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Estimation of the lightning attractive width of high voltage transmission lines

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ESTIMATION OF THE LIGHTNING ATTRACTIVE WIDTH OF HIGH VOLTAGE

TRANSMISSION LINES

By

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This research is devoted to an investigation on the attractive width of high voltage transmission lines to lightning strikes. In order to design the optimal lightning protection, the estimated number of lightning flashes on the line, which is based on its attractive width, needs to be determined. The investigation was performed using experiments with model tests at the Mississippi State University High Voltage Laboratory.

For laboratory experiments, a total of 2,100 negative and positive switching impulse voltages were applied to transmission line models from a conducting rod, which represented a lightning downward leader. Different tested models of transmission lines on a scale of 1:100 were used. The effects of overhead ground wires, phase conductors, tower structures, and the magnitude and polarity of lightning strokes were also studied.

The attractive width increased gradually with the height of overhead ground wires and towers as well as the magnitude of the lightning stroke current. Impulse polarity had an impact on the attractive width, and the attractive width for negative polarity was larger than that for positive polarity. The taller tower had more effect on flash distribution to transmission lines than the

shorter one. The experimental results agree with the actual transmission line observations published in literature.

The new expressions for the attractive width of transmission lines, based on the experimental results, were established. The accurate estimation of the attractive width can help electric power utilities plan transmission systems reliably and economically. The detailed description of the background problem, proposed method, experimental results, and analysis are presented in this dissertation.

DEDICATION

I would like to dedicate this research to my mother, Sumol Disyadej.

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CHAPTER I

INTRODUCTION

This dissertation is the result of research motivated by a need for electric utilities to improve the reliability of power grids. For electric utilities, the service continuity of high voltage transmission lines is the major objective. However, in the actuality, transmission lines may encounter interruptions for many reasons, including lightning, which often causes line outages. One factor that affects power system performance is the stability of transmission lines. To operate transmission lines stably with minimum interruption, the lightning performance of transmission lines must be known.

Lightning performance is one of the primary considerations for design and operation of transmission lines. Typically, lightning performance is expressed in the form of the annual number of lightning flashovers per unit length and varies greatly between transmission lines. The first problem for power systems is outages of transmission lines by the way of direct lightning strikes. Lightning strokes to the transmission line can cause an overvoltage. If the overvoltage on the transmission line exceeds the electrical strength of string insulators, flashover and then an outage may occur. The second problem is that lightning flashover causes damage to the insulators. The method to approximate the lightning performance of transmission lines has been presented in many publications. Estimated lightning performance or outage rate is a very common concern for electric utilities when the decision involves optimizing both reliability and cost of transmission lines.

1.1 Problem Statement

In order to evaluate the lightning performance of transmission lines, a number of parameters are used in computation. The degree of accuracy depends on the availability of data and plays a major role in the calculated performance. One of the parameters that affects the limited precision of the evaluation is the number of lightning flashes to a transmission line, which is based on the attractive width. However, the current international standard [16] still uses the equation for the attractive width which was primarily derived from empirical data collected from extensive observations of the lightning incidence on practical structures including transmission lines. In fact, lightning flashes can appear anywhere along a transmission line, e.g. overhead ground wires, tower tops, or phase conductors.

Much research [9, 10, 18-25] related to this topic has been conducted to develop the new models for estimating this attractive width of transmission lines. According to the literature review section, the problem has been investigated using three different methods: field observations, analytical methods, and computer simulations. Knowledge of these models has been studied slightly by using experiments in laboratories. Some models also did not consider realistic factors in practice, such as tower structure geometry, sag of overhead ground wires, lightning stroke polarity, and probability of lightning flashes to ground wires and towers. In order to solve this problem, a more precise model, one based on the basis of the real phenomena of lightning flashes to the transmission lines, needs to be developed. The conclusion of this dissertation aims to be the practical value for transmission line engineers to either design new lines or improve existing lines.

1.2 Objective of the Dissertation

In order to accomplish the desired goal of the dissertation, the following intermediate objectives were established:

- Identification of the methods used in relevant past works and analysis of their strengths and weaknesses.
- Experimental results of different models and configurations of transmission lines. The results would show the impact on the attractive width from configurations and dimensions of transmission lines as well as from the polarity and magnitude of lightning strokes.
- Experimental results from the tests, which will focus individually on each part of a transmission line: overhead ground wires and tower structures. All parts have been anticipated to have impact on the attractive width also.
- The new model for the attractive width based on all results. The new expression will be simplified for a practical use.
- Verification and validation of the developed model.
- Publication of the research work in the related technical publication.

1.3 Contribution of the Dissertation

Since models in the past did not consider realistic factors in practice, this research is expected to investigate the impact of the combined position of ground wires and tower structure geometry, lightning stroke polarity, and probability of lightning flashes to ground wires and towers. Assuming similarities between the breakdown mechanism in a laboratory and the natural lightning phenomena, a study of breakdown under lightning condition can be another methodology to investigate the lightning incidence to transmission lines. The more precise model will be based on the simulated phenomena of lightning flashes to the transmission line. Published data of transmission line observations will validate the accuracy of the experimental results. Finally, the new expression will be simplified for practical use in order to reasonably estimate the lightning attractive width of transmission lines. The contribution of this research work can help power utilities plan reliable and economical transmission systems.

1.4 Dissertation Structure

The structure of the dissertation is as the following. Chapter II describes the lightning phenomena and the lightning performance of transmission lines. Chapter III presents the concept of lightning attractive width and the summary of previous works done on estimation of the lightning attractive width. The laboratory experiments performed in the present work are presented in Chapter IV. Chapter V presents all results of laboratory experiments, and these results are analyzed in Chapter VI. Finally, the dissertation is concluded in Chapter VII along with possible future works in this topic.

CHAPTER II

LIGHTNING FLASH AND LIGHTNING PERFORMANCE OF TRANSMISSION LINES

2.1 Introduction

The protection of transmission lines from lightning flashes has been a significant concern for scientific communities over a period of 100 years. Numerous lightning flashes to transmission lines occurred throughout the service time. It has been found that the line outage rate is related to the number of lightning flashes on the line. In this chapter, a general description of the phenomena of lightning discharges and the lightning performance of transmission lines is provided.

2.2 Phenomena of Lightning Discharges

As of the fundamental of cloud electrification, the bottom part of an active thundercloud usually contains negative charges with small regions of positive charges [1]. The top part of a cloud contains positive charges. Electrification of a thundercloud is shown in Figure 2.1. The charging mechanism of a cloud is a very complex process and will not be discussed in this dissertation. It has already been well presented by Gold [2], Uman [3], Rakov [4], and Cooray [5]. The estimated height of the origin of the lightning is typically about 2-5 km above ground. There are four possible types of lightning discharges: cloud-to-ground, intracloud, intercloud, and cloud-to-air. Even though the intracloud discharge is the most frequent type, the cloud-to-ground discharge is always the one that creates problems for the humans, so this type of lightning discharge is the most concerning.

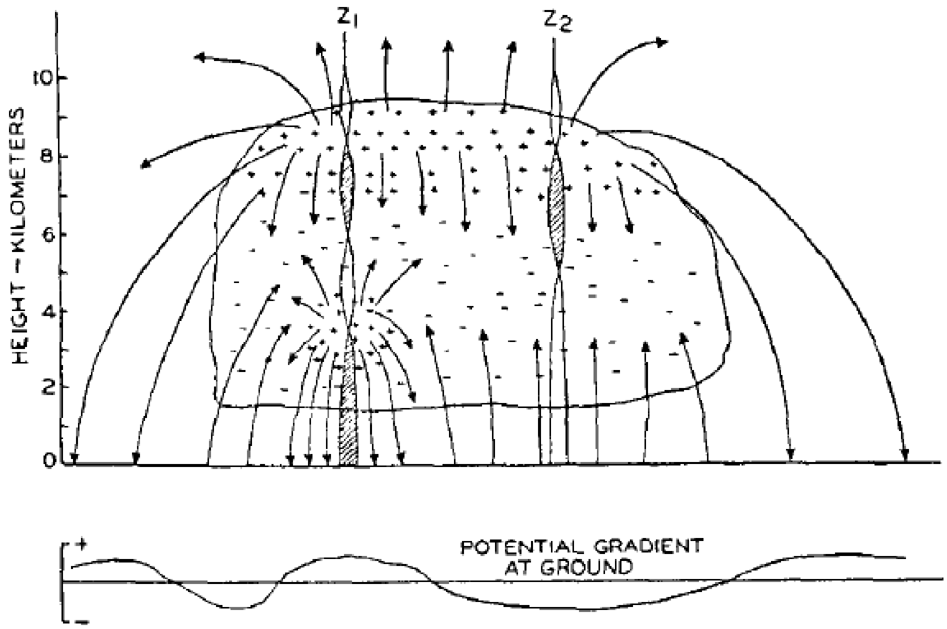
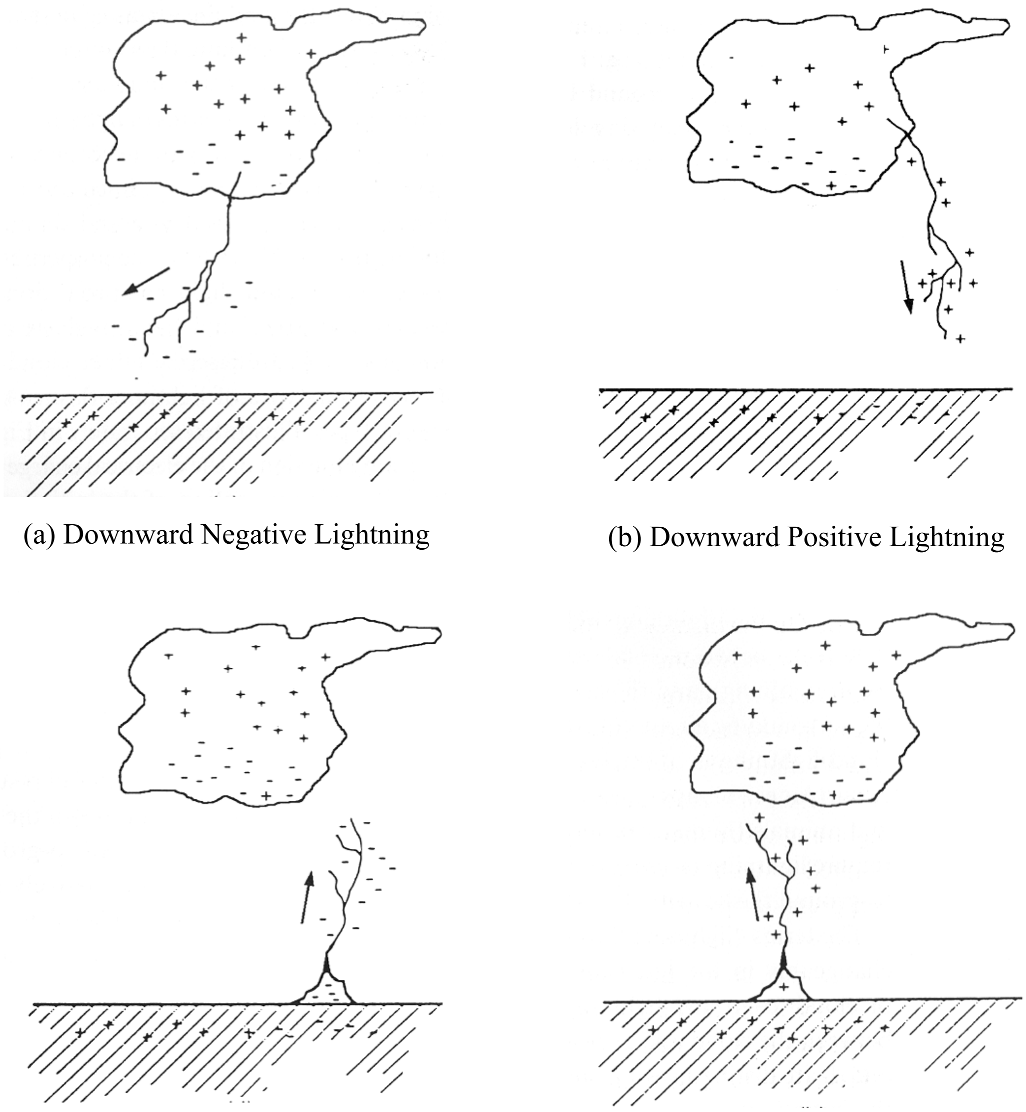


