Selection of Suitable Features of Lightning Rods for Secure Lightning Protection

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***Abstract*—Lightning rods play a very important role in lightning protection system. In this work, a study of the effect of using lightning rods with different tip surfaces and diameters is conducted. Hence, suitable features of lightning rods can be identified. All experimental results were analyzed using descriptive and inferential analyses. From this research, blunt tip surface with smaller diameters were proven to be the best lightning rod for safer lightning protection.**

***Index Terms*—Voltage Impulse; High Voltage Protection; Analysis Of Variance (ANOVA)**

I. INTRODUCTION

Lightning is an electrical discharge between cloud and earth; it comprises one or more impulses that carry very high current. According to [1], the Earth is getting hit by lightning more than 8 million times per day. Thus, for the purpose of protection, a lightning rod should be installed at the top of high buildings or structures exposed to lightning. This technique has been in existence since 250 years ago, when Benjamin Franklin invented the lightning rod [2].

In a lightning protection system, a copper (or lightning) rod with earth connection is the only component exists in the protection system. It comes with a variety of design such as hollow, solid, pointed, rounded, flat strips and others. Nevertheless, regardless of all designs, each lightning rod should be able to conduct electricity efficiently. Hence, when a lightning bolt strikes a building, the lightning rod will directly conduct it to the ground, preventing electrocuted and fire.

The effectiveness of using different shape of lightning rods has become an endless debate among researchers. It is because there are no proper standards for the shape of lightning rods. Therefore, many studies have been conducted primarily associated with the tip surface of lightning rods [3]. In addition, usual failure of lightning rods to protect nearby objects has also inspired by many researchers to come up with new shapes of lightning rods [4].

In 1990s, an experiment conducted at the Langmuir Laboratory had proven that a lightning rod with moderate blunt tip was a best receptor for lightning strike. Hence, many researchers believed that a lightning rod with pointed tip, elevated and grounded is unable to discharge lightning effectively. However, in 2013, Karl Berggren had proven that a lightning rod with sharp tip is a better lightning strike receptor [5]. Nevertheless, some people still believe that a blunt tip is better than a shape tip, even among people in the lightning protection business [6].

Therefore, this work focuses on studying the relationship between the lightning impulse voltage and the tip surface and diameter of lightning rods. Hence, suitable features of lightning rods for better protection system can be selected. To achieve these objectives, laboratory experiment and descriptive and inferential analyses were conducted. In this work, both sharp and blunt tips of lightning rods were used. The diameter of each lightning rod was varied while the distance between the rod and the lightning source was kept constant [7]. A high voltage impulse (of lightning) was generated within a range of 50 kV to 70 kV.

II. METHODOLOGY

Figure 1 shows the methodology of the research work. It starts with the experimental setup to generate a lightning impulse and applies it to a lightning rod. To achieve the research objective, a lightning impulse voltage test was conducted. The test was selected since it is able to generate lightning impulse voltages in accordance to IEC 60060-1 standard [8]. The impulse was generated within a range of 50 kV to 70 kV.

The lightning impulse voltage test system comprises an impulse voltage generator, voltage divider, chopping sphere gap and overvoltage correction. Additionally, it also has a digital MIAS transient recorder to record high voltage generation and breakdown activity. Hence, accurate measurements of the voltage and evaluation of its values can be achieved [9]. Experimental setup and schematic diagram of the test system are shown in Figure 2 and Figure 3, respectively.

