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Study of Lightning Safety Distance Using Rolling Sphere Method

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ABSTRACT

The development of a computer program for evaluation of lightning safety distance between the tower and satellite dish is written in M-File MATLAB. The 3-dimensional illustrative graphics model is used to capture better understanding on how lightning protection system (LPS) works. The study of physical length of grounding electrode used on the tower is found to be significantly affecting the grounding system performances where they depend on magnitude of dispersed lightning strikes current and the settling time for the current to completely disperse. The grounding system performance is studied by using lightning impulse current (LIC) generator, simulated in OrCad PSpice software. It is found that the optimum length of vertical lightning rod in LPS is the same with the striking distance. There is no significant improvement is observed in lightning safety distance if the length of vertical lightning rod is higher than striking distance. The lightning strike peak current that has larger magnitude than the withstanding insulation level of specified object causes no physical damage. It is because the lightning safety distance increases when the lightning strike peak current becomes higher. It is also found that the lower grounding impedance generates higher magnitude of dispersed peak current and faster settling time.

Keywords: Lightning Protection System (LPS); Rolling Sphere Method (RSM); Striking Distance

1. Introduction

The lightning protection system (LPS) relies upon the application of the physics of electrical discharges. It is needed to protect the electrical and electronic equipment against the lightning strikes, for example the telecommunication tower. There are two types of subsystems in designing conventional LPS. The first subsystem is called air termination system which consists of natural conductive components in vertical form of structure from the horizontal ground level surface, also known as lightning rod. The protection zone of LPS is defined as the volume of space where the air termination provides protection against a direct lightning strike by attracting the strike to it. The Rolling Sphere Method (RSM) is based on Electro-geometric Model (EGM) which is one of the techniques used to determine the lightning safety distance. The striking distance is the total distance of the lightning strikes to the rod. It can be determined using the amplitude of lightning strike peak current. There is another protection method called the Cone Protection Method. However, this method yields inaccurate results

and has low protection efficiency [1,2].

The second subsystem is called earth termination system used to conduct the lightning strike current from the air termination system to the ground by connecting downward conductors to a grounding cylinder electrode. The grounding electrode is important as it keeps the enclosure voltage of the equipment to be equal to the earth potential [3]. The amount of magnitude of dispersed lightning peak current is affected by the grounding impedance values. In fact, it is influenced by the characteristics of water or soil resistivity and length of grounding electrode.

This paper aims to investigate and determine the new lightning safety distance based on level I lightning protection standard according to IEC 61024-1. The computer software will demonstrate the distance and illustrate the LPS scheme operation. In addition, the performance of grounding system will also be investigated based on grounding input impedance. The findings are expected to deliver the best grounding system with higher dispersed lightning peak current and faster settling time.

2. Lightning Protection System Scheme

2.1. Lightning Safety Zone Using RSM

Figure 1 shows the concept of RSM technique for LPS scheme. The protection zone can be visualized as the surface of a sphere with radius striking distance, S is rolled toward the mast. This concept has led to the given rolling sphere scheme for simplified Electro-geometric Model [5]. The striking distance, S with respect to lightning strike peak current, I_s is calculated by using (1).

$$S = 10 \times I_s^{0.65}$$

Here, the equipment will be protected under the boundary of protected zone. The horizontal ground safety radius, R_g for height of lightning rod, h_1 is governed by (2).

$$R_g = \sqrt{2 \times S \times h_1 - h_1^2} \tag{2}$$

The lightning object safety radius, R_o for height of object, h_2 is given by using (3).

$$R_o = R_g \times \left[1 - \sqrt{\frac{2 \times S \times h_2 - h_2^2}{2 \times S \times h_1 - h_1^2}} \right] \tag{3}$$

From (3), the vertical lightning rod that has a radius equals to its striking distance will attract the stepped leader. The I_s that is discharged at a distance away from S will be grounded to the ground.

Table 1 shows the lightning protection standard based on International Electro-technical Commission (IEC 61024-1), where the protection levels can be interpreted as level I, level II, level III and level IV. The maximum I_s in each level is given by 2.9 kA, 5.4 kA, 10.1 kA and 15.7 kA respectively. This eventually gives the lightning interception efficiency at 99%, 97%, 91% and 84% respectively. By adopting the IEC 61024-1 standard, the lightning safety distance can be calculated using the level of protection required.

