Evaluation of Rolling Sphere Method Using Leader Potential Concept: A Case Study

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ABSTRACT

Lightning protection design for a structure using Rolling Sphere Method is undertaken. In this case radius of the sphere is calculated using the ‘Leader Potential Concept’ for calculating striking distance. The purpose is to evaluate lightning protection performance based on the ‘Leader Potential Concept’. It is also demonstrated how low grounding resistance and bonding could be used to mitigate Ground Potential Rise (GPR) and secondary effects of lightning activities on electronic equipment.

INTRODUCTION

Lightning is a phenomenon that has often caused severe damage to life and property. Direct hits may cause for instance structural failure whereas indirect hits, through inductive or capacitive coupling, may affect the reliability and integrity of electronic equipment within the structure.

Basically, a conventional method of lightning protection system consists of lightning rods exposed and placed at the highest levels of structures and connected through downward conductors to a grounding system. A design method is normally used to identify the most suitable locations for the lightning rods, based on the area of protection offered by each one.

There are different methods of lightning protection systems. Examples of existing methods include geometrical constructions, such as the “Cone of Protection” and “Rolling Sphere Method” which is based on “Electrogeometric” models (EGMs). In practice, the Rolling Sphere Method is widely used. The method recognizes that the attractive effect of the lightning rod is a function of a striking distance which is determined by amplitude of lightning current. This method is considered relatively simple and easy to apply but often result in over design. This is because calculated results for lightning strike to protected object using this method do not always agree with observed data [1].

Mazur et al proposed using Leader Potential Concept as a means of calculating striking distance [2]. The Leader Potential concept uses line charge model. The model assumes that lightning leader is equivalent to conducting wire within an ambient electric field of a thundercloud. According to Mazur et al, striking distance is a function of both the leader potential and a constant electric field along the negative streamer head of the leader tip.

Using striking distance formula by Mazur et al based on the 'Leader Potential Concept', a more reliable and economical protection system could be designed.

The purpose of this paper is to evaluate lightning protection performance based on the 'Leader Potential Concept'. It is also demonstrated how low grounding resistance and bonding could be used to mitigate Ground Potential Rise (GPR) and secondary effects of lightning activities on electronic equipment.

Electrogeometric Model (EGM)

Protection zone of a lightning protection system may be defined as the volume of space inside which an air termination provides protection against a direct lightning strike by attracting the strike to itself [3]. The commonly used engineering tool for determining zone of protection of lightning protection system is the 'Electrogeometric Model'. This method recognizes that the attractive effect of the air terminal device is a function of a striking distance which is determined by the amplitude of lightning current. The striking distance is the length of the final jump of the stepped leader as its potential exceeds the breakdown resistance of the last gap of air to ground [4]. The EGM model assumes that point on a structure equidistant from the striking distance are likely to receive a lightning strike, whereas points further away are less likely to be struck.

The Rolling Sphere Concept

A sphere of radius equal to the striking distant is usually employed to visualize the likely stroke termination point, the so-called Rolling Sphere Method (RSM). Application of RSM involves rolling an imaginary sphere of a prescribed radius over the air termination network. The sphere rolls up and over (and is supported by) air terminal, shield wires, and other grounded metal objects intended for direct lightning protection. A piece of equipment is protected from a direct stroke if it remains below a curved surface of the sphere by virtue of the sphere's being elevated by air terminals or other devices. Equipment that touches the sphere or penetrates its surface is not protected. The basic concept is shown in Figure 1.

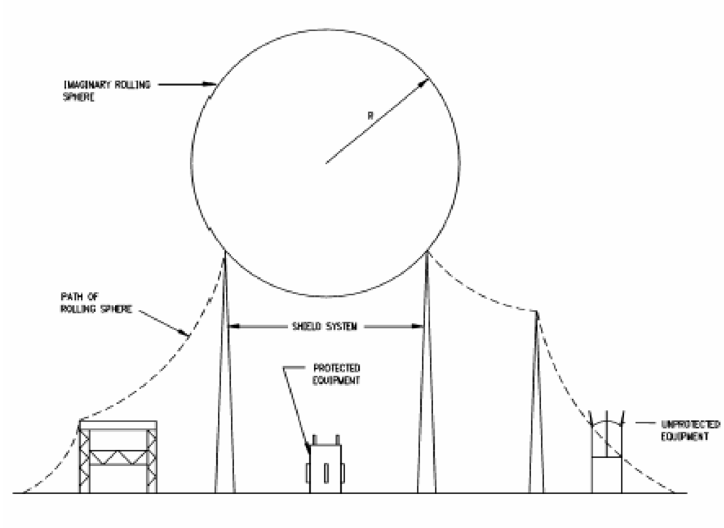

Figure 1: Protection Design by Rolling Sphere Concept

The effectiveness of the Rolling Sphere Method has been verified from theoretical and empirical basis and found to be useful for engineering application [5]

SYSTEM DESIGN

The concept of striking distance is essential in the design of lightning protection system for earthed structures. According to the basic idea of EGM, a downward leader stroke is considered to propagate randomly and uncontrollably at the beginning. As a charge of a cloud is lowered along the downward leader, electric field on the surface of a grounded object increases. Finally, at a striking distance, the critical electric field for breakdown of air at the surface of the grounded object is reached, and an upward streamer starts from the object to meet the leader stroke. Since the electric field at the tip of a structure is mainly influenced by the downward leader propagation and charge distribution in the leader channel, and the charge is related to the return-stroke current, it was believed that the striking distance is a function of the lightning current.