Figure 2.1 Electrical Structure of Thunder Cloud [1]

Moreover, the cloud-to-ground discharge can be subdivided into four different types depending on the polarity and the direction of a stepped leader, as shown in Figure 2.2 [3]. The negative and positive cloud-to-ground discharges are the types of lightning that are studied in this research because they are more common for transmission lines compared to the other two types. Downward negative lightning (the most frequent) accounts for 90% of all cloud-to-ground discharges, while downward positive lightning accounts for the other 10%. Upward lightning occurs very rarely, usually on tall structures with heights of 100 m or above. On average, typical transmission lines have heights ranging from 20 m to 60 m.

Because of the very fast process of a lightning discharge, it is seen by the human eye as a single discharge. However, as shown in Figure 2.3 [6], there are actually various steps of a lightning discharge, which was detected by a high-speed camera. The mechanism of a downward negative lightning, which is the most frequent, is explained here. The negative charges at the bottom of a thundercloud induce the opposite polarity (positive) charges at earth below. A



(a) Downward Negative Lightning

(b) Downward Positive Lightning

(c) Upward Negative Lightning

(d) Upward Positive Lightning

Figure 2.2 Four Types of Cloud-to-Ground Lightning Discharges [3]

stepped leader initiates from the bottom part of a thundercloud in the region of negative charges where the electric field intensity reaches the critical values, around 10-30 kV/cm. The stepped leader propagates toward the earth below in a step and branching manner, with the step length of 50 m and the pause time of 20-50 μs after each step [4]. When the tip of the negative downward leader approaches the earth, it causes the electric field around the earth's surface and objects on earth, such as buildings, trees, power lines, and substations. If the electric field intensity reaches the critical values, a positive upward leader will initiate and propagates toward the approaching negative downward leader. As both leaders meet, the lightning attachment completes, and the subsequent return stroke flows from the earth to the cloud. Then, the negative charges are completely discharged. The return stroke current is in the range of 5-200 kA, with the median value of 30 kA [7].

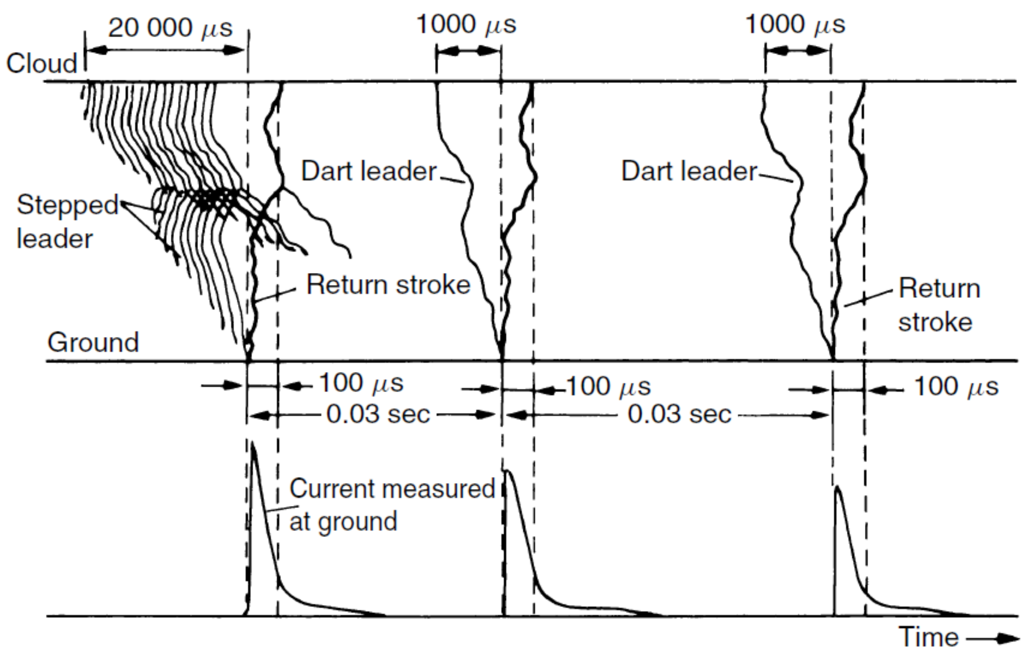


Figure 2.3 Mechanism of Lightning Flash with Relative Time and Ground Current [6]

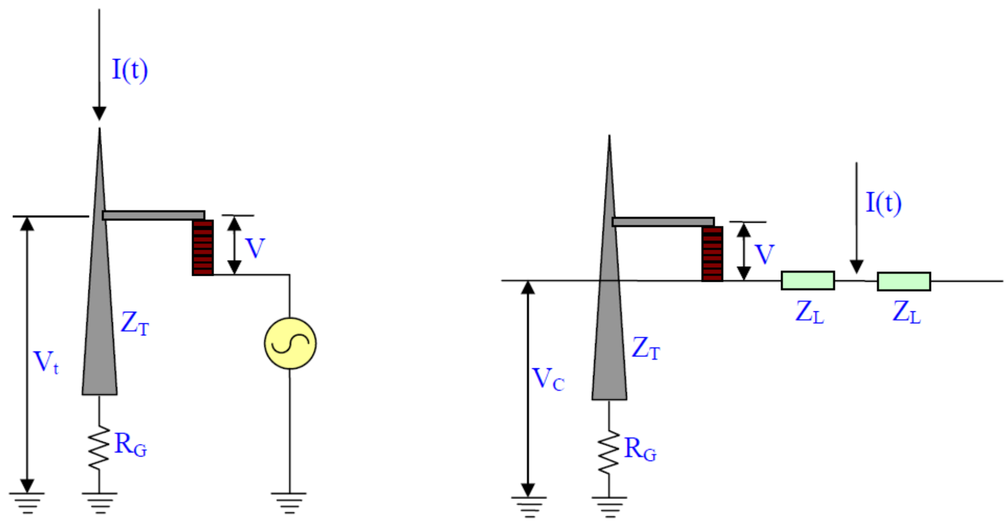
The mechanism of the lightning flash has not yet finished because the bottom of the cloud can have other regions of negative charges. As a result, one lightning flash may have more than one lightning stroke, i.e. multiple strokes, usually about 3-5 strokes per flash [4]. The second or subsequent leaders, dart leader, succeed the same channel of the stepped leader, but not in a step and branching manner and with much faster speed. When the dart leader approaches the earth, the upward leader again initiates and meets the dart leader. Then, the second return stroke flows, and the negative charges at the other region of the cloud are discharged.

The incidence of lightning discharge varies from one area to another and from year to year. Characteristics of lightning activity such as duration, ground flash rate, thunderstorm days, thunderstorm hours, and ground flash density have high variations. The period of observation and methods and devices used to detect the lightning incidence affect the accuracy of records.

2.3 Lightning Performance of Transmission Lines

The major cause of interruptions of high voltage transmission lines is flashover of insulators due to lightning. As shown in Figure 2.4, flashover can occur two ways: backflashover or shielding failure. Basically, backflashover can occur when lightning strikes a tower or an overhead ground wire; shielding failure can occur when lightning strikes a phase conductor directly [8]. If the lightning overvoltage in either of these situations exceeds the electrical strength of the insulator, flashover will occur.

Moreover, the mechanism of flashover can be also explained in two steps, lightning incidence on a transmission line followed by electrical response of a transmission line after lightning flash. Knowledge of the second step has been widely studied using theoretical methods, laboratory tests, and computer simulations. However, knowledge of the first step has been primarily studied through observations from field measurements. Knowledge of the lightning incidence to the line is not yet complete because it has some statistical uncertainties of data and is time consuming.



(a) Backflashover (b) Shielding Failure

Figure 2.4 Two Types of Flashover on Insulator String

Theoretically, the basic idea of lightning overvoltage on insulator strings is about traveling waves on a transmission line [8]. In a complicated circuit with many junctions of impedances, traveling waves initiated by a single incident wave will split into many reflected and refracted waves as multiple reflections occur. We can calculate a voltage at any point and any time by adding all the waves that pass that point. The voltage response at the insulator due to a lightning flash can be determined with a series of computations using the traveling wave theory [9]. Computation of overvoltage at the insulator, the difference between the crossarm voltage and the phase conductor voltage, can be done by using many parameters, such as lightning stroke current, surge impedances of the overhead ground wire and tower, and the footing resistance. Reflections from adjacent towers and the power-frequency voltage at the phase conductor also have an impact on overvoltage.