2.2. Grounding System Performances Based on Termination Impedance

**Figure 2** shows the typical grounding electrode used in
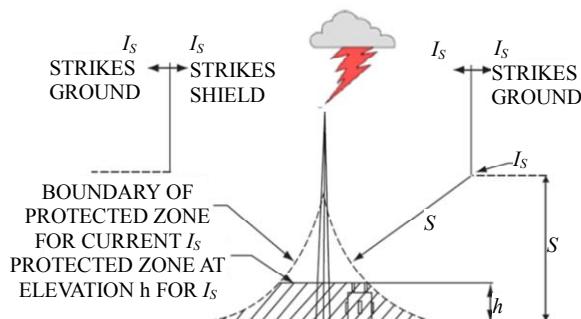
Figure 1. Lightning protection zone area by RSM technique [4].

Table 1. EC 61024-1 lightning protection standard [6].

| Maximum Lightning Peak Current Value (I_s)	Protection Level	Interception Efficiency
2.9 kA	I	99%
5.4 kA	II	97%
10.1 kA	III	91%
15.7 kA	IV	84%
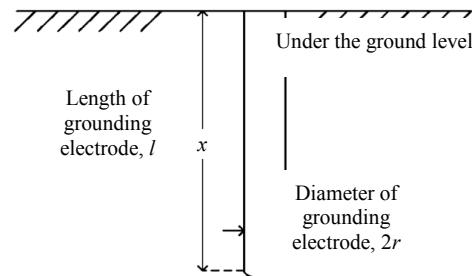
Figure 2. The grounding electrode.

this study where the grounding impedance will be affected by soil or water resistivity [7]. Nevertheless, there are also other criteria that can influent the grounding impedance such as length of grounding electrode, l, the radius of grounding electrode, r and also the burial depth of grounding electrode, t. The grounding impedance, Z_A is given by using (4).

$$Z_A = \frac{\left(\rho \times \left[\ln\left(\frac{2 \times l}{\sqrt{2 \times r \times t}} \right) - 1 \right] \right)}{\pi \times l} \tag{4}$$

3. Design Issue

In order to design a direct stroke shielding system for satellite dish, the engineer must consider several elusive factors inherent in lightning phenomena. The factors are:

- The magnitude of lightning strikes peak current is unpredictable.
- The complexity and cost of the solution involved to analyze a lightning protection system design in detail.

The unavailability data of lightning strikes occurrences and its frequency at telecommunication station. In the real application of LPS, there is no known method that can be providing 100% safety protection against the lightning strikes. The uncertainty, complexity, and cost of performing a detailed analysis of the LPS have historically resulted in simple rules of thumb being utilized in the design. In order to design the LPS, the four-step approach is suggested:

- Select an appropriate design method and lay out the LPS configuration.
- Evaluate the cost of the solution and effectiveness of the resulting design.

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- Evaluate the significant and value of the facility being protected.
- Investigate and analyze the frequency of lightning strikes occurrences at the facility that required protection.

3.1. Configuration of Existing Protection System

Figure 3 shows the configuration of existing protection system. It can be seen that the lightning safety distance between the tower (height of 20 m) and satellite dish is 30 m. This arrangement can be interpreted as a level III lightning protection standard according to the IEC 61024-1. It is found that the interception efficiency of the LPS is 91%.

Therefore, the new distance arrangement should provide the highest level of protection to reduce the possibility of satellite dish failure due to lightning strike. Also, the existing Z_A at the tower is determined as 15 Ω. This value is usually recommended to be in between 1 Ω and 10 Ω based on water or soil resistivity [6].

4. Methodology

4.1. Lightning Safety Distance

Equations (1)-(3) are used to find the new lightning safety distance for satellite dish. To do this, the programming script is built in M-File Matlab software to allow users to key in the necessary inputs data before the result of lightning safety distance can be simulated. The required input parameters are:

- The, I_S based on IEC 61024-1 Lightning Protection Standard in **Table 1**.
- The h_1.

The dimensions of protected object include height, h_2, width, w_2 and length, l_2.

Table 2 shows the parameters to be studied in finding their relationship with the lightning safety distance. The
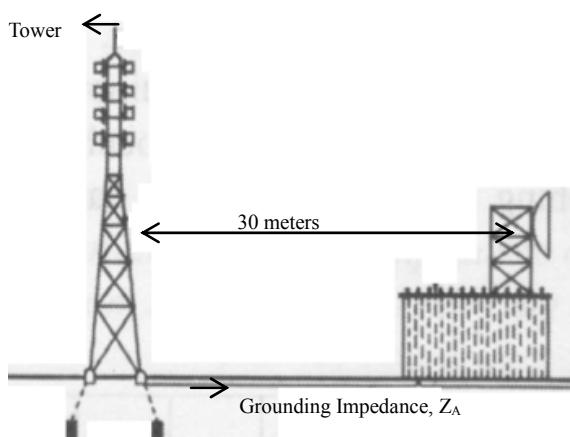

Figure 3. Existing configuration at telecommunication station.