The generated lightning impulse is applied on sharp or blunt tip lightning rods with different diameters. In order to justify all experimental results, the gap between the lightning impulse and each lightning rod is kept constant at 3cm. Meanwhile, the diameters of both types of lightning rods are

NOMENCLATURE

i	Indexes levels of factor A; i =1,…,a
j	Indexes levels of factor B; j =1,…,b
l	Indexes plot (for each factor combination); l = 1,…,n
n	Number of trials
$\bar{Y}_{i\cdot\cdot}$	Mean of the i^{th} factor level of factor A
$\bar{Y}_{\cdot j\cdot}$	Mean of the j^{th} factor level of factor B
$\bar{Y}_{\cdot\cdot\cdot}$	Overall mean of all observations
$\bar{Y}_{ij\cdot}$	Mean of observations at the i^{th} level of factor A and the j^{th} level of factor B
Y_{ijl}	Observations at the i^{th} level of factor A, the j^{th} level of factor B and n^{th} level of factor combination

9.5 mm, 10 mm, 13 mm and 16 mm. The experiment was conducted on various combinations of lightning source surfaces and lightning rod's tips and diameters. All of the combinations are presented in Table 1.

Table 1
List of Combination of Lightning Source Surfaces and Lightning Rod's Tips and Diameters

Lightning source surface	Lightning rod	
	Tip	Diameter (mm)
Flat	Blunt	9.5, 10, 13, 16
Flat	Sharp	9.5, 10, 13, 16
Sharp	Blunt	9.5, 10, 13, 16
Sharp	Sharp	9.5, 10, 13, 16

Once the test was completed, all the experimental results were assessed in several types of analyses and tests. In this work, descriptive and inferential analyses were conducted.

According to [10], a descriptive analysis can be defined as the numbers that sum up the data with the idea of describing what happened in the sample. The analysis was able to evaluate samples from one study to another. Moreover, it can also assist researchers to detect sample characteristics that may influence their conclusions. For this work, the chopping time of the lightning impulse was measured for five times in every condition.

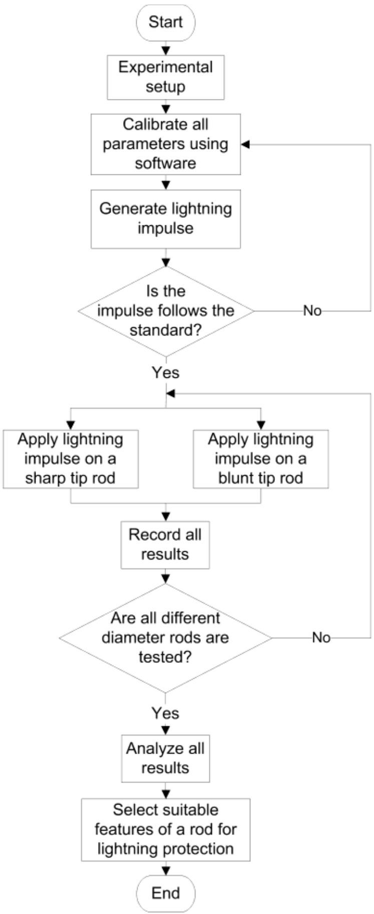


Figure 1: Flowchart of the research work

Next, an inferential analysis was conducted to verify the finding of the descriptive analysis. It was conducted using statistical method known as analysis of variance (ANOVA) on Minitab software. ANOVA was used to determine possible differences in the mean values of more than 2 data samples [11]. It involves variance analysis of overall data to identify factors that can result variations beyond the inherent experimental variation. Additionally, F-test was performed to determine whether the overall variance of all samples is significantly greater than the inherent experimental variance. If the F-test gives a significant result, it can be concluded that there is a significant difference between the mean values of all samples [11].

In order to obtain a valid ANOVA result, all samples must comply with these following assumptions:

1. The dependent variable is measured at the interval or ratio level, and it is a continuous data.
2. The independent variable must consist of two or more categories, and it is in independent groups.
3. There is no association between the observations in each group or between the groups.
4. There are no significant outliers.
5. The dependent variable is approximately normally distributed for each category of the independent variable.
6. The variances are homogenous.

Figure 2: Experimental setup for lightning impulse voltage test

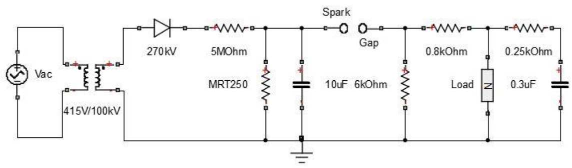


Figure 3: Schematic diagram for generating lightning impulse voltage

Since this study has two main effect variables with different levels, the F-test falls into two-factor Completely Randomized Design (CRD) factorial experiment. All parameters of ANOVA table format are presented in Table 2.