As presented above, because of the complexity of computation, it is usually performed by using a computer program, such as the Electromagnetic Transient Program (EMTP). After the critical stroke current that causes the insulator flashover is computed, the probability of lightning stroke can be determined from the stroke probability curve in Figure 2.5 [7]. This probability, represented as percentages, and the estimated number of lightning flashes to the line, in flashes per 100 km per year, will be used to calculate the lightning performance or the predicted lightning outage rate of the line. This is commonly expressed in the value of number of outages per 100 km per year. It can be observed that the number of lightning flashes to the line, which will be discussed in the next chapter, has direct impact to the lightning outage rate.

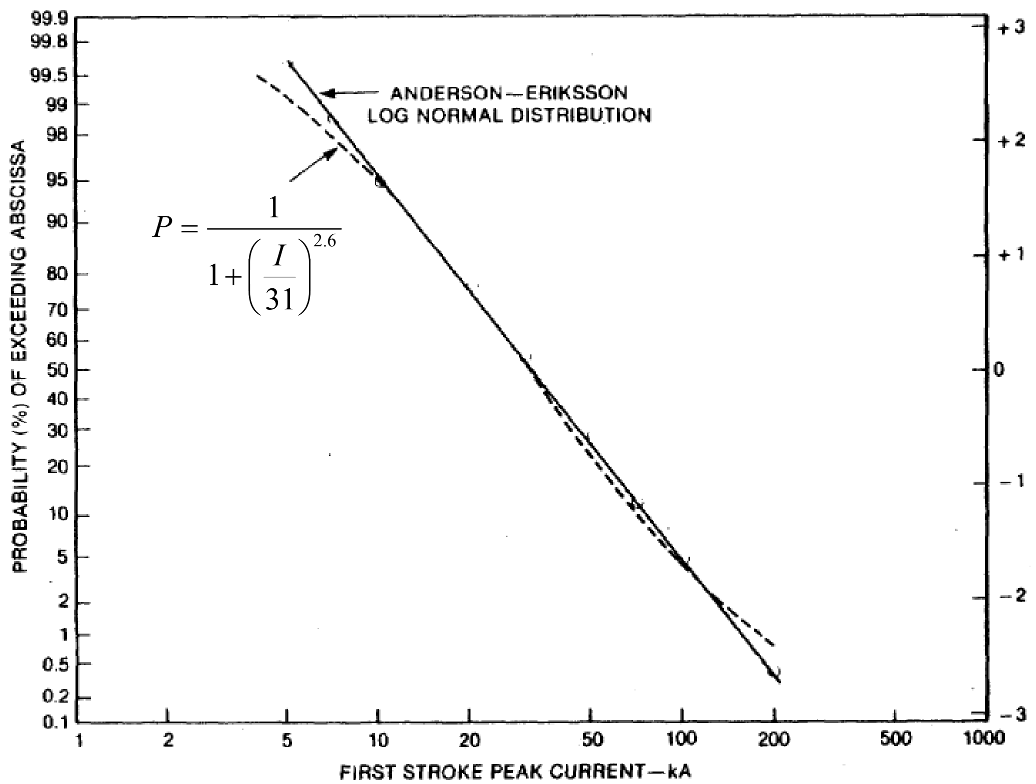


Figure 2.5 Cumulative Probability Distribution of Lightning Stroke Current [7]

Since the AIEE committee of 1950 [12] presented a method of estimating lightning performance of transmission lines based on collective evaluation of factors, engineers have obtained significant data toward improvements in the design of transmission systems. The method has been widely accepted and has given many satisfactory results. Later, several new approaches have been developed to improve calculations obtained by the conventional method, which failed to accurately predict performance of some cases, as in [13, 14]. Because of improved knowledge in areas such as stroke characteristics, shielding design, and impulse current behavior of grounds, the IEEE working groups have developed a simplified method [7], its updated version [15], and a standard for improving the lightning performance [16]. The computer program for estimating lightning trip out rates is also presented in this standard.

To obtain minimum line interruptions, power utilities place emphasis on the proper design of major factors: line route, shielding, insulation, and tower footing impedance. Knowledge about these factors has improved in recent years through advanced research, but some parameters are still not well defined because they are difficult to study and to model. Lightning performance can be degraded if the parameters are not selected properly by transmission line designers. However, in the real life, some restrictions such as economic constraint dictate the proper decisions that will affect the lightning performance of transmission lines. Therefore, power utilities always balance the increased costs of improvement against the improved reliability.

2.4 Summary

Knowledge about lightning phenomena has improved in the past century in such areas as physical characteristics and mechanisms of lightning discharges. From all types of lightning discharges, only the negative and positive downward lightning will be studied for the attractive width of transmission lines. Insulator flashover due to lightning is the primary cause of outages, and lightning performance is a very important factor for the stability and economy of power systems.

CHAPTER III

LIGHTNING ATTRACTIVE WIDTH OF TRANSMISSION LINES

3.1 Introduction

Because transmission lines are structures that are exposed above the surrounding environment, they are always a target for lightning strikes. This chapter presents the concept of lightning attractive width and its related studies from other research in the past. Since the accurately estimated attractive width is very important to the calculation for the lightning performance of transmission lines, many approaches have been developed. Compared results of the attractive width from different methods are also presented and discussed.

3.2 Concept of Lightning Attractive Width

For simplicity, the number of lightning flashes to a transmission line could be predicted by using the number of lightning flashes to earth and the attractive width of the line. Figure 3.1 presents the mechanism of the lightning incidence to a transmission line. According to the Electrogeometric Model (EGM) [17, 47, 48], when the downward lightning leader reaches the vicinity of a transmission line, there are two possible lightning attachments. If the tip of the leader reaches striking distance of the line, r, the lightning may jump to the line. On the other hand, if the tip of the leader reaches striking distance of the ground, r_g, the lightning may jump to the ground instead. X is the lateral attractive distance of an overhead ground wire. Consequently, the width, W, at which the line attracts lightning strokes is the attractive width. This attractive width is a very important factor in predicting the number of lightning flashes to the transmission line.

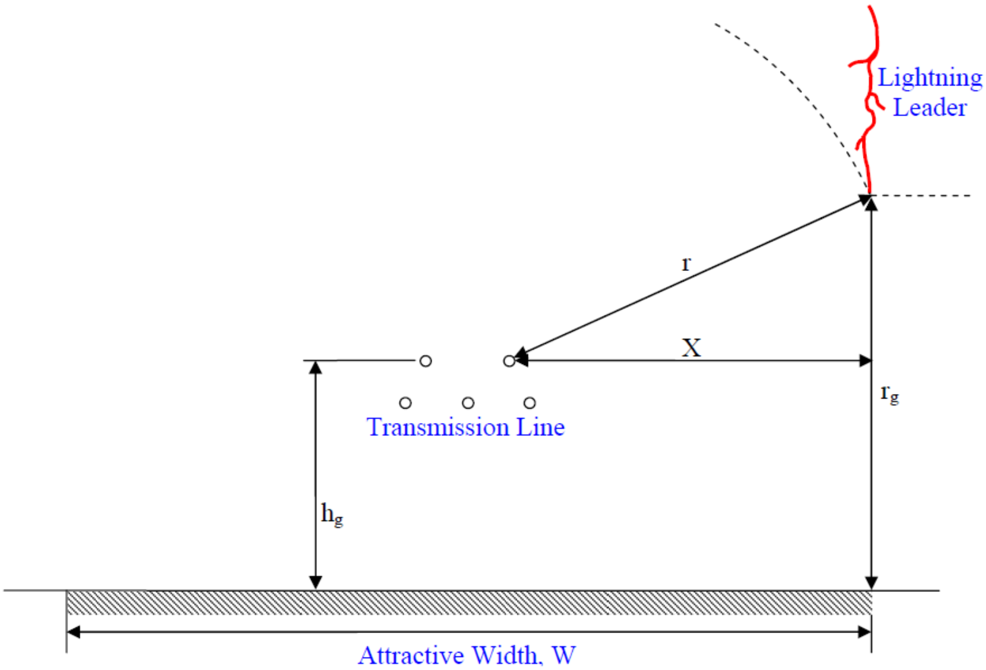


Figure 3.1 Incidence of Lightning Stroke to Transmission Line

An approximation [10] for the number of lightning flashes to any line per 100 km per year, N_L, is provided by the following equation:

$$N_L = N_g W / 10 \tag{3.1}$$

where N_g is the ground flash density (GFD) in flashes/km^2/year, and W is the attractive width of the line in meters.

In the past, the number of ground flash density has relied on the use of the isokeraunic level, which is based on observations of thunderstorm days. Various expressions were developed to relate the observational thunderstorm day to the ground flash density [10]. The second development in the estimation of the ground flash density was found using thunderstorm hour data, which has more temporal sampling [15]. At the present time, the successful technology for the lightning detection network has proved the strongest advantage on counting the actual number of cloud-to-ground strokes in thunderstorms [11]. Therefore, the attractive width is the last parameter that must be known for a specific transmission line before the number of lightning flashes to the line can be computed. The best results will occur when this research on the attractive width is completed because a wrong approximation in this important parameter will cause an error in calculation of lightning performance.

Once the number of lightning flashes to the line has been estimated, electrical response (lightning overvoltage) at different parts can be computed, and then the outage rate can be estimated. The estimated lightning performance of a transmission line in the form of outage rate is one of the key factors that affects the reliability of transmission systems. In order to design an optimized transmission line reliably and economically, its lightning protection needs to be investigated so that it has the minimum outage rate and also the minimum cost. This research focuses only on the attractiveness of transmission lines to lightning strokes, which is commonly known as "the attractive width".

3.3 Review of Previous Studies on Lightning Attractive Width

There has been a long history of research for determining the attractive width and the number of lightning strokes to the transmission line. In 1945, an exposure area formula by Golde [18] demonstrated the area, on an average, covered by various types of transmission lines. Because of the absence of enough data for the physical phenomena of lightning discharges, some assumptions were made. The attractive radius of a tower is 2 times its height, and the attractive distance of an overhead ground wire is 1.5 times its average height (80% of the tower height). The formula for a transmission line with one and two overhead ground wires was given, respectively, as:

$$A = 3.6\pi h_t^2 + 3h(L - 3.2h_t) \tag{3.2}$$

$$A = 3.2\pi h_t^2 + (b + 3h)(L - 3h_t) \tag{3.3}$$

where A is the exposure area in m^2/span, h_t is the ground wire height at the tower in meters, h is the average ground wire height in meters, b is the horizontal distance between two ground wires in meters, and L is the mean length of the span in meters.