Table 2. Set of parameters for lightning safety distance.

Input	Criteria	Case #1	Case #2	Case #3	Existing Case
	High	37.1	67.6	3.7	
h_1	Medium	19.9	19.9	2.8	20.0
	Low	15.7	8.0	2.6	
	High		11.6		
I_s	Medium		2.9		2.9
	Low		0.7		
MIN R_o		12.20	8.10	0.35	1.41

input parameters are h_1 and I_s. Here, the LPS will be protected if R_o is larger than the MIN R_o or vice versa.

4.2. Grounding System

Table 3 shows the values of Z_A used in this work. The low, medium and high length of grounding electrodes are 10 m, 100 m and 350 m respectively. The calculation of Z_A is based on Equation (4). Each of Z_A value will be applied into the lightning impulse current (LIC) generator. The height of grounding electrode value is adjusted to let Z_A become lower than 10 Ω. Other constant parameters used are r and t of 0.004 m and 0.5 m respectively.

Figure 4 shows the R-L-C circuit diagram used to produce the natural lightning waveform characteristics [8,9]. Using this circuit, the grounding impedance will be applied to analyze the performance of the grounding system.

5. Results & Discussions

Figure 5 shows the relationship between R_o, I_s and h_1. The R_o increases when the lightning strike current is larger than I_s in all cases. For an example in case #1, the R_o of high current I_s (11.6 kA) is 27.8678 m whilst for the medium current I_s (2.9 kA) is 12.6311 m. The result shows that R_o of high current I_s has wider coverage than the medium current and therefore the object is securely protected. Nevertheless, R_o decreases when the lightning strike current is smaller than the medium current I_s for all cases. In case #1, the R_o of low current I_s (0.7 kA) is 3.4312 m and for the medium current is 12.6311 m. The result shows that R_o of low current I_s is smaller than the medium current. Here, the object lies out of the protection region and hence prone to lightning strikes. However, if the value of medium current I_s was selected based on the withstand insulation level of specified object, low current I_s should cause no damage to the equipment.

Figure 6 shows the relationship between R_o and h_1. As for case #1, the R_o of high lightning rod (37.1 m) is

Table 3. Grounding impedance values depending on the type of soil or water resistivity.

Type of Soil or Water	Resistivity, ρ ($\Omega \cdot$m)	Grounding Impedance, Z_A (Ω)		
		Low	Med.	High
Clay	100	15.14	2.25	0.76
Groundwater, well, spring water	150	22.71	3.37	1.13
Sandy clay, cultivated soil	300	45.421	6.741	2.27
Rain water	1300	196.82	29.12	3.83
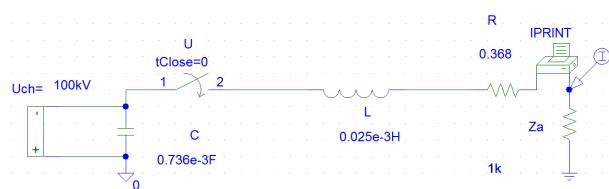
Figure 4. LCI generator with grounding impedance insertion.

	CASA #1	CASA #2	CASA #3
MIN. Safety Distance Required	12.2	8.1	0.35
High Current	27.8676	27.0479	0.877
Medium Current	12.6311	8.5377	0.5231
Low Current	3.4312	1.2868	0.2679
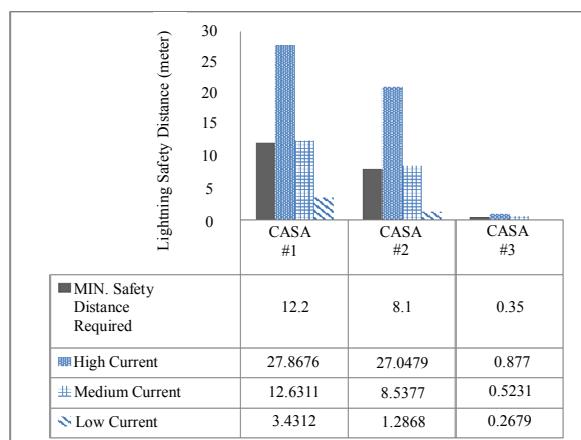
Figure 5. Lightning safety distance, R_o versus lightning strike peak current, I_s.