Table 2
Analysis of Variance Table for Two-factor CRD Factorial

Source of variation	Degree of Freedom (DF)	Sum of Square (SS)	Mean Square (MS)	F
First factor A	$DF_A A = a-1$	SSA	$MSA = SSA/DFA$	MSA/MSE
Second factor B	$DFB = b-1$	SSB	$MSB = SSB/DFB$	MSB/MSE
Interaction AB	$DFAB = (a-1)(b-1)$	$SSAB$	$MSAB = SSAB/DFAB$	$MSAB/MSE$
Error	$DFE = ab(n-1)$	SSE	$MSE = SSE/DFE$	
Total	$DFT = nab-1$	SST		

From the table, SS can be calculated using the following equations:

$$SSA = bn\sum_{i=1}^{a}(\bar{Y}_{i}.. - \bar{Y}...)^2 \quad (1)$$

$$SSB = an\sum_{j=1}^{b}(\bar{Y}_{\cdot j}. - \bar{Y}...)^2 \quad (2)$$

$$SSAB = n\sum_{i=1}^{a}\sum_{j=1}^{b}(\bar{Y}_{ij}. - \bar{Y}_{i}.. - \bar{Y}_{\cdot j}. - \bar{Y}...)^2 \quad (3)$$

$$SSE = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{l=1}^{n}(Y_{ijl} - \bar{Y}_{ij}.)^2 \quad (4)$$

$$SST = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{l=1}^{n}(Y_{ijl} - \bar{Y}...)^2 \quad (5)$$

Results of ANOVA were validated using two tests, namely as the assumption of normality of variance and the assumption of homogeneity of variance. The assumption of normality of variance was conducted to determine the normality of a set of data. To satisfy this assumption, the variance distribution must exhibit a symmetrical bell-shaped (normal) curve. For this study, the variants (or residuals) of the model was decided to be normally distributed depending on the majority of the observation values on the normal probability plot.

On the other hand, the assumption of homogeneity of variance was conducted to identify the correlation between all variances [12]. According to this assumption, a satisfied model should have a structure with less variance. In this case, the variances should be unrelated to any other variables, including the predicted response. For this study, the residuals of the model are expected to be scattered in the plot of residuals against fitted value. Moreover, this plot should not reveal any obvious pattern.

III. Results and Discussions

As mentioned, the objective of this work is to determine suitable features of lightning rods for better protection system. In the experimental work, there are two manipulative variables: tip surface and diameter of copper lightning rods. To verify the effectiveness of each lightning rod to chop the lightning impulse, all waveforms resulted from the experiment were compared to a full lightning impulse voltage waveform. The response of this experiment is chopping time T_c.

Figure 4 shows a waveform of full lightning impulse voltage generated by the lightning impulse voltage test. According to the standard, a full lightning impulse voltage should raise its peak value less than a few microseconds and falls, appreciably slower than the normal value, ultimately back to zero [13].

Since the waveform in Figure 4 inherits the same characteristics stated in the standard, the production of lightning impulse using the lightning voltage test has been achieved successfully. The peak voltage V_p of the waveform is 51.03 kV. The points corresponding to the 30% and 90% of V_p is the front time $T1$ which is 1.13 µs. Next, 50% of V_p is called the tail time $T2$; it is 48.97 µs.

Pictures of the generation of lightning impulse voltage are shown in Figure 5. Each lightning impulse voltage was applied on a blunt tip lightning rod as shown in Figure 5(a) or a sharp tip lightning rod as shown in Figure 5(b). Additionally, Figure 6 presents the waveforms of lightning impulse voltage for all conditions shown in Figure 5.