The corresponding number of lightning strokes [19] to the transmission line per 100 km per year, N_L, is:

$$N_L = N_s N_g A \times 10^{-4} \tag{3.4}$$

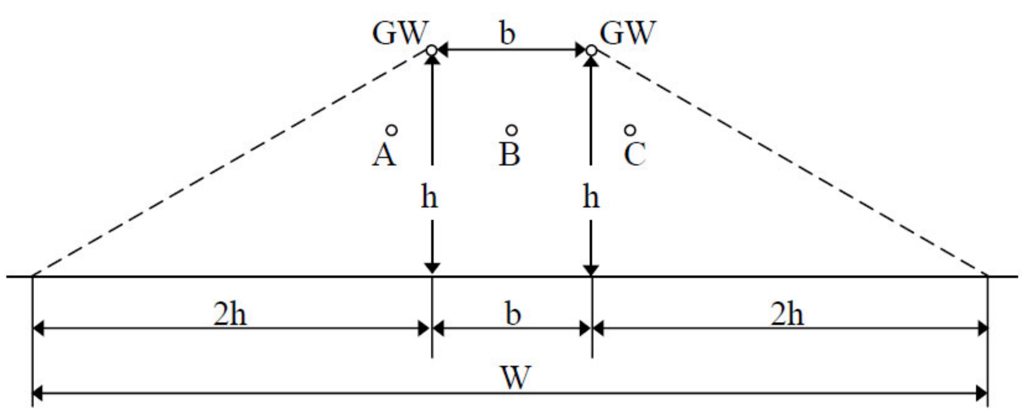
where N_s is number of spans/km and N_g is the ground flash density in flashes/km^2/year.

Hagenguth [20] modified Golde's equation in the form:

$$A = (2\pi + 1)h_t^2 + 4h(L - h_t) \tag{3.5}$$

which yielded a closer result compared to the field data.

Anderson was the researcher who demonstrated the simplified concept of lightning incidence on the transmission line [9]. As shown in Figure 3.2, the simple model assumes that the transmission line has an electrical shadow width or attractive width, W, on earth.



W = shadow width on earth's surface
GW = ground wires
A, B, C = phase conductors

Figure 3.2 Electrical Shadow Width of Transmission Line [10]

Lightning flashes inside this width will strike the transmission line (strike ground wires), while lightning flashes outside this width will not strike the line and will strike the earth instead. The attractive width, W, in meters, is given as:

$$W = b + 4h \tag{3.6}$$

where b is the ground wire separation distance and h is the mean ground wire height, both in meters.

The mean ground wire height is given by

$$h = h_t - \frac{2}{3}(h_t - h_{gw}) \tag{3.7}$$

where h_t is the ground wire height at the tower and h_{gw} is the ground wire height at the midspan, both in meters.

Whitehead developed the simple model of Anderson with only slight modification [19]. The modified attractive width becomes:

$$W = b + 4h^{1.09} \tag{3.8}$$

The modified attractive width resulted in better estimates for the number of lightning flashes on the line compared to the magnetic link data. It therefore appears that the Whitehead's model is more accurate provided the magnetic link records are taken accurately. However, because of lack of sophisticated lightning location systems at that time, the attractive width was derived from the ground flash density, which is empirically related to thunderstorm days, keraunic level.

Eriksson presented the new expression for attractive width, as represented in equation (3.9), which is the combination of extensive empirical data and an analytical model [21].

$$W = b + 28H^{0.6} \tag{3.9}$$

where H is the tower height in meters, not the mean ground wire height as the previous model.

The empirical data was based on 3,000 observed lightning flashes to structures, and the analytical model was based on the modern knowledge of the critical radius concept and the electric field enhancement factor at the structure top. The expression developed for structures was also compared to transmission line observations in many countries. The observed lightning incidence data showed dispersion due to recorded uncertainties, such as the varied thunderstorm days over the periods of observations. Moreover, the model seemed to have an excessive dependence on tower height when calculating attractive width. Nevertheless, this expression is suggested in the international standard for lightning performance of transmission lines [16].

While the traditional methods are primarily based on the observational data, Mousa and Srivastava determined the lightning incidence by applying the revised Electrogeometric model to transmission lines [22]. They presented a computerized solution that can determine the frequency and characteristics of the collected lightning strokes, which takes into account the sag of ground wires, the existence of towers, and the inequality of the striking distances to towers and to ground wires. Several available forms of the striking distance can be selected for calculation. Some examples of the program's results were presented, but, unfortunately, none of mathematical equations or application graphs was presented for a practical use.

In 1990, Rizk introduced a new model for assessing the exposure of horizontal conductors to direct lightning strokes [23]. His model started from a developed criterion for positive leaders initiated from a horizontal conductor under a negative descending lightning stroke. The trajectory of the positive upward leader to encounter the negative downward leader was analyzed to determine the lateral attractive distance. Regression analysis yielded the approximate expression for the attractive width [15]:

$$W = b + 38h^{0.45} \tag{3.10}$$

In [15], some of these above models were compared on the same plot as shown in Figure 3.3 (adapted from [15]). As suggested in the paper, Eriksson' model is based on the tower height while the others are based on the average ground wire height. To compare them exactly, the tower height should be offset to 10-20% greater than the ground wire height. The comparison showed that the models agreed reasonably up to the range of 30 m of the ground wire height only. Above 30 m, each model tended to divert from others, and, at 60 m, the maximum difference is almost 100%.

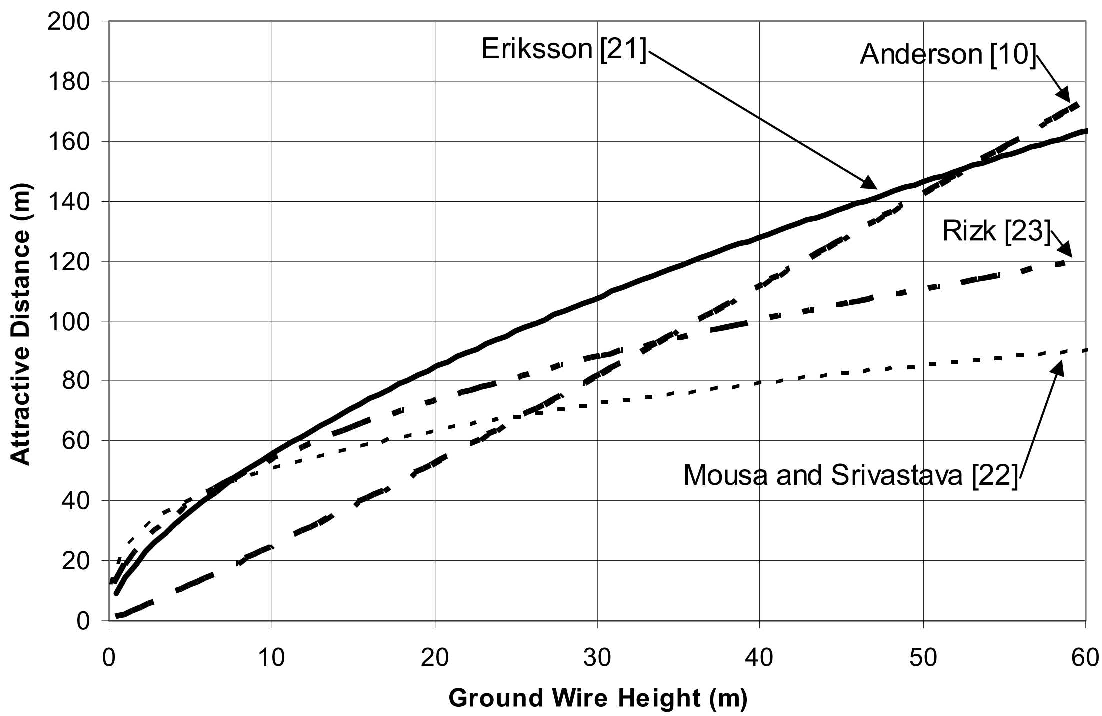
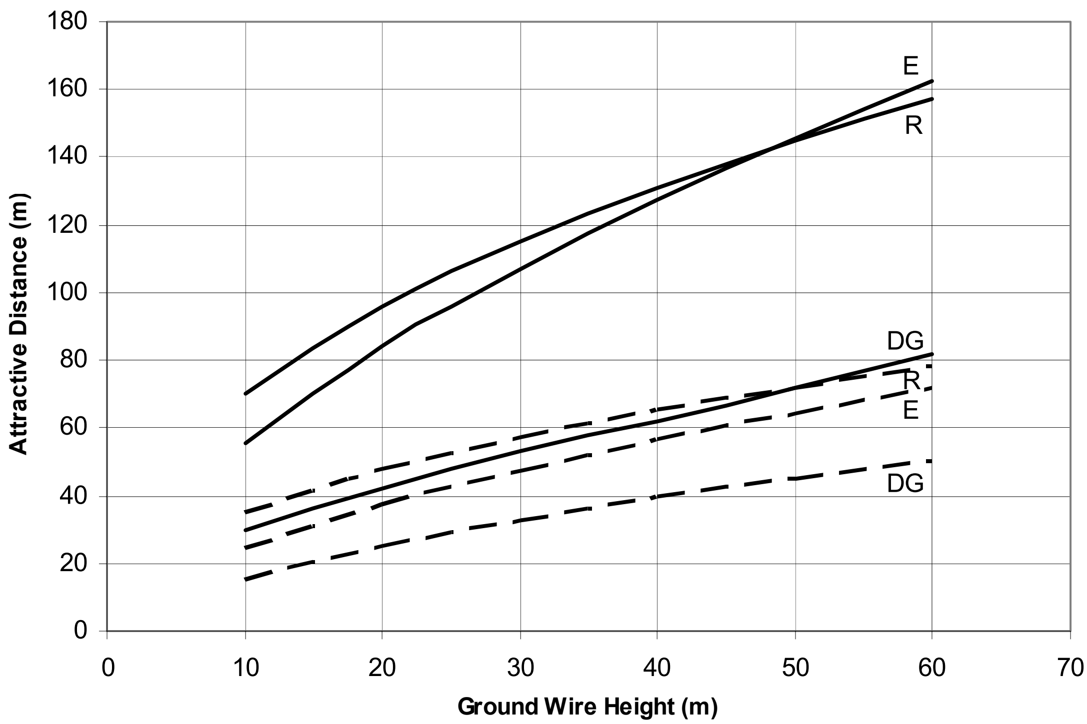


Figure 3.3 Attractive Distance of Transmission Lines by Different Methods [15]

Dellera and Garbagnati also introduced a simulation of lightning strokes to transmission lines by means of the leader progression model [24, 25]. The model of lightning channel progression towards the earth is based on the physics of discharge on long air gaps. The electric field was calculated by the charge simulation method, which adopted all parameters involved in the progression of the negative downward leader and in the inception and propagation of the positive upward leader. Then, the model was applied to the analysis of the exposure to lightning of transmission lines.