|	CASA #1	CASA #2	CASA #3
MIN. Safety Distance Required	12.2	8.1	0.35
High Lightning Rod	12.6312	8.5379	1.9054
Medium Lightning Rod	12.6311	8.5377	0.5231
Low Current Lightning Rod	12.1678	4.5487	0.1431
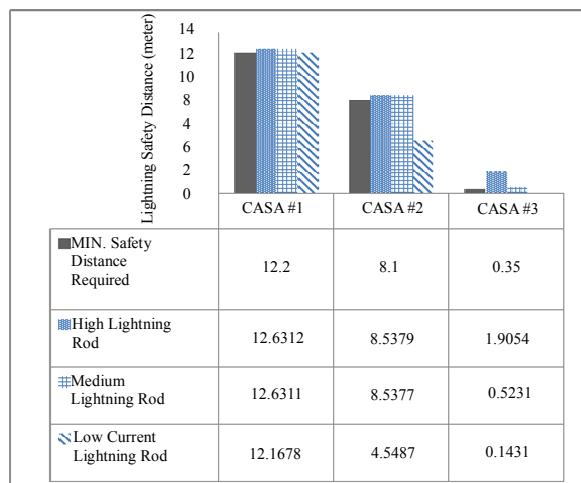
Figure 6. Lightning safety distance, R_o versus length of lightning rod, h_1.

12.6312 m while for the medium lightning rod (19.9 m) is 12.6311 m. This small difference in R_o indicates that in order to be protected, at least the medium length of lightning rod must be applied. The object will not be secured for a lower length (15.7 m). The same explanation goes for case # 2 and case # 3.

5.1. Comparative Assessments

Figure 7 shows the existing R_o of satellite dish, based on Level III protection. The interception efficiency level is 91 %. As shown in the figure, the R_o at the telecommunication station is 30 m. Since the satellite dish is vulnerable to lightning strike, higher safety level of protection is need to be implemented. This can be improved by using Level I.

Figure 8 shows the improved R_o of satellite dish, using Level I protection system. The new R_o is 11.27 m. It has closer distance compared to **Figure 7**. The R_o is reduced by 62.43% indicating an improvement. Hence, the tower has then been equipped with the 99 % of lightning interception efficiency.

5.2. Grounding System Assessments

Figure 9 shows that the relationship between the dispersed lightning peak current, I_{ds} and length of electrode, l. The resistivity, ρ ($\Omega \cdot$m) depends on the type of soil or water. Using l of 350 m, this makes Z_A to be less than 10 Ω and hence gives result in highest I_{ds}. As an example for the clay resistivity, the I_{ds} is found to be 82.285 kA compared to 37.431 kA and 6.441 kA in medium (100 m) and low (10 m) electrode length respectively. Therefore, the amount of dispersed lightning peak current is proportional to the length of electrode. This shows that a lower Z_A will make I_{ds} larger and hence better grounding system.

Figure 10 shows the relationship between the settling time, t_s for lightning current dispersal, and length of electrode, l. In the analysis, the t_s will become longer (slower speed) when l of 350 m is used, for instance in clay, the t_s is given as 907.2 ms. This indicates that the t_s is inversely proportional to l. Therefore, the low Z_A and l values are preferred to make the t_s shorter ie completely disperse lightning current faster.

Figure 11 illustrates the I_s by using Z_A of 15 Ω. The simulated waveform indicates that the amount of I_{ds} is 6.5 kA. In addition, the t_s is determined as 98.421 ms. **Figure 12** shows the magnitude of I_{ds} using $Z_A = 0.004$ Ω. Here the I_{ds} shows and increase in current of 196.471 kA with faster t_s of just 2.3684 ms. This satisfies the expectation in the hypothesis.