According to Berger [6], the equation relating peak current *I* to a charge Q transferred in a negative stroke is

$$I = 10.6Q^{0.7} \qquad (1)$$

From this expression (1), an equation relating striking distance and stroke peak current I_p can be established in the following form:

$$d = kI^{p} \qquad (2)$$

The values of constants *k* and *p* depend on the model of electric field distribution used [6].

Accordingly, varieties of empirical formulae for striking distance have been developed over the years in an attempt to ensure efficiency in lightning protection designs [6, 8, and 7]. These include:

Golde (1977): $d_s = 2h[m]$ (3)

Anderson and Eriksson (1980): $d_s = 16.3h^{0.61}[m]$ (4)

Mousa & Srivastava (1988) $d_s = 8kI_p^{0.65}[m]$ (5)

Petrove & Waters (1995): $d_s = 0.8[(h+15)I_p]^{2/3}[m]$ (6)

Yuan (2001) $d_s = 7.28h_1^{0.770 I_p} I_p^{0.4862}[m]$ (h_1 <13m) (7)

Yuan (2001): $d_s = 52.47I_p^{0.4862} + 0.35(h_1 - 13)[m]$ (h_1>13m) (8)

E.R. Love: $d_s = 10I_p^{0.65},\ [m]$ (9)

Where, h is height of grounded object in metres.

The formula developed by E.R Love (9) is widely used by power transmission and distribution engineers [9].

In a related investigation, striking distance based on "Leader Potential" was developed by Mazur [2].The Leader Potential Concept is based on line charge model. The model assumes the lightning leader is equivalent to conducting wire within an ambient electric field of a thundercloud. The Leader Potential is calculated using the following formula:

$$V = -\frac{q}{2\pi\varepsilon} In \frac{3.10^6 \pi\varepsilon Z}{q} \quad (10)$$

Where,
q is charge per unit of the leader channel [mC/m], Z is the height from thundercloud base to the ground in metres. Z is obtained by measurement and q can be calculated from (11)[10].

$$Q_t = \frac{q^2}{2\pi\varepsilon_0 E} \quad (11)$$

Where Q_t is the charge in the downward leader head in coulombs, E is electricfield in the streamer zone of the leader in kV/m, obtained by measurement.
Typical average data for a size of charges and their base height are shown in Table 1[11].

Table 1: Data on thundercloud height

Country	Q+ (C)	Z+ (m)	Q- (C)	Z- (m)
South Africa	40	10,000	-40	5000
England	24	6000	-20	3000
Japan	120	8500	-120	6000

According to Mazur, the estimated striking distance is a function of both the leader potential in kV, and a constant electric field along the negative streamer head of the leader tip, which is 750kVm^{-1}. He obtained the striking distance as:

$$d_s = \frac{v}{750} \quad \text{kV} \qquad (12)$$

As can be observed from the above relations, almost all striking distance formulae, which are essential in the Electrogeometric Model, have relation with lightning current.

It can be shown that given the same conditions (at the same protection level), striking distance obtained by (9) is smaller than that obtained with the leader potential concept. Thus the use of lightning currents in calculating striking distances could result in over design of lightning protection system and unnecessary cost to the client [1].

Also, lightning current measurement are obtained at selected ground installation (usually tall structure) that are frequently struck by lightning. These current measurements are limited in number, and current values obtained are strongly affected by the dimensions of the structure, and also by climatological and topographical conditions that influence the nature of local thunderstorms. Because of these factors, the data cannot characterize the entire range of the lightning current.

Using striking distance formula by Mazur based on ‘Leader Potential Concept’, a more reliable and economical protection system could be designed.

APPLICATION OF ROLLING SPHERE METHOD

Application of the RSM could be simplified by the use of ‘Attractive Radius’ of a lightning rod. According to the Rolling Sphere Method and referring to Figure 2, attractive effect of the lightning rod is effective within the lateral distance (R). When the downward leader moves beyond R the attractive capability of the lightning rod becomes ineffective.