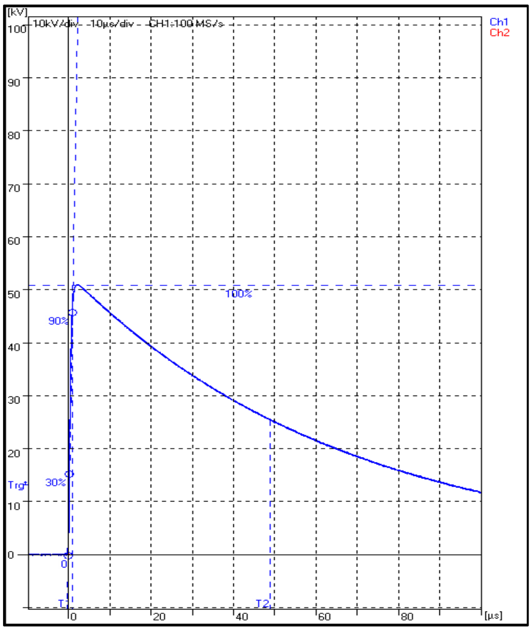
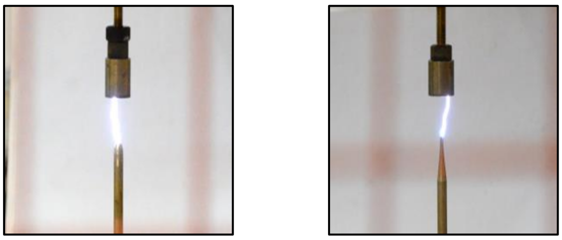


Figure 4: Full lightning impulse voltage

According to Figure 6, we can see that all the waveforms exhibit different characteristics as compared to the standard waveform of full lightning impulse voltage shown in Figure 4. From the starting point, we can observe that the raise of voltage of all the waveforms is not as fast as the full lightning impulse voltage waveform. However, after V_p, the voltage value of all the waveforms drops drastically. These waveforms are known as lightning impulse voltages chopped on the front. The point where voltage starts to decrease is called T_c. From the result, we can notice that the use of lightning rods with different tips has resulted different T_c and peak voltage. By referring to Figure 6, we can observe that the use of the blunt tip lightning rod has resulted higher V_p than the sharp tip lightning rod. It may happen because the blunt tip has a bigger surface as compared to the sharp tip. Hence, it receives higher voltage than the sharp tip. Other than that, because of T_c, all the waveforms do not have $T2$. Nevertheless, based on the results, we can confirm that all types of lightning rods are capable to chop the lightning impulse. Hence, they serve as lightning protection devices.

As discussed in the methodology, the experiment using the same configuration as shown in Table 1 was repeated for five times. Then, the average T_c and V_p for all configurations were plotted against the diameter of each lightning rod. Figure 7 and Figure 8 depict 2 graphs: diameter versus T_c and diameter versus V_p.



(a) (b)

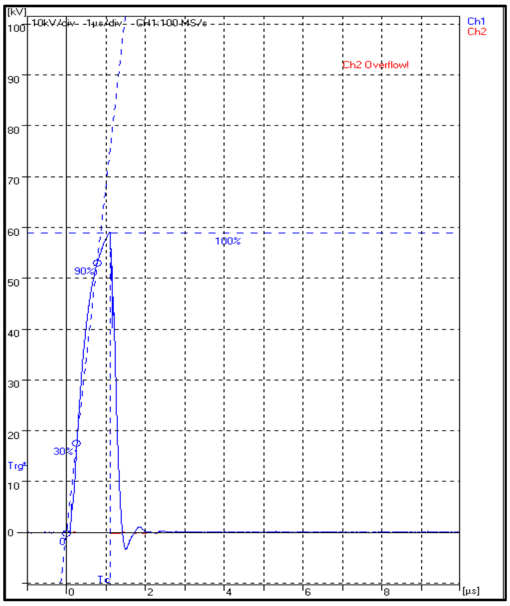
Figure 5: Lightning impulses applied on (a) blunt and (b) sharp tips of lightning rods