Thus, in order to produce the Z_A smaller than 10 Ω, the ρ of items and l need to be considered. It is found that the lower Z_A will make the grounding system performance

Interception Efficiency is
91%

Height of Tower,
h_1 = 20.00 meters

Safety Distance,
R_O = 30.00 meters
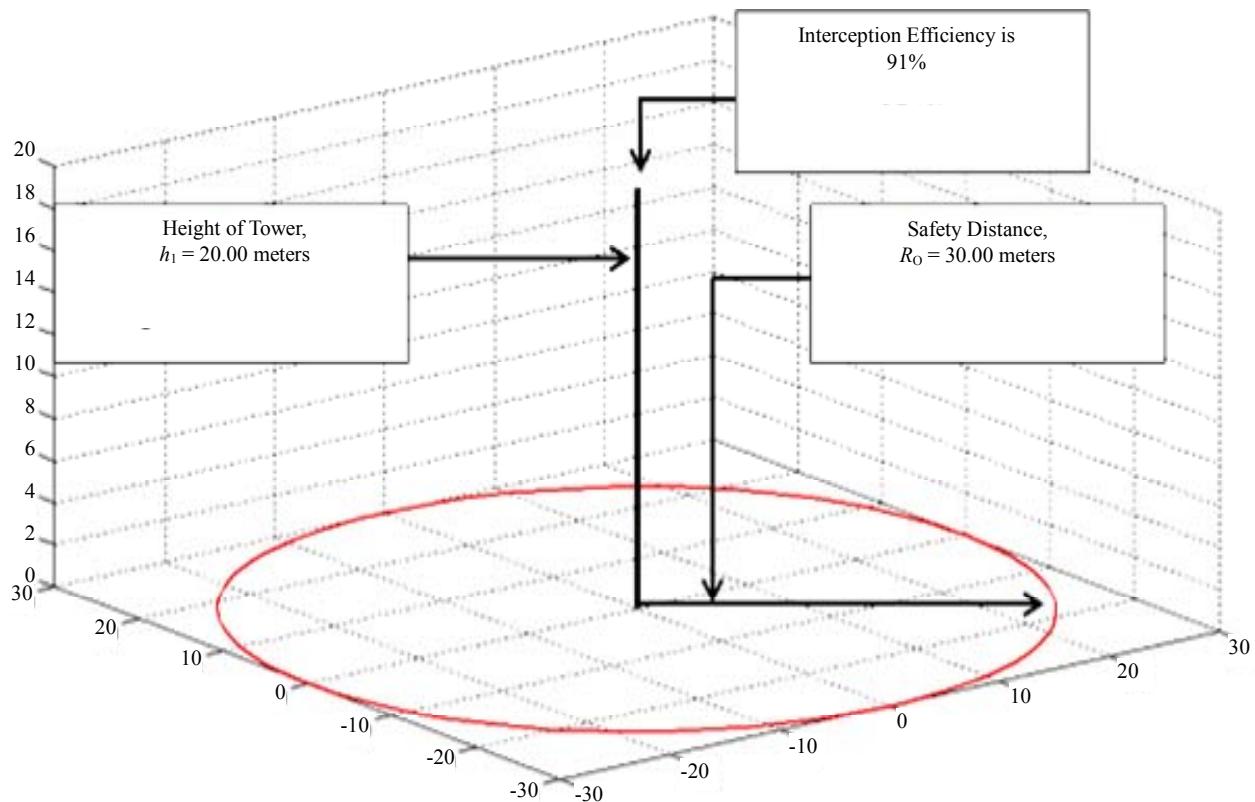
Figure 7. Existing LPS configuration.