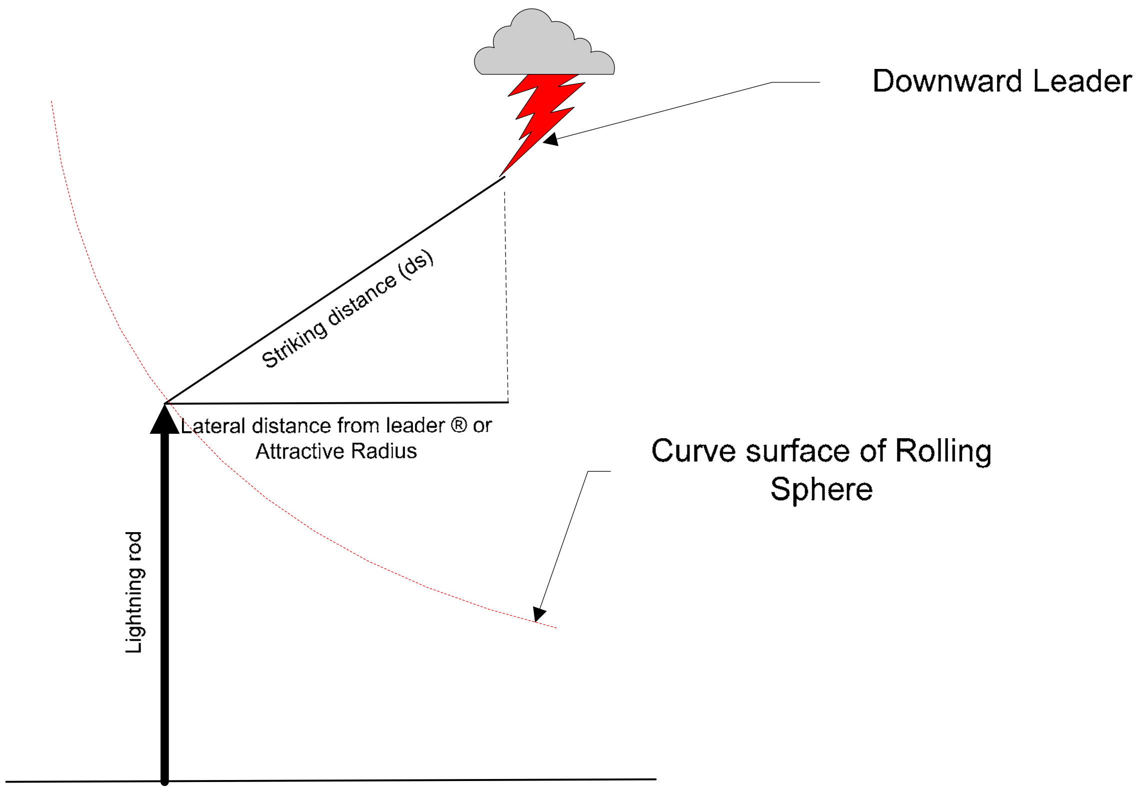

Figure 2: Attractive Radius Concept

Accordingly, the attractive radius may be defined as the lateral distance of a leader from the lightning rod beyond which the collection / attractive capabilities of the rod remained inactive.

Using the Attractive Radius, protection zone of object near the lightning rod can be calculated. Also, in placement of lightning rods on structures, separation distance between lightning rods could be obtained by calculating attractive radii of the lightning rods.

Referring to Figure 3, the attractive radius *R* for rod of height h_x is given by equation:

$$d^2 = R^2 + (d - h_1)^2 \qquad (13a)$$

from which

$$R^2 = 2dh_1 - h_1^2$$

or

$$R = \sqrt{h1(2d - h_1)} \qquad (13b)$$

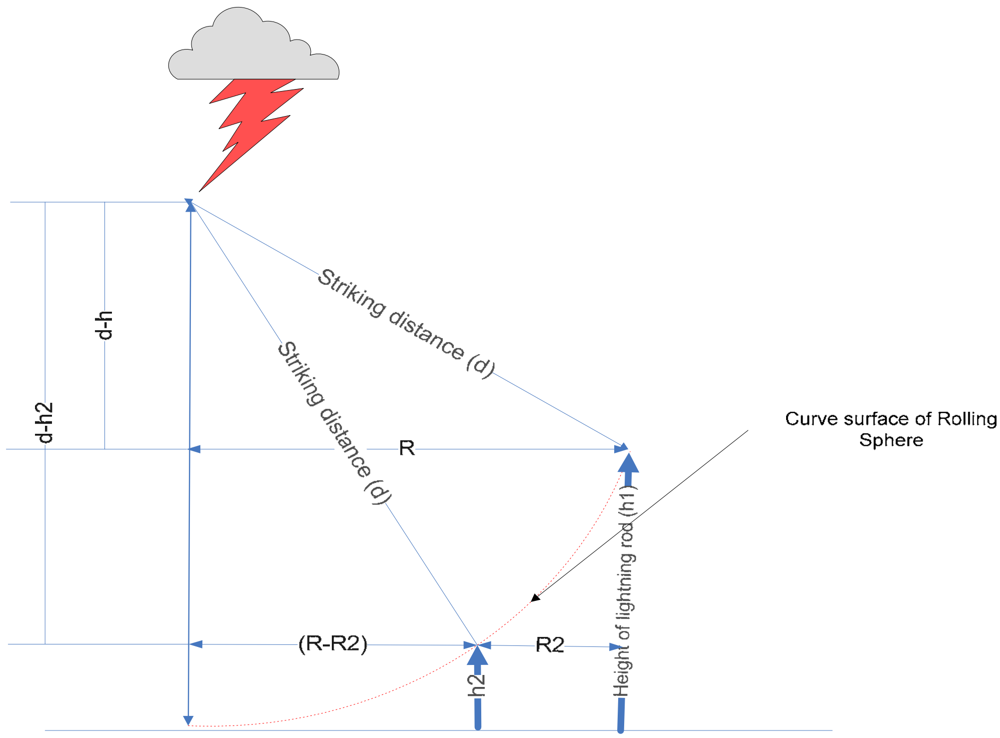

Figure 3: Attractive Radius (R) of Lightning rod and Protective Zone of Object under the Rod