As shown in Figure 3.4, the values of the attractive width of Dellera and Garbagnati were much lower than those obtained with Eriksson's model and Rizk's model [26]. These lower values are a result of the different relationships between current stroke and both charge values and charge distribution in the downward leader.



—— 60 kA; – – – 20 kA
E (Eriksson); R (Rizk); DG (Dellera and Garbagnati)

Figure 3.4 Attractive Distance of Ground Wire for Different Lightning Stroke Current [26]

A. J. Phillips and J. G. Anderson [27] developed a special transmission line lightning simulation program to examine the factors involved in the approach of a lightning leader toward a line. Three different methods, including critical charge criteria, a critical gradient between the leader tip and the ground wire, and striking distance equations, were used to model the development of the upward leader. As presented in the paper, the number of line flashes by Eriksson's equation and those by striking distance equations, both recommended by the IEEE [16], did not coincide. Moreover, not only line height but also striking patterns, bending leaders or straight leaders, have an influence on the attractive width.

3.4 Summary

The lightning attractive width is a very important parameter that is needed to compute the accurate number of lightning flashes to a transmission line. As has been previously presented, the three different methods (analytical, observational, and computational) were developed to evaluate the attractive width of transmission lines. However, each model gives different results for the attractive width.

CHAPTER IV

LABORATORY EXPERIMENTS

4.1 Introduction

Researchers have shown certain similarities between the breakdown mechanism of natural lightning and that of lightning simulated in a laboratory. The experiment in a laboratory, which uses impulse voltages to simulate lightning condition, is the method that can be used to investigate engineering problems about lightning phenomena. A laboratory experiment using model tests was conducted to investigate the effects of factors on the shielding of transmission lines [28]. The results of the tests have been utilized to find out the recommended value of protective angle. Furthermore, research at the MSU HV Lab have been conducted on the lightning performance of 115-kV transmission and 13-kV distribution lines [29, 30]. The investigation was conducted to evaluate the effectiveness of a lightning protection device installed on the lines. At the same place, other research on laboratory study of the lightning striking distance and protection zone of the Franklin rod and the effectiveness of lightning protection devices have also been conducted [31-35].

Similarly, it is reasonable to perform the study of lightning incidence to transmission lines to determine the effects of some factors on the attractive width. Estimation of the attractive width has not been widely studied by using experiments in the laboratory. With figures and parameters used in the tests, various types of laboratory experiments using test models are presented in this chapter. Test procedures used to conduct the experiments are also explained.

4.2 Test System for Experiments

A challenge of this research is to simulate the phenomena of a lightning downward leader toward the earth. The entire downward leader behaves like a conductor storing space charges in the corona envelope around the leader core, especially at the tip. There will not be any effect of the progressing leader on the transmission line until the leader tip approaches approximately 100 m above the earth. At the moment, the leader charges create a strong electric field on the transmission line and on the earth's surface. Consequently, the upward leader is initiated from the transmission line and/or the earth and intercepts the tip of downward leader. The electric field simulation in a high voltage laboratory can be produced by using long-front impulse voltage (several hundreds microseconds) [36]. In practice, the impulse electric field created by a switching impulse has a rise rate, in average, similar to the time-dependent electric field created by a downward leader. Figure 4.1 shows the waveform of the switching impulse used in laboratory experiments; only the negative polarity is presented.

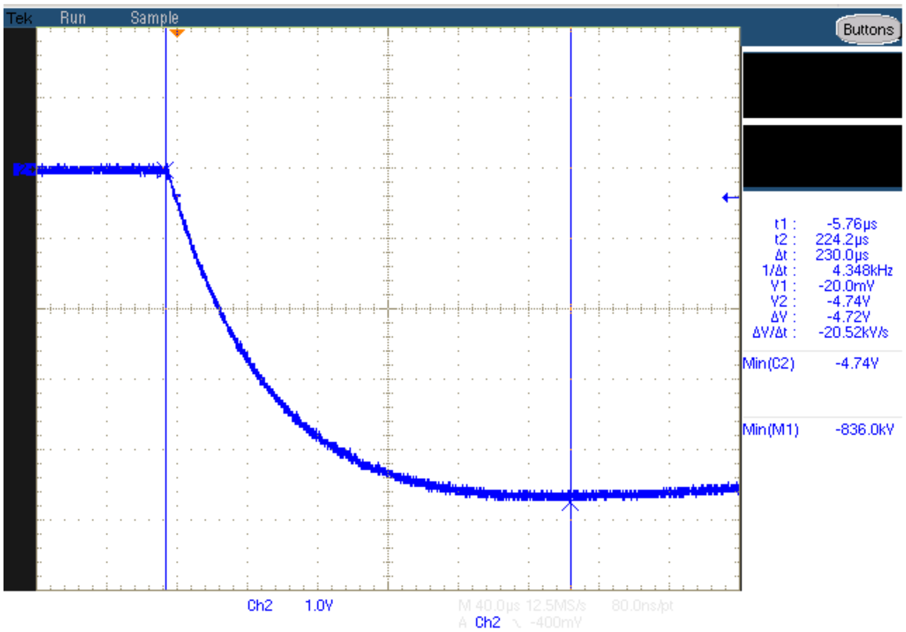


Figure 4.1 Waveform of Negative Switching Impulse Used in Laboratory Experiments

All experimental studies of this research were conducted in the MSU High Voltage Laboratory. The measurement set-up of the tests is shown in Figure 4.2. In this study, standard 250/2500 ❍s switching impulse voltages were applied to the upper rod, which represented a lightning downward leader, in order to simulate the condition of final discharge. The increase of the electric field during the development of a downward leader (stepped leader) is well represented by the switching impulse [36]. The switching impulses were obtained from a 3 MV, 57 kJ, 20-stage impulse generator. The capacitive voltage divider connecting with a Tektronix TDS 7104 digital storage oscilloscope was used to measure voltages and to monitor waveforms of impulses. The simple models of transmission lines, on a scale of 1:100, were constructed in the laboratory by using horizontal conducting wires to represent overhead ground wires and phase conductors. At the ends of the line model, the ground wires and the phase conductors were connected to the ground. Copper sheets were used on the floor of the laboratory to simulate a conducting ground plane. Figure 4.3 shows the actual set-up for laboratory experiments.