Interception Efficiency is
99%

Height of Tower,
h_1 = 20.00 meters

Safety Distance,
R_O = 11.27 meters

Total Horizontal Safety Distance,
R_g = 20.00 meters
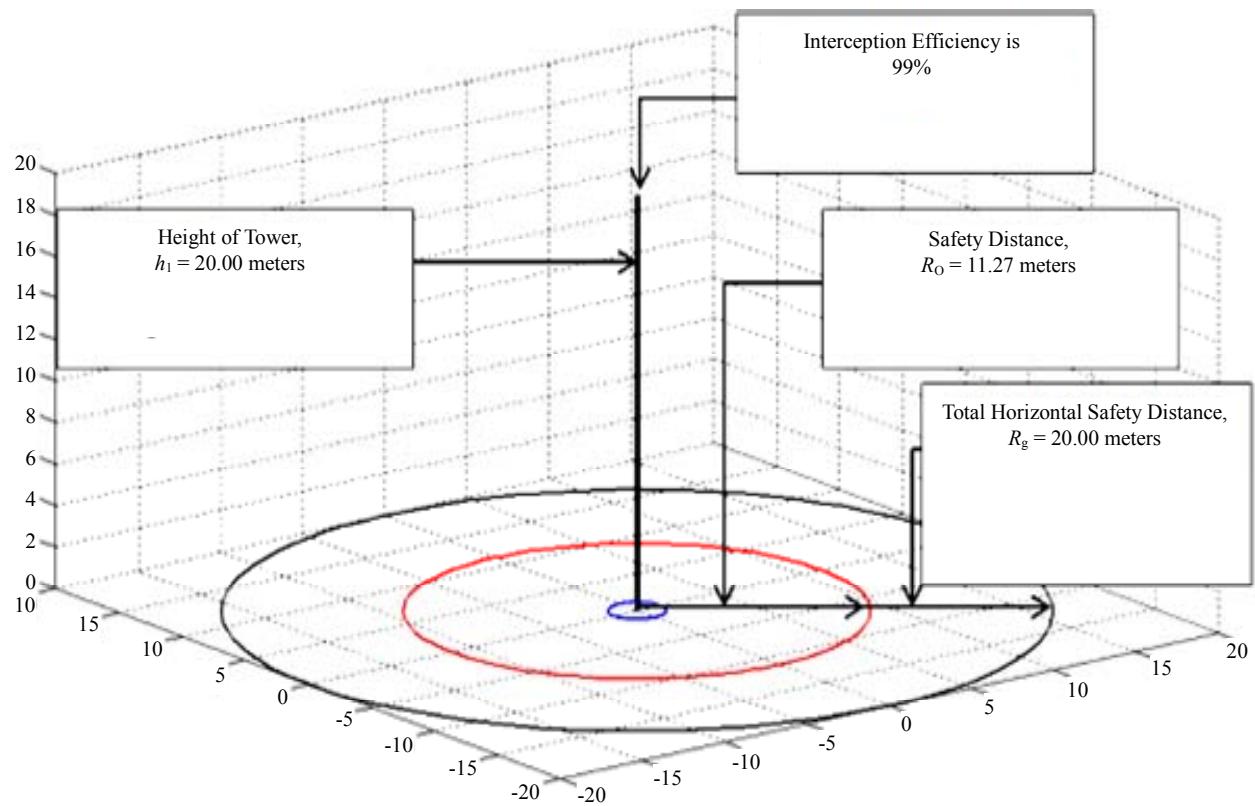
Figure 8. Improved LPS configuration.
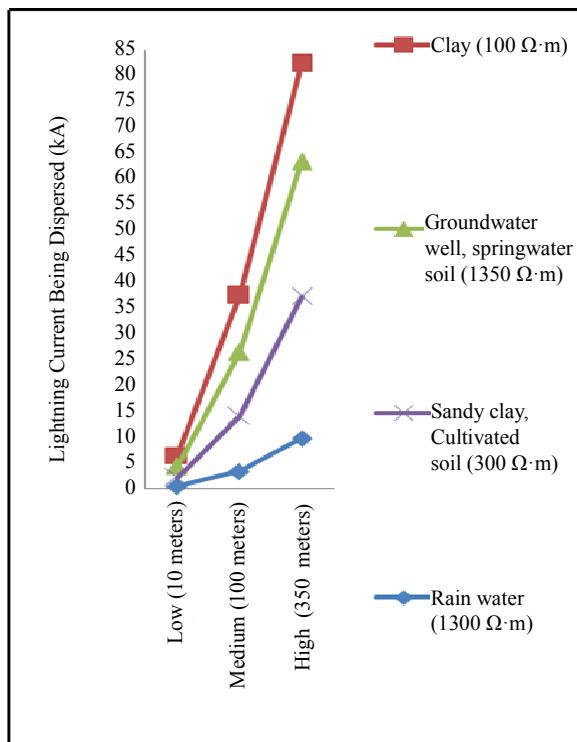
Figure 9. Dispersed peak lightning current, I_{ds} versus type and length of electrode, l.
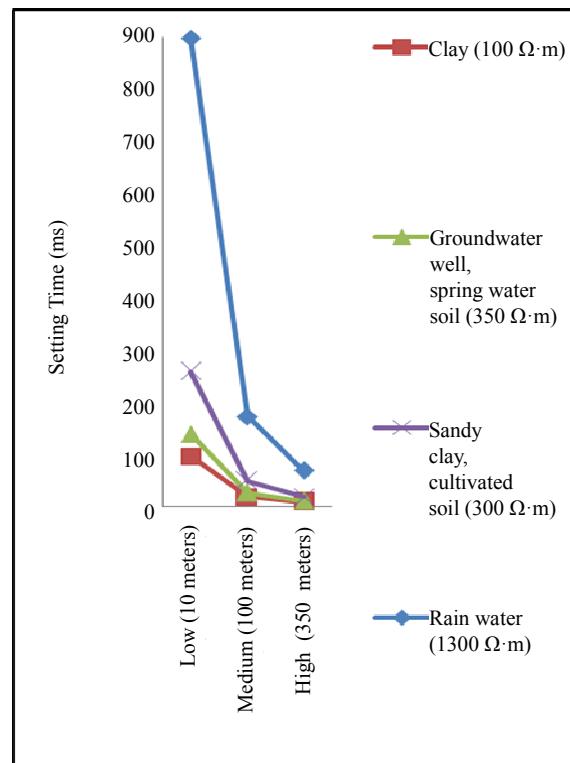
**Figure 10. Settling time, t_s versus length of electrode, l.**