By referring to Figure 7, we can see that the use of blunt tip lightning rods has resulted the lowest T_c than using sharp tip lightning rods. On average, the use of blunt tip lightning rods has recorded 85.6% lower T_c than using sharp tip lightning rods. Nevertheless, by considering V_p in Figure 8, we can note that the use of blunt tip lightning rods has resulted higher V_p than using sharp tip lightning rods. On average, the use of blunt tip lightning rods has recorded 16.3% higher V_p than using sharp tip lightning rods. This percentage is considered low as compared to the different percentage of T_c. Based on all conditions, we can say that lower T_c can be obtained when V_p is higher than 60 kV. Moreover, we can see that lightning rods with smaller diameter exhibit lower T_c than lightning rods with bigger diameter. In overall, the use of the 9.5 mm diameter of blunt tip lightning rod has recorded the lowest T_c than other diameters.

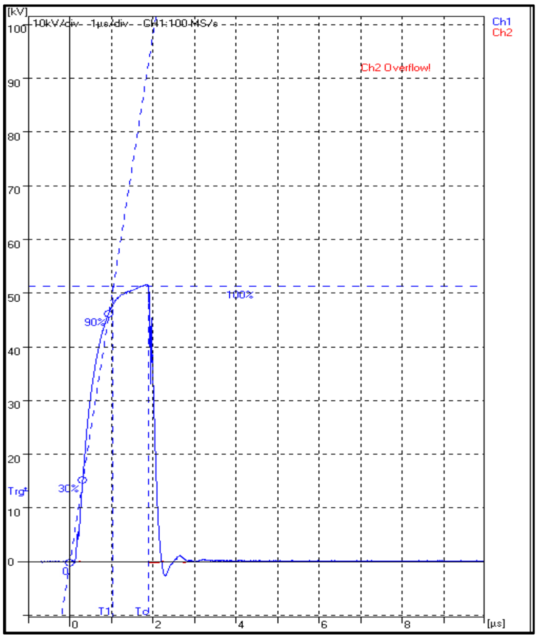
In order to verify the descriptive analysis, a CRD factorial experiment was conducted. Table 3 tabulates all ANOVA outputs. Referring to the ANOVA outputs, the two main effect factors have a significant different towards response variable (time).

According to both tables, the tip surface show high statistically significant different towards time; $F(1{,}32) = 9758.75$, $p < 0.001$. This condition also appear for the rod diameter main effect; $F(3{,}32) = 2622.16$, $p < 0.001$. Moreover, the findings have revealed that the interaction between tip surface and rod diameter also show high statistically significant different towards time; $F(3{,}32) = 2586.91$, $p < 0.001$.

Additionally, the statistic R^2 was used to represent the percentage of variation in a response variable (time) that is explained by its relationship with one or more predictor variables. In the table, the adjusted R^2 percentages indicate that 99.85% of the variation is explained by the tip surface and the rod diameter.



(a)



(b)

Figure 6: Waveforms of lightning impulses applied on (a) blunt and (b) sharp tips of lightning rods

Table 3.
ANOVA Table

Factor	Type	Level	Value
Tip surface	Fixed	2	Blunt and sharp
Rod diameter (D)	Fixed	4	D9.5, D10, D13 and D16

Analysis of variance for time, using adjusted *SS*

Source of variation	*DF*	Adj *SS*	Adj *MS*	*F*	Significant level, *p*
Tip surface	1	9.5326	9.5326	9758.75	0.000
Rod diameter	3	7.6842	2.5614	2622.16	0.000
Tip surface* Diameter	3	7.5809	2.5270	2586.91	0.000
Error	32	0.0313	0.0010		
Total	39	24.8289			
R^2 (adj) = 99.85%					

In order to verify all the ANOVA results, the assumption of residual normality distributed and also the assumption of homogeneity of the residual were performed.

