatched roofs	0.05
Equipment on the roof	a_4
No equipment	1
No earthed equipment, antennas	0.5
Electric apparatus	0.2
Sensitive electric parts	0.1

$$a = a_1 \times a_2 \times a_3 \times a_4$$

$$a_1 = 0{,}5\,; \quad a_2 = 0{,}1\,; \quad a_3 = 0{,}05\,; \quad a_4 = 1$$

Table 12-4: Factors depending on the contents of structure [1]

Description	Factor
Risk of panic	b_1
No risk of panic	1
Normal risk of panic	0.1
High risk of panic	0.01
Kind of contents	b_2

Non combustible	1
Combustible	0.2
Explosive	0.1
Power mill	0.01
Nuclear plant	0.001
Value of contents	b_3
Valuable	1
Very valuable	0.1
Irreplaceable	0.01
Measures for reduction of damage	b_4
Automatic fire extinguishing system	10
Fire resisting structures	5
Fire alarm system	2
No measures	1

$$b = b_1 \times b_2 \times b_3 \times b_4$$

$$b_1 = 1; \quad b_2 = 0{,}2; \quad b_3 = 1; \quad b_4 = 2$$

Table 12-5: Factors depending on the consequential losses [1]

Description	Factor
Danger to the environment	c_1
No	1
Common	0.5
High	0.1
Very high	0.01
Loss of services to the public	c_2
No	1

High	0.1
Very high	0.01
Other consequential losses	c_3
Low	1
Normal	0.5
High	0.1
Very high	0.01