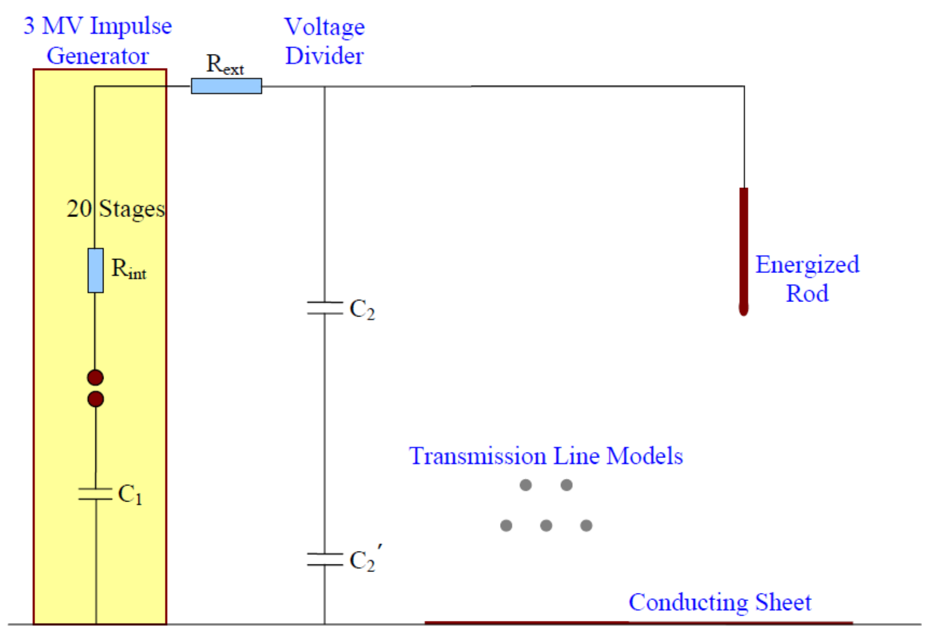


Figure 4.2 Diagram of Laboratory Set-Up

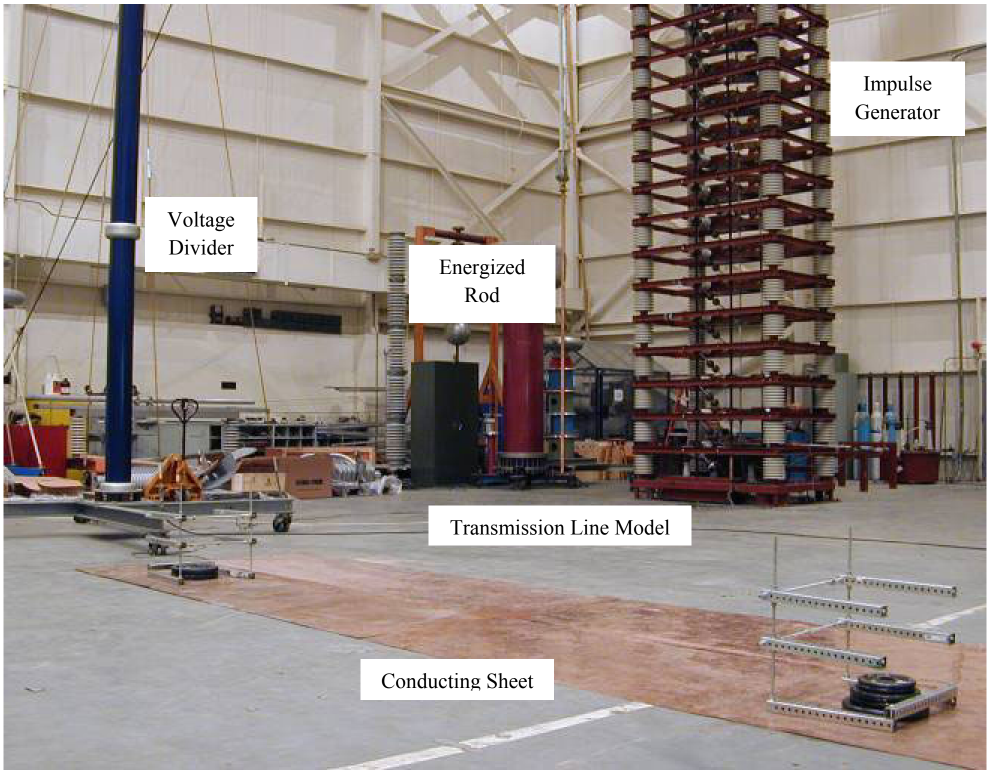


Figure 4.3 Actual Test Set-Up in Laboratory

Laboratory experiments were conducted under both negative polarity and positive polarity of switching impulses. A digital still camera was used for the study of the visual characteristics of the incidence of flashes during experiments. Recorded photographs not only showed the character of arc paths but also helped identify the location of flashes, either to the ground wire or to the ground.

4.3 Tested Models

Four laboratory experiments using seven tested models were performed. The tested models were for overhead ground wires, typical transmission lines, a vertical rod, and transmission line towers; all were placed over the copper sheets and connected to the ground.

4.3.1 Experiment for Overhead Ground Wires

The purpose of this experiment is to evaluate the attractive distance, X, of overhead ground wires at different height, h_g and to investigate the effect of varying ground wire separation at each value of the ground wire height. For the tests, models of one and two overhead ground wires were used. The ground wire height varied from 10 to 60 cm, in a step of 10 cm. The ground wire separation width, b, varied from zero (one ground wire) to the same number as the ground wire height, also in a step of 10 cm. Note that the value of ground wire separation, b, which is larger than that of ground wire height, h_g, is not common for typical transmission lines. The span was 4 m long for all tests. Figure 4.4 illustrates both tested models.

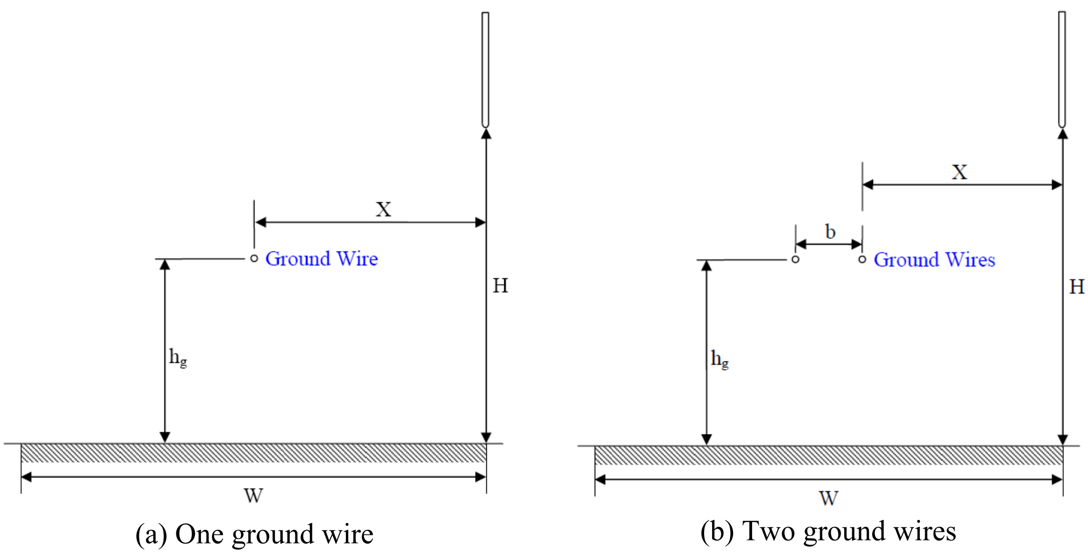


Figure 4.4 Models of Overhead Ground Wires

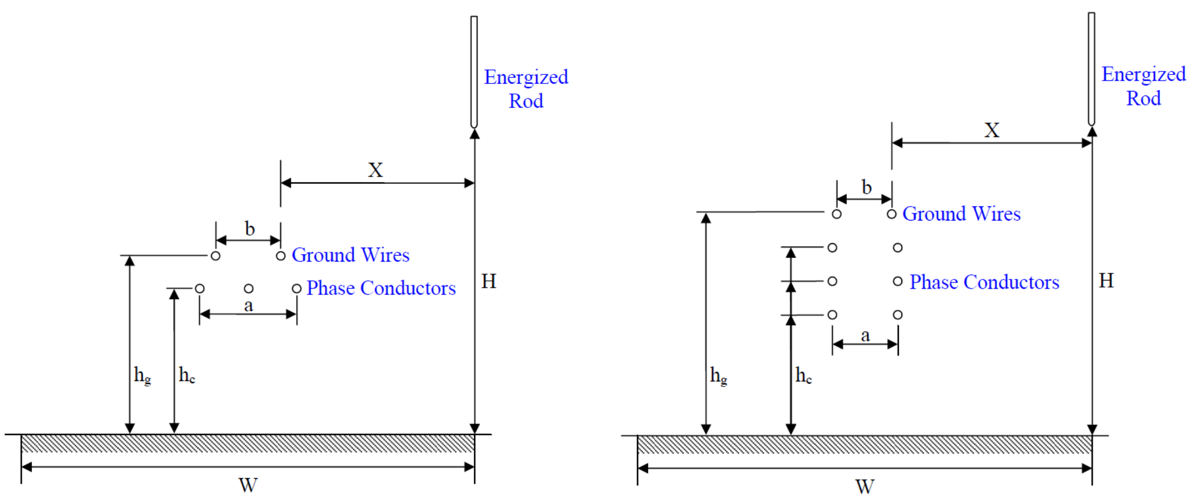
The height of the energized rod, simulating the lightning downward leader, H, is 73 cm, which corresponds to the distance of the striking distance to the ground of the median lightning stroke of 30 kA (see Figure 2.4). The length of the striking distance to the ground [10], as a function of lightning current, can be approximated using the Electrogeometric model by the equation:

$$r_g = \beta 10 I^{0.65} \tag{4.1}$$

where I is the lightning stroke current in kA and β = 0.8 was used. Then r_g in m was scaled down to H in cm.

4.3.2 *Experiment for Transmission Line Models*

The purpose of this experiment is to evaluate the attractive distance, X, of transmission line models at different energized rod height, H, and to investigate the effect of phase conductors. The different base case of scaled models for HV, EHV, and UHV typical transmission lines were selected to study the dimension impact on the attractive distance. A number of single and double circuit transmission lines including horizontal and vertical configurations were tested in the study. Figure 4.5 illustrates both configurations of transmission line models. Table 4.1 presents parameters of 9 base case configurations including 230, 345, 500, 765, and 1100 kV transmission lines [11]. The span was 4 m long for all tests.



(a) Single-circuit horizontal transmission line (b) Double-circuit vertical transmission line

Figure 4.5 Models of Transmission Lines

Table 4.1 Parameters of Base Case Line Configurations [11]

Voltage (kV)	Single-Circuit Horizontal Line				Double-Circuit Vertical Line			
	Phase Conductors		Ground Wires		Phase Conductors		Ground Wires	
	h_c (m)	a (m)	h_g (m)	b (m)	h_c (m)	a (m)	h_g (m)	b (m)
230	10.3	9	18	7.5	10.3, 12.8, 15.3	5	26.3	5.5
345	12.5	15	22.2	9.4	11.5, 19, 26.5	6	37.8	4
500	14	20	24.3	14.6	13, 22, 31	10.2	40.7	6
765	18.5	28	30.7	22.1	17.6, 29.6, 41.6	14	55	9
1100	24	37	40	33.8	-	-	-	-

The height of the energized rod, simulating the lightning downward leader, H, was 56, 73, and 101.7 cm, which correspond to the distance of the striking distance to the ground of the lightning stroke of 20, 30, and 50 kA, respectively. The length of the striking distance to the ground, as a function of lightning current, can be approximated by the equation (4.1).

4.3.3 Experiment for Vertical Rod

The purpose of this experiment is to evaluate the attractive radius, R, of a grounded vertical rod at different rod height to be used later as the reference data for the attractive distance of transmission towers. The rod height, h_r, varied from 20 to 60 cm (typical height of towers = 20-60 m), in a step of 10 cm. Figure 4.6 illustrates the tested model, and the height of the energized rod, simulating the lightning downward leader, H, is 73 cm.

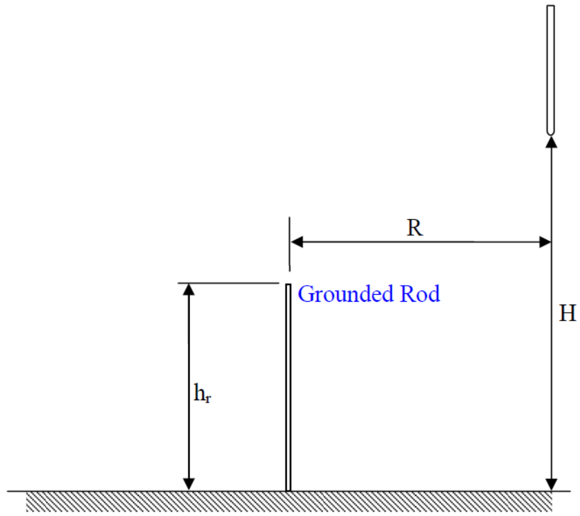


Figure 4.6 Model of Vertical Rod

4.3.4 Experiment for Transmission Line Model with Tower

The purpose of this experiment is to evaluate the attractive distance of transmission line towers and investigate the effect of towers on distribution of lightning flashes. In this experiment, two models of transmission lines were represented by using not only the horizontal conducting wires but also the tower structures. 230-kV single-circuit horizontal and 765-kV double-circuit vertical tower models [11, 42, 43] were built for the tests, and their parameters are shown in Table 4.2. The existence of tower structures and the sag of overhead ground wires, which has been ignored before, were studied.