Also for radius of protection R_2 away to a lightning rod of height h_2 the corresponding protection zone R_2can be obtained from the following relations :

$$d^2 = (R - R_2)^2 + (d - h_2)^2$$

$$(R - R_2)^2 = 2dh_2 - h_2^2 \qquad (14)$$

Dividing (13a) by (14) yields:

$$R_2 = R\left[1 - \sqrt{\frac{2dh_2 - h_2^2}{2dh - h^2}}\right] \qquad (15)$$

For any object of height h_x under a lightning rod, the above equation

(15) can be used to calculate radius of its protection R_X from the rod.

For example, if a lightning rod is set at 12 metres above local earth, then for a striking distance *d* of 33m the attractive radius R_a:

$$R_a = \sqrt{h1(2d - h1)} = 25 \text{ metres to ground zero}$$

And for a person of 1.5 metre height, the protected radius R_P is:

$$R_P = 25\left[1 - \sqrt{\frac{2(33)(1.5) - 1.5^2}{2(33)(12) - 12^2}}\right]$$
$$= 15.3 \text{ metres}$$

In the other words, a person of 1.5 metres in tall is safe out to about 15.3 metres from the lightning rod.

Figure 4, present the radius of the protected zone as a function of the height of the object to be protected from a lightning rod of height 12 metres.

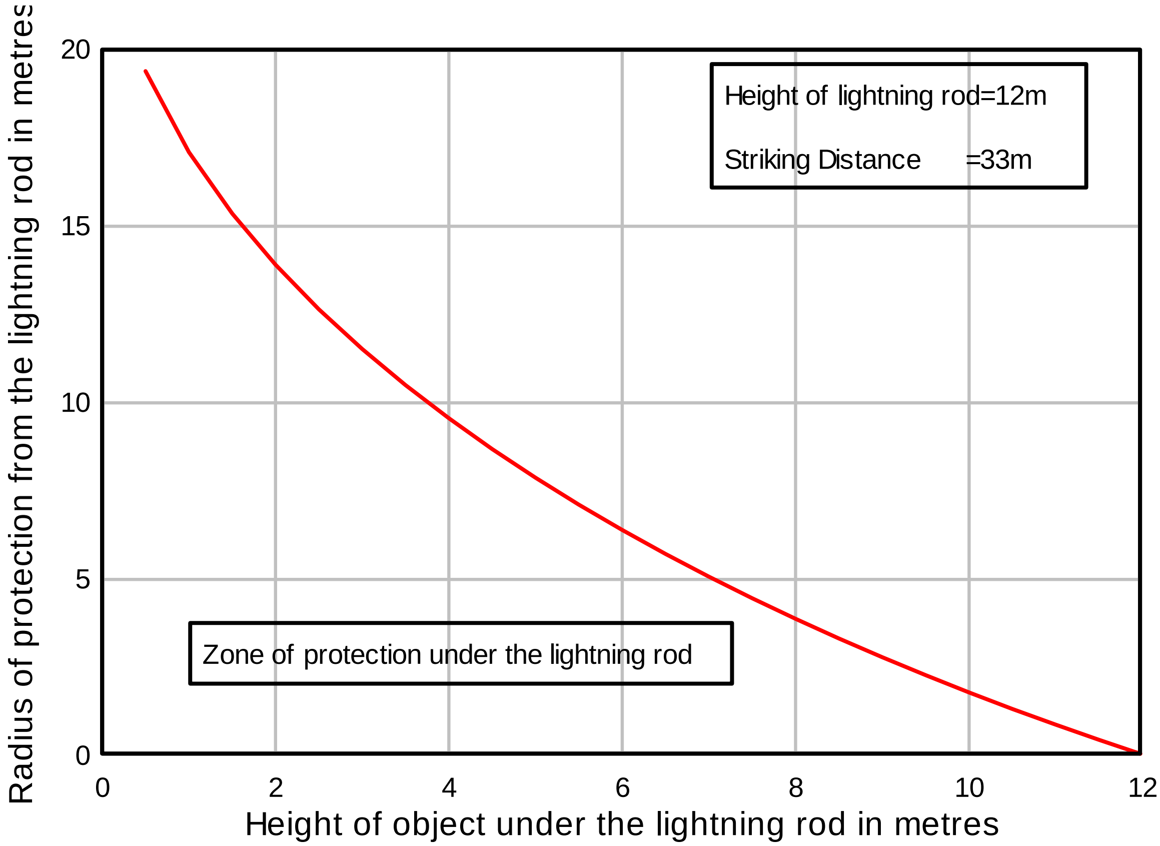

Figure 4: Radius of protected zone as a function of height of object to be protected from a Lightning.

Efficiency of Lightning Protection System

A quantitative measure used to determine protection level of lightning protection system is 'interception efficiency'. This is commonly defined as the probability of lightning protection system intercepting the minimum value of the lightning current in a given protection level [8].