$$c = c_1 \times c_2 \times c_3$$

$$c_1 = 1; \quad c_2 = 1; \quad c_3 = 1$$

12.4 Test and measurement system

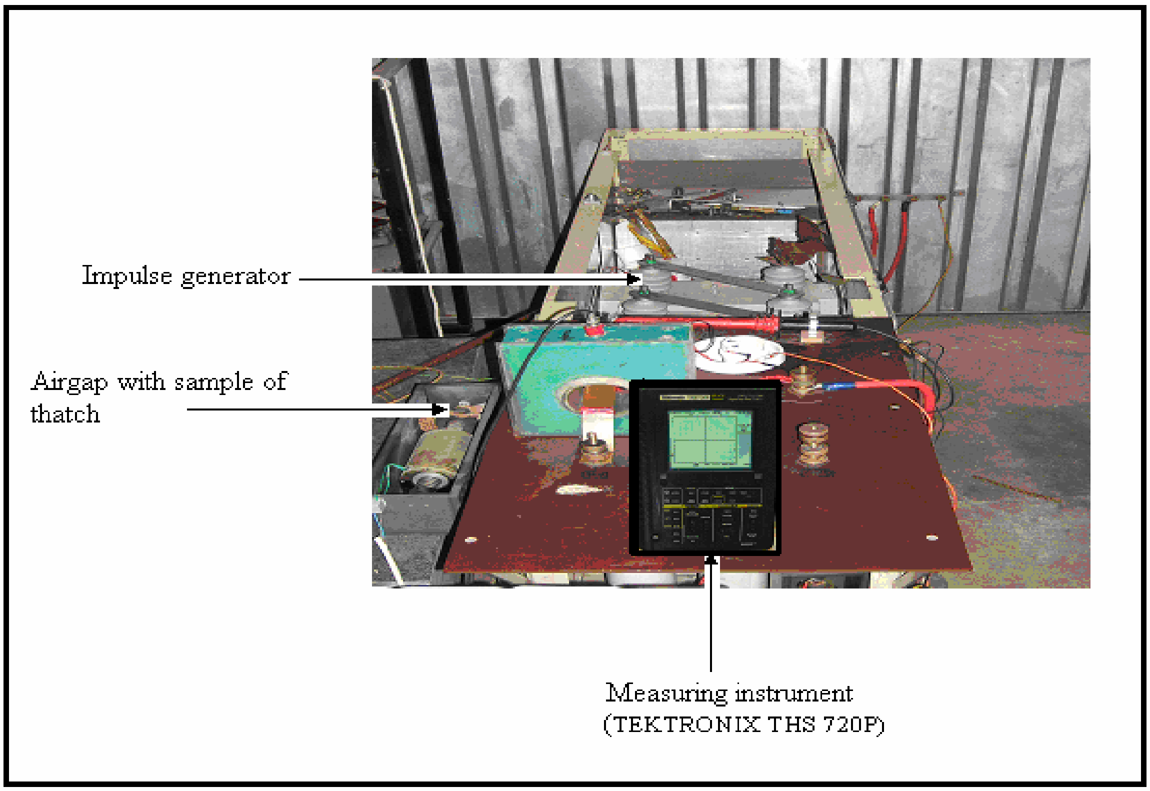


Figure 12-1: Test and measurement system

12.5 Equivalent circuit

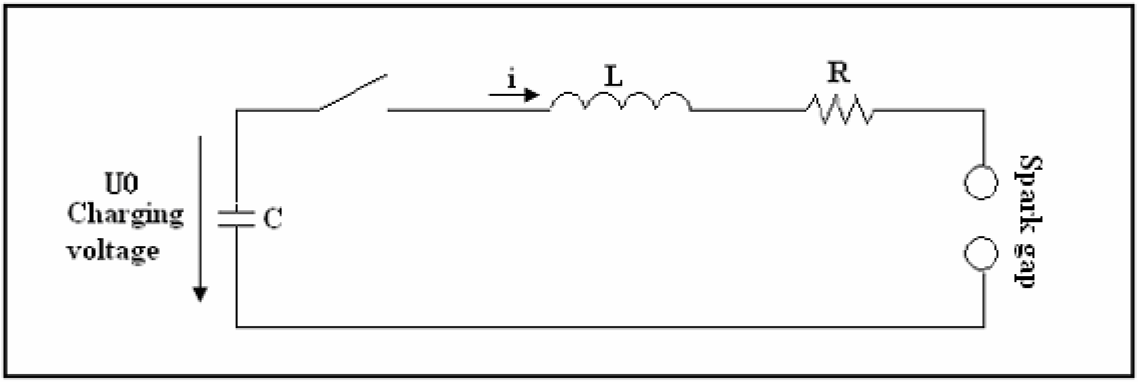


Figure 12-2: Equivalent circuit of current impulse generator (8/20 µs) [13]

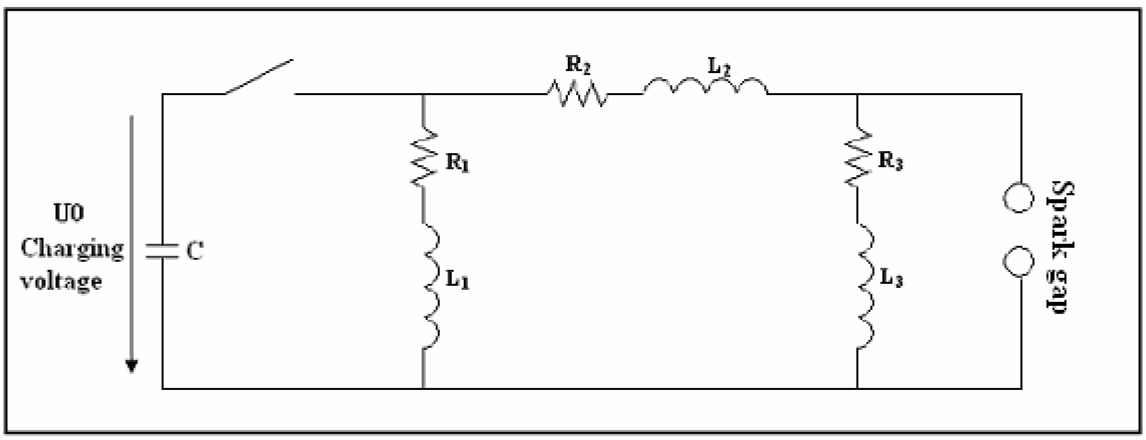


Figure 12-3: Equivalent circuit of combined (Voltage, Current) impulse generator (1.2/50 µs, 8/20 µs) [13]