Table 4.2 Parameters of Transmission Line Models with Tower

Transmission Line Model	b (cm)	h_t (cm)	h_m (cm)	L (m)
1-cct horizontal 230-kV Line	10	23.5	17.5	2.44
2-cct vertical 765-kV Line	9	61	52	3.05

The measurement set-up of the experiments for the attractive width, W, of towers is shown as a diagram in Figure 4.7. The two different ground wire heights, at the tower, h_t, and at the midspan, h_m, were used separately. The height of the energized rod, simulating the lightning downward leader, H, is 73 cm. The measurement set-up of the experiments for distribution of flashes to a transmission line is shown as a diagram in Figure 4.8.

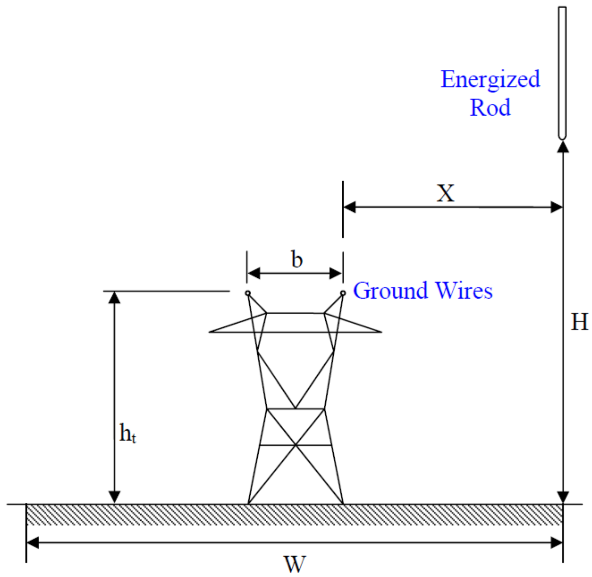


Figure 4.7 Diagram of Test for Attractive Distance of Transmission Line Model with Tower

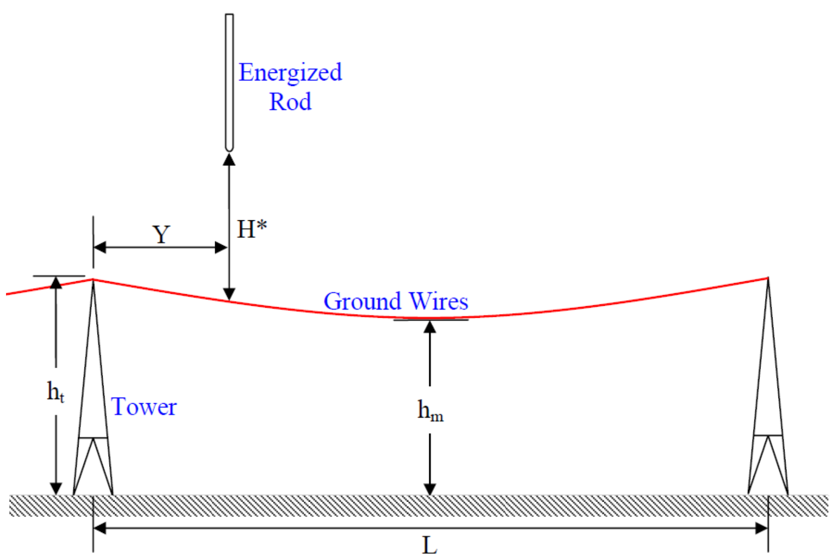
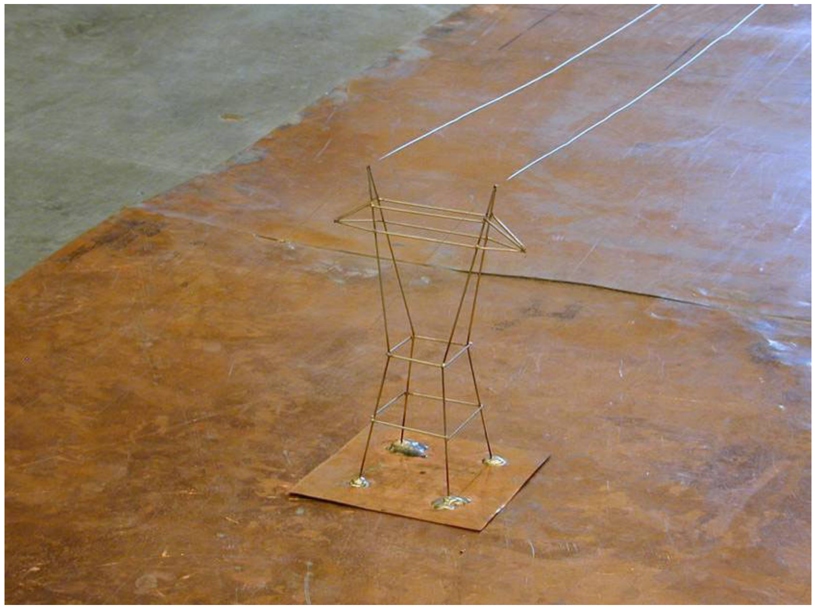
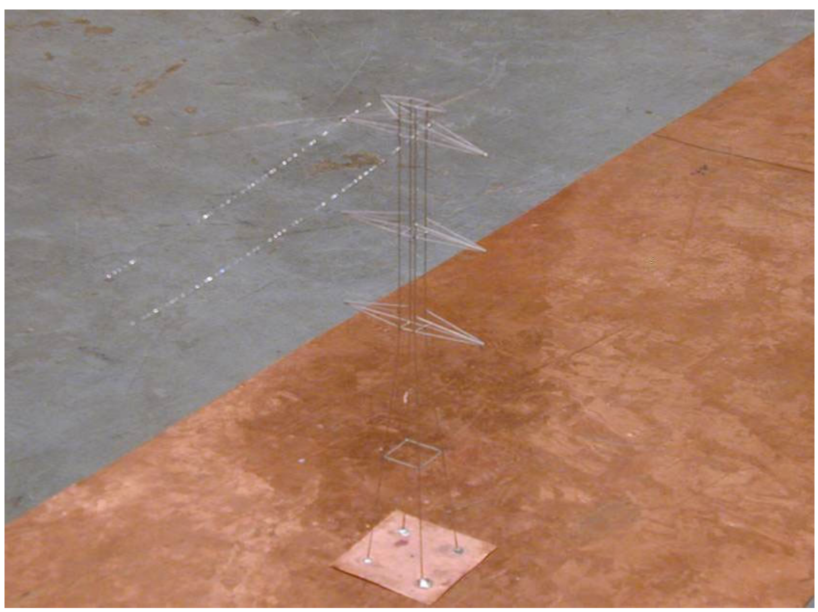


Figure 4.8 Diagram of Test for Distribution of Flashes to Transmission Line Model with Tower

Figure 4.9 shows the pictures of two transmission line tower models, with overhead ground wires suspended at the crossarms, placed over a copper sheet.



(a) 230-kV 1-cct Horizontal Tower Model



(b) 765-kV 2-cct Vertical Tower Model

Figure 4.9 Actual Transmission Line Tower Models with Sag of Overhead Ground Wires

The height of the energized rod directly above overhead ground wires, H*, was 91.2 cm, which corresponds to the striking distance to the ground wire of the median lightning stroke of 30 kA, and the location of the rod along the transmission line, Y, was varied gradually during the tests. The length of the striking distance to the ground wire [10, 44], as a function of lightning current, can be approximated by the equation:

$$r = 10I^{0.65} \tag{4.2}$$

4.4 Test Procedure

Another challenge of this research is the statistical method for the test procedure on evaluation of the attractive width. Usually, high voltage testing in a laboratory for breakdown of an air gap has a random characteristic [6]. Therefore, the proper number of repeated switching impulses applied to the rod simulating a downward leader must be considered. This selected number should be able to establish good experimental results, but not be time consuming, i.e. too many shots are unnecessarily applied.

In order to determine the appropriated number, a short experiment was performed first on the model of one overhead ground wire with the energized rod height, H, equals to 73 cm, and the ground wire height, h_g, equals to 36.5 cm (half of H). 40 negative impulses were consecutively applied, and the number of flashes to the ground wire and to the ground was counted. The cumulative sum of the number of flashes to the ground wire after each n number of applied impulses were calculated, and the probability of flashes is presented in Figure 4.10 starting from n = 2. As mentioned above, because of the random behavior of discharges, the probability of flashes to the ground wire appeared to have the variation in results. However, the probability converged to some specific value after a few shots, and the final probability of flashes at the shot number 40 is 50%. The probability at n =10 is 50%, at n = 20 is 45%, and at n = 30 is 47%.