For a design of lightning protection system, International Electrotechnical Commission (IEC 61024-1) presents four protection levels for protection of structure. See Table 2. The level of protection that should be chosen depends on the risk that one wants to accept. For example, at 99% interception efficiency (protection level I), the protection system is expected to intercept all stroke current from 2.9kA and above. Impliedly, stroke current below 2.9kA is likely to by pass the protection
System

Table 2: Lightning Protection Efficiency

Maximum Current Exceeding the Peak Value (Ip)	Protection Level	Interception Efficiency	Charge per Unit Length
2.9kA	I	99%	0.09mC/m
5.4kA	II	97%	0.38mC/m
10.1kA	III	91%	0.93mC/m
15.7kA	IV	84%	1.7mC/m

The interception efficiency is calculated from the standard cumulative frequency distribution of peak current [7]:

$$p(I_m) = \frac{1}{1 + \left(\frac{I_m}{24}\right)^{2.6}} \times 100 \qquad (16)$$

where,

$p(I)$ is the interception efficiency

I_m is the minimum stroke current exceeding the peak current

From the Table 2, each protection level has a related minimum stroke current and its corresponding charge per unit length of downward leader that the protection system can intercept.

CASE STUDY

The administration block of Bibiani Mines, a subsidiary of Anglogold- Ashanti Limited is used as a case study. This block houses over 60% of the company's electronic equipment and these equipment must work during the most difficult times including bad weather conditions. The purpose is to evaluate protection performance based on the 'Leader Potential Concept'.

The Bibiani Mines is located in a lightning prone area, in the western region of Ghana, with isokeraunic number of 160 [12].

Since its inception in 1998, the company had been plagued with high incidence of electronic equipment failures including lightning strikes to a satellite dish at the administration area. Lightning is also reported to hit the satellite dish at least once in every two years resulting in physical damage to the device and its secondary effects affecting the safety and reliability of electronic equipment that feeds on the satellite dish.

On the average, the company spent $177,000 annually on maintenance and replacement of UPS, computers, various electronic cards in the telecommunication systems and other internet link devices [13].

Configuration of Existing Protection System

In an attempt to mitigate the high incidence of equipment failures, the company embarked on some method of lightning protection system, as described below, at the administration block. Layout of the administration area is shown in Figure 5.

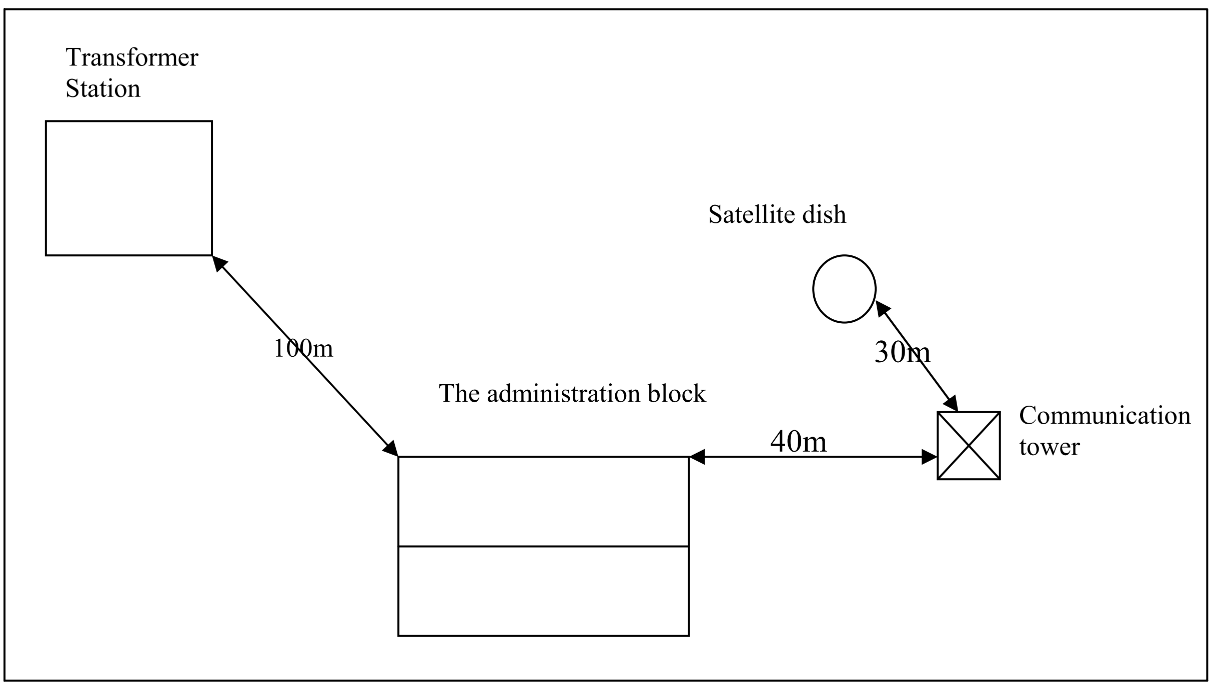

Figure 5: Layout of Administration Area

Four lightning rods were erected around the administration building and grounded by four electrodes through a down-conductor, see Figure 5.2. Earth resistance of 31 0hms was measured.