Lightning
Peak Current
(kA)

(12.219u, 6.5000k)

Lightning dispersed peak
current,
I_{ds} = 6.5 kA

6.0KA

4.0KA

2.0KA

98.421m,0.000

t_s = 98.421 ms

0A

0s   50ms   100ms   150ms   200ms

□ -I(PRINT7)   Time
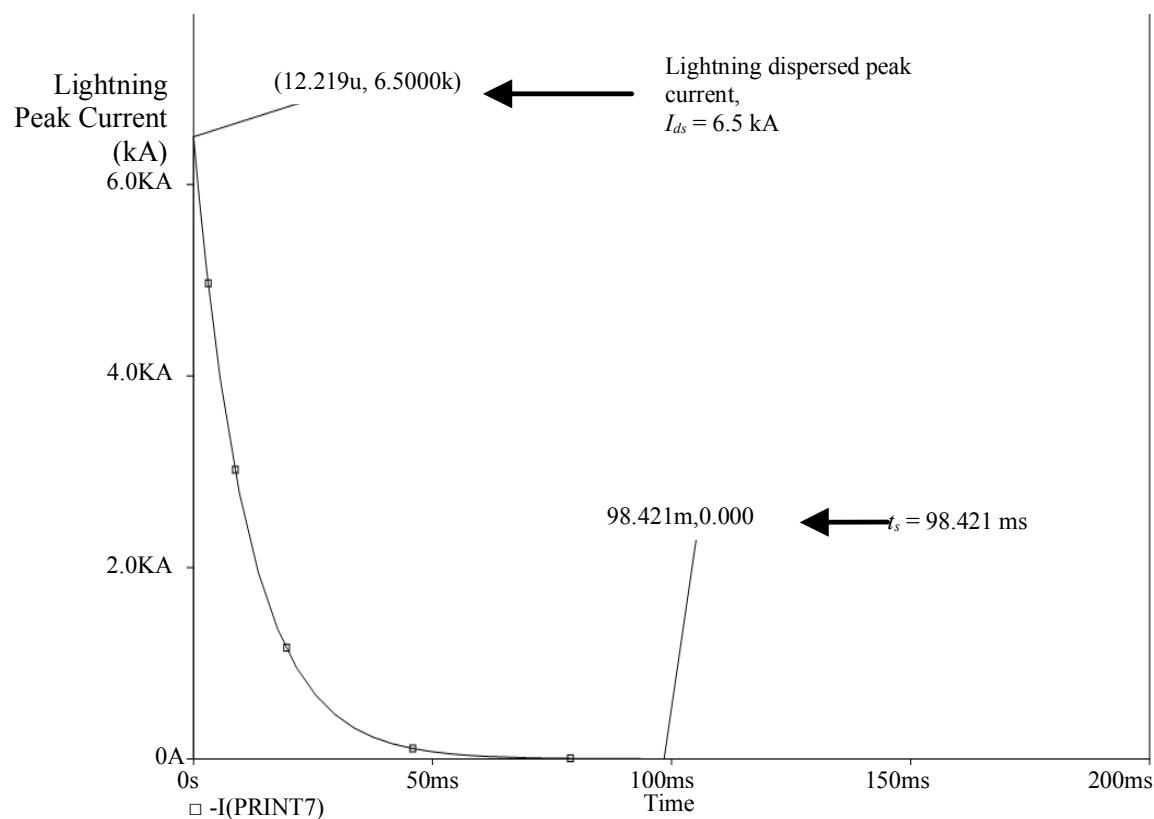
Figure 11. Lightning impulse current (LIC) with 15 Ω grounding impedance, Z_A.