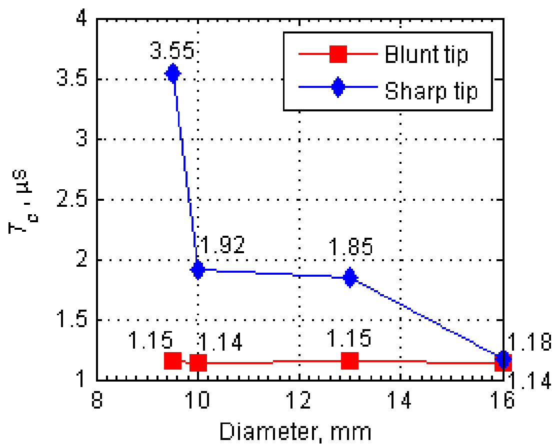


Figure 7: Relationship between average T_c and the tip and diameter of lightning rods

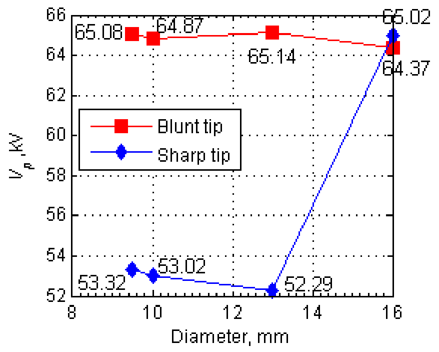


Figure 8: Relationship between average V_p and the tip and diameter of lightning rods

According to the normal probability plot in Figure 9, we can confirm that the residuals of the model are normally distributed. It is because the majority of the observation values (small red dots) lie on the straight lines. Meanwhile, the residuals against fitted value plot as shown in Figure 10 were used to verify the assumption of homogeneity of the residual. Based on the figure, the residuals of the model do not show any serious non-constant residuals pattern; the plot exhibits random pattern.

Since the important assumptions of the ANOVA analysis have been met, it can be confirmed that the findings from the ANOVA results are reliable and valid. Subsequently, the results of the descriptive analysis are also verified.

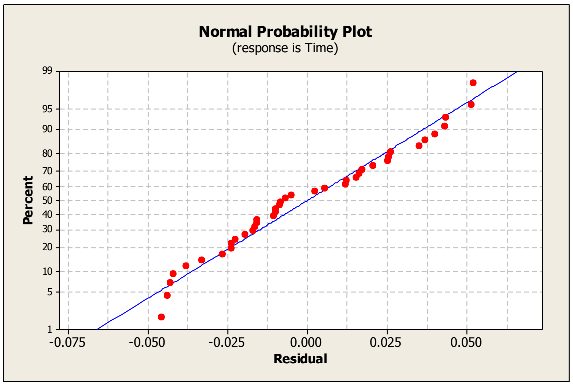


Figure 9: Normal probability plot

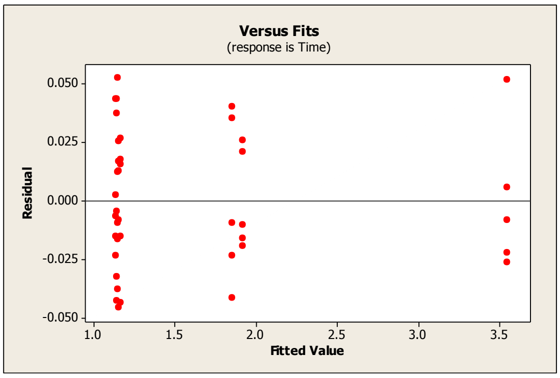


Figure 10: Plot of residuals against fitted value

IV. CONCLUSION

In this study, we have found that lightning rods with different tips and diameters exhibit different T_c and V_p, despite of different lightning source surface. According to the result, the blunt tip lightning rods exhibit lower T_c than the sharp tip lightning rods. However, in order to achieve low T_c, V_p should be higher than 60 kV. Furthermore, based on ANOVA results, we can determine that the tip surface factor and the rod diameter factor have high statistically significant different towards response variable (time). Based on the descriptive and ANOVA analyses, a lightning rod with a blunt tip and 9.5 mm diameter is the most suitable for lightning protection system. Hence, the objectives of the study are achieved.

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