Referring to Figure 6, a communication tower of 20m tall is mounted at 40m from the building.

Figure 6: Front View of Administration Building

The tower has one lightning rod installed on it and grounded through the tower footings with earth resistance of 13-ohms, Figure 8. A satellite dish of 2m high, see Figure 7, supposed to be protected by the tower, is about 30m away. Coaxial cables from the satellite dish to main internet server in the building had its sheath grounded at the base of the satellite dish with earth resistance reading of 14-ohms.

Figure 7: The Satellite Dish at the Administration Area

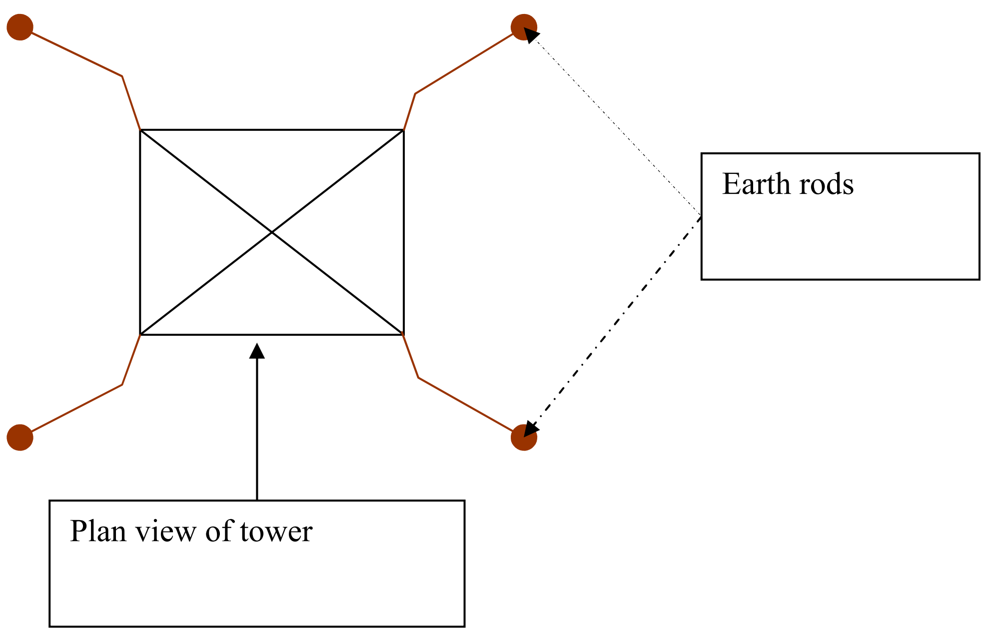

Figure 8: Grounding of Tower Footing

The building is powered by a three-phase, 200kVA, 33/0.4kV, delta-star transformer at the transformer station, see Figure 5.1. At a service entrance of the building, an Automatic Voltage Switcher [AVS] was installed. The output of the AVS was connected to an input of a 10kVA Uninterruptible Power Supply [UPS] from whose outputs the electronic equipment were connected. See Figure 9 for the protection configuration.