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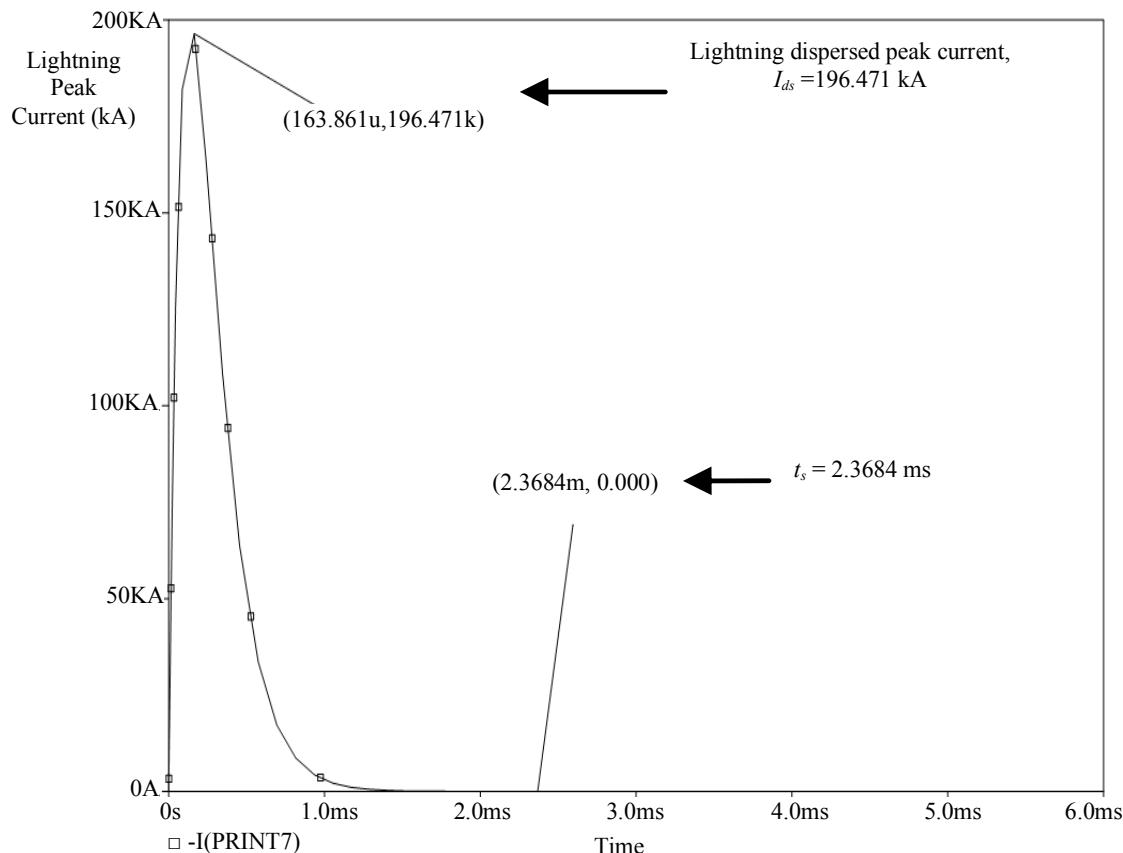
Figure 12. Lightning impulse current (LIC) with 0.004 Ω grounding impedance, Z_A.

becomes better. In addition, when the lower Z_A is used, the magnitude of I_{ds} becomes higher and hence makes the t_s for I_{ds} to completely disperse faster.

6. Conclusions

This work has produced the simulation results about the lightning protection system based on International Electro-technical Commission (IEC 61024-1) standard. The results are summarized as follow:

- Generally, the optimum length of lightning vertical rod should be the same with the striking distance.
- The striking distance will extend when the peak current magnitude of lightning strike gets bigger. This will improve the lightning safety distance and eventually protect the object.
- Low grounding impedance can be produced by having longer grounding electrode and low resistivity in the soil or water. Hence, this makes the grounding capability better.

The new LPS configuration using rolling sphere method has improved the lightning interception efficiency by 8%. It is found that the new lightning safety distance between tower and satellite dish with level I has been reduced by 62.43%. This also applies to the grounding impedance where the improvement to 99.97% is monitored having more lightning peak current being dispersed up to 96.69%. In addition, the lightning strike current has dispersed completely faster having a remarkable speed increase by 97.59%.

7. Acknowledgements

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