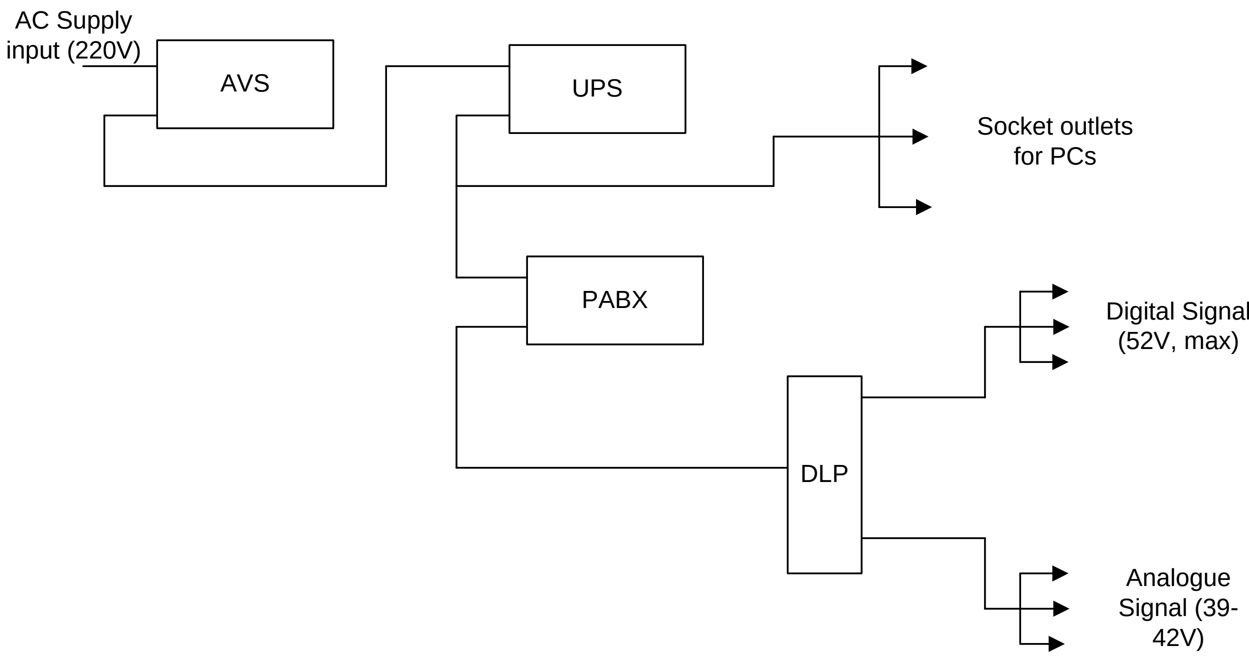

Figure 9: Schematic Diagram of Existing Protection System

Where:
AVS- Automatic Voltage Switcher
UPS-Uninterruptible Power Supply
PABX-Private Automatic Business exchange
DLP-Data Line Protector

The transformer station is built on high soil resistivity of 500Ωm and located about 100m from the administration block, see Figure 5. The 33kV side of the transformer is protected against lightning by arrestor of 10kA, 8/20μs rating. The arrestors are bonded to the ground with earth resistance reading of 87Ω. The arrestors' grounding is connected separately from the transformer neutral earth. Earth resistance test on the neutral earth was 110Ω. Copper conductor size of 75sqmm was used for both the arrestor and the neutral earth.

This protection arrangement resulted in a marginal degree of success. Financial statistics available indicate that this method resulted in about 10% reductions in the annual maintenance cost [13].

For the purpose of this study, the lightning protection system for tower and the satellite dish was redesigned and its performance evaluated. The design was considered at 99% protection level. At this protection level, the corresponding unit charge according to Table 3.2 is 0.09mc/m. Calculation of striking distance at this specified protection level follows these steps:

- Step 1: obtain thunder base height Z from Table 3.1. In this case 5000m thunder based height is used. This is generally used [4].

- Step 2: obtain the corresponding unit charge. This is 0.09mc/m from Table 3.2

- Step 3: Calculate Leader Potential using (10)

$$V = -0.09 \times 10^{-3} \times 18 \times 10^{6} \ln \frac{3.10^{6}}{0.09 \times 10^{-3} \times 32.10^{6}}$$

$$= -29160\text{kV}$$

- Step 4: Calculate striking distance using (12)

$$d_s = \frac{29160}{750} = 38.8\text{m}$$

METHODOLOGY

The satellite dish and the tower are 2m and 20m tall respectively. Thus with a striking distance of 38.8m, the limit of protection for the satellite dish from the tower according to (15) is 24.7m. By this analysis, the present location of the satellite dish from the tower was found to be unsafe. To shield the satellite dish from direct lightning protection, it was relocated 15m from the tower. At the base of the tower the earth resistance was improved to 5-ohms by backfilling critical radii of the four electrodes with soil resistivity of 5 ohm-metre [14]. The coaxial cable from the satellite dish was bonded to the tower grounding.

At the administration building all the four vertical electrodes had their critical resistance areas backfilled with of resistivity 5 ohms at 20% moisture content [14]. Each of the electrodes was connected to a bare 75 square-millimetres copper conductor, laid radially from the electrode at 8m away. This arrangement was to take advantage of the horizontal nature of lightning discharge and also improves on a ‘ground potential profile’ during lightning discharge [15].

At the transformer station, the existing ground electrodes were left in place but supplemented with six earth electrodes installed in accordance with the critical resistance area concept at a moisture content of 5 ohm-metre [14]. The transformer arrestor earth was bonded to the neutral earth.

As a further step, equipment bonding was used to eliminate differences in potentials between the equipment and the structures

RESULTS AND DISCUSSION

The design of the protection system and the earth improvement was undertaken in the mid 2004. There was no Lightning Event Counter [LEC] to monitor the effectiveness of the protection system to attract and divert the lightning at the protected area. However, the burning of a down conductor insulation at the tower base, see Figure 10, which was noticed after the installation of the protection system, was enough evidence to show that the protection system did attract and safely diverted the lightning to ground. The nature of the burn, as evidenced by Figure 10, suggests a large amount of lightning current discharged into the ground. Even at this severe lightning strike, incidence of equipment damage was not recorded [12].

Figure 10: Bunt insulation of the tower down conductor

Earth resistance reading that were taken after the improvement in the grounding system are given in Table 3. Groundings at the transformer station were bonded together resulting in total resistance of 3 ohm. The general reduction in the earth resistance values was expected to improve on the performance of the surge arrestors and ultimately result in overall performance of the protection system.

Table 3: Result Earth Resistance Improvement

Area of Concern	Earth Resistance in ohms		% improvement
	Previous	Present	
Tower	13	5	61.54
Building	31	1.7	94.52
Transformer arrestor	87	5	94.25
Transformer neutral	110	5	95.45

For a critical evaluation of the protection performance, we took data before and after the installation of the protection system and analyzed [13]. Raw data were collected and the results of analysis reported in Table 4 and Figure 11.

Table 4: Data on equipment failure rate from 2002 to 2005

Types of equipment	Failure Rate			
	2002	2003	2004	2005
Computers	54%	47%	29%	18.50%
Printers	39%	20%	10%	10%
Photocopier	66%	67%	0%	0%
Fax machine	20%	50%	0%	0%
PABX	120%	88%	50%	37.50%
Internet link device	100%	67%	25%	0%
servers	200%	0%	0%	0%
Phones	55%	41%	50%	21%

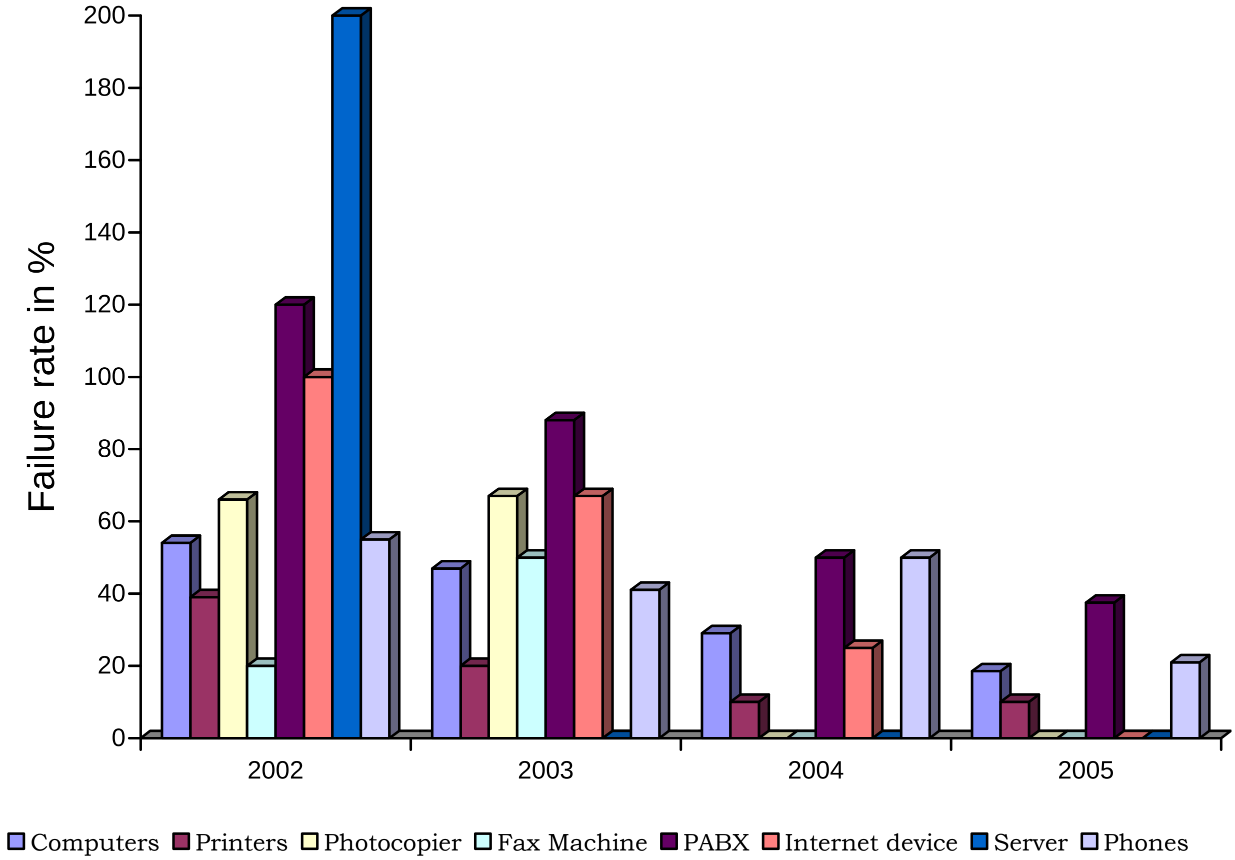

Figure 11: Chart on equipment failure rate from 2002 t0 2005

Ever since the protection system was installed, no strike has hit the satellite dish and the reliability of the electronic equipment has improved significantly as shown by Figure 11. To some of the electronic equipment (Photocopier, Phones, Fax machines and internet link device), zero incidence of failure rate was recorded in 2004 and 2005. In the history of the company, it was the first time such equipment have ever recorded zero failure rate. Even though frequency of lightning strikes to the protection system was not effectively monitored, the general downward trend of the failure rate as depicted by Figure 11 and elimination of lightning strikes to the satellite dish is a strong indication of the validity of the Leader Potential Concept. It also noted that the general earth improvement also contributed to the reliability of the protection system.

CONCLUSION

It is shown in this study that the Leader Potential Concept in calculating striking distance for lightning protection design can be relied upon. However, further monitoring with a requisite instrument is necessary to obtain quantitative results.

Qualitative benefits to the Bibiani Mines from this study include:

- Increased productivity and reduced idle staff and equipment during lightning activities

- Losses of transaction and orders experience during lightning event have reduced significantly.

- Revenue and accounting problems such as invoices not prepared, payment held up, and early discount missed has become almost history.

- Overtime required to make up for lost work time during lightning event has significantly been reduced

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