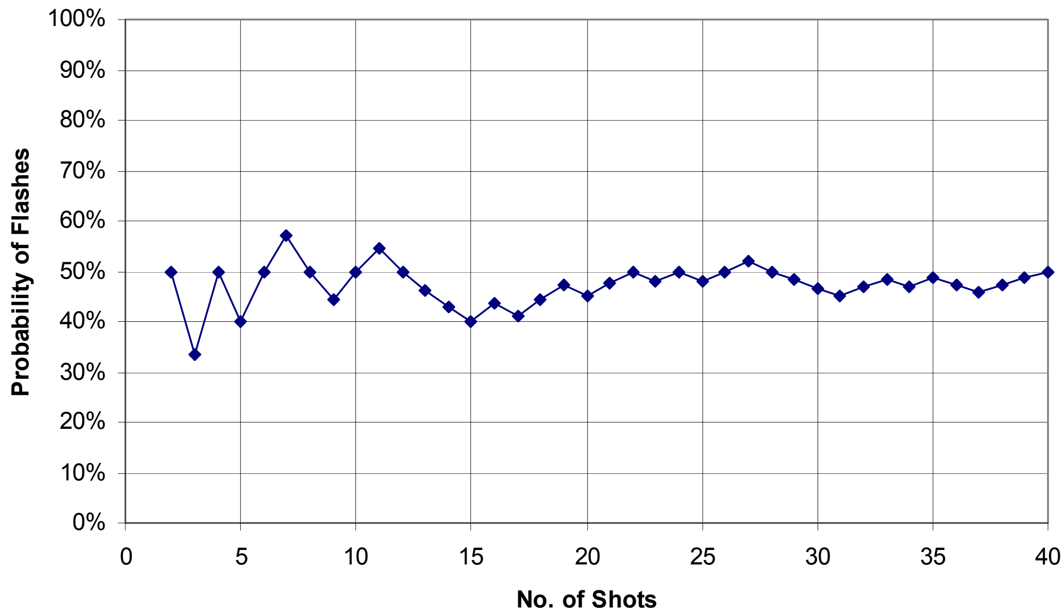


Figure 4.10 Probability of Flashes to Tested Ground Wire at n No. of Applied Impulses

Mostly, the test procedures described in international standards are for breakdown voltage and time to breakdown, but this research has a different purpose. In the up-and-down method, the standard [41] suggests 20 impulse voltages to be applied for $V_{50\%}$, on flashover and withstand voltage tests. That means 10 flashovers and 10 withstands out of 20 shots, and applied voltages are varied (up and down). However, for this research, all shots cause flashes, and applied voltages are constant at the specific value (5% larger than the CFO voltage of the rod-plane gap for height H). The test objective is to determine the probability of flashes at the transmission line and the ground, not the probability of flashes and withstand. Moreover, as observed in Figure 4.10, the probability at n = 10 is just only +5% higher than at n = 20 and +3% higher than at n =30, while the practical error of any high voltage testing is in the range of +/- 3%. Note that the probability at n =10 is the same as that at n = 40, as well. Figure 4.11 shows the flash to the ground wire that was recorded during the test.

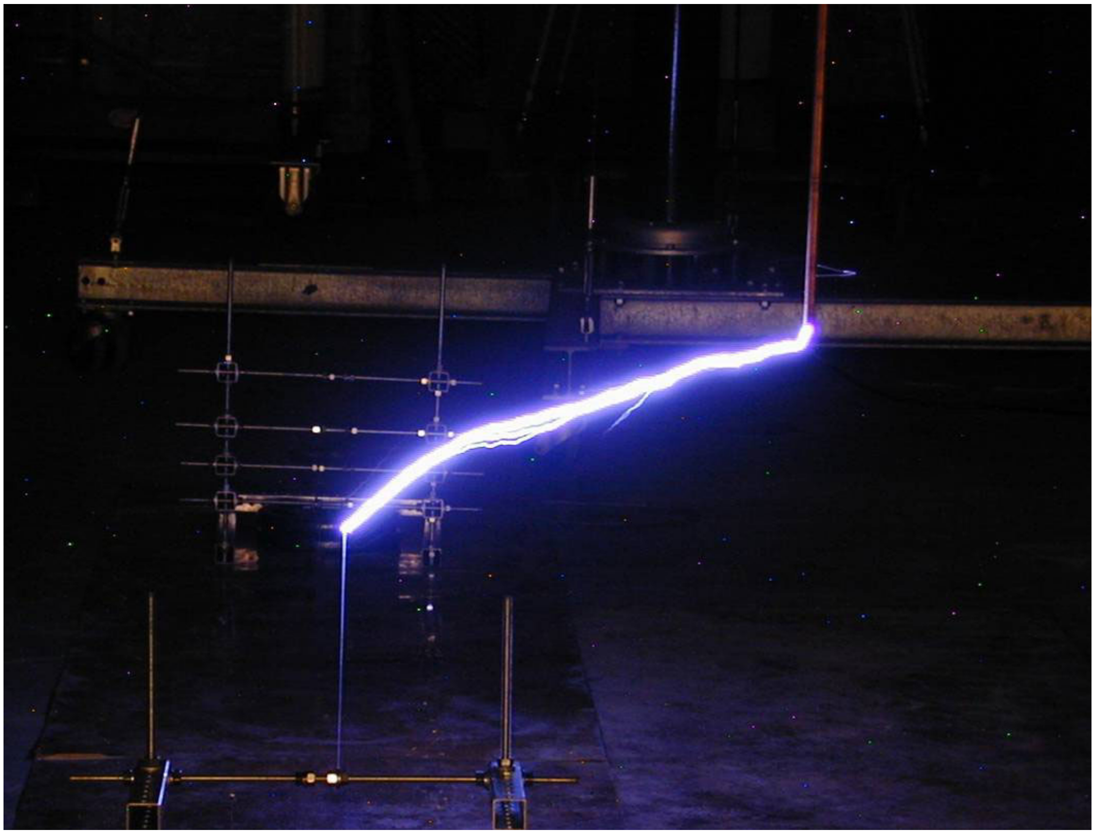


Figure 4.11 Flash to Tested Ground Wire during Experiment

In the studies, the lightning attractive width of a particular model configuration was based upon statistical results of experiments. Assuming the symmetry of both sides of a line model, only the attractive distance, the horizontal distance from an overhead ground wire to the energized rod, on one side was evaluated. For the selected height of h_g and H, the attractive distance, X, was changed gradually while a specified number of impulses were applied to the rod at each distance X. The number of flashes to the ground wire and to the ground was observed. As X decreased, more flashes terminated to the ground wire; on the other hand, as X increased, more flashes terminated to the ground. For each value of h_g and H, the obtained distance X was the distance at which flashes terminated to the ground wire or to the ground, on the equal probability.

The attractive width of transmission lines can be evaluated from that specific distance X. In total, 2,100 switching impulses were applied in order to study the attractive width of transmission lines.

Figure 4.12 presents an example of probability distribution of flashes to the overhead ground wire from the experiment of the 765-kV single-circuit horizontal transmission line (see Tables D.11, Appendix D). The ground wire height is 30.7 cm, and the energized rod height is 73 cm. The probability of flashes to the ground wire at distance X = 70, 80, 85, and 95 cm are shown with the approximated curve fitting. In order to avoid time consuming experiments, an interpolation could be done. From the curve, the attractive distance, X, the distance with 50% probability of flashes to line, is 75 cm, while from linear interpolation, X = 76 cm (error = 1.3%).

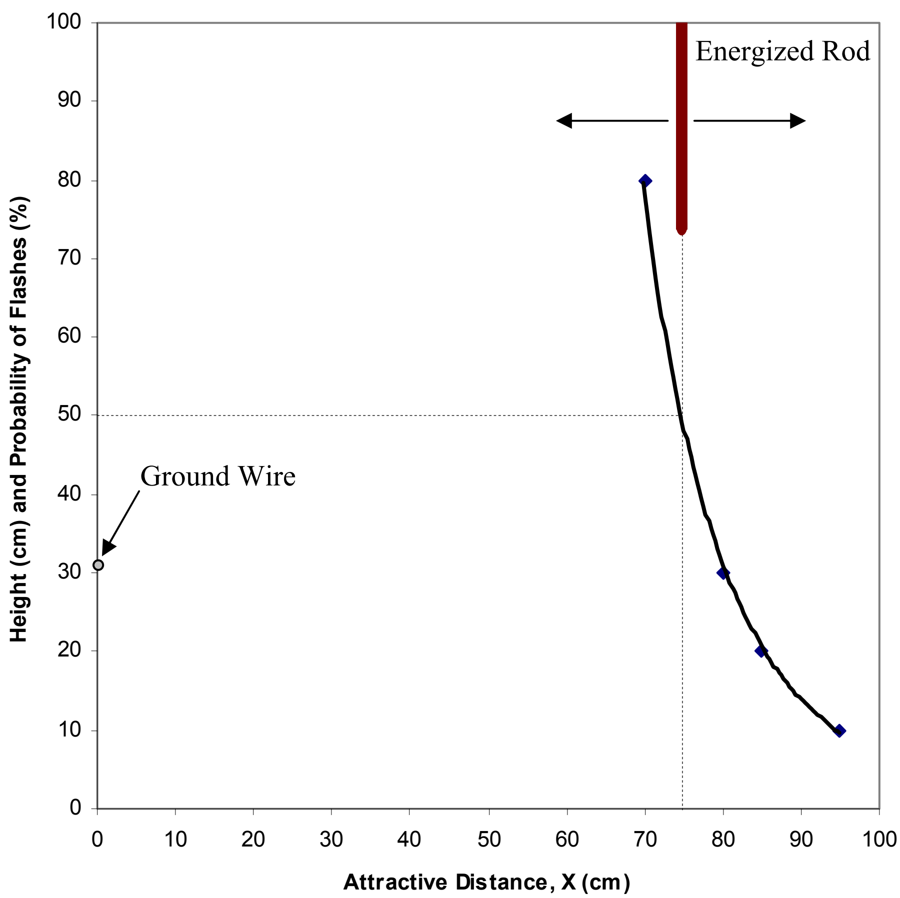


Figure 4.12 Probability Distribution of Flashes to Ground Wire for Different Distance X

In addition, another probable error caused by the number of applied impulses may occur. According to Figure 4.10, after n =10, the worst possible case is +/- 10% for the probability of flashes to the ground wire. However, as seen from Figure 4.12, error of 10% for the probability of flashes does not cause 10% error on the attractive distance. The error is just only +/- 2 cm from 75 cm, or +/- 2.7%, which is practically the very small error for high voltage experiments and can be neglected.

4.5 Summary

Experimental set-up, tested models, and test procedure for the evaluation of the lightning attractive width have been presented in the chapter. In total, 2,100 negative and positive switching impulses were applied for four laboratory experiments using seven tested models. Assuming the similarity between the real lightning and the simulated lightning, laboratory experiments could be the method to investigate the lightning incidence to transmission lines.

CHAPTER V

RESULTS OF LABORATORY EXPERIMENTS

5.1 Introduction

The measured data for different laboratory experiments are summarized and presented in this chapter. Detailed information of each experimental result can be found in Appendices A-H. Power curves fitting these experimental data with very small dispersion are also presented for better interpretation. First, switching impulse Critical Flashover (CFO) Voltage of a rod-plane gap and then results of all experiments are respectively presented. Some recorded photographs of flashes during experiments are also shown. Obtained results will be analyzed and used to develop mathematical expressions for the attractive width in the next chapter.

5.2 Critical Flashover Voltage of Rod-Plane Gap

The switching impulse critical flashover voltage tests under negative and positive polarity for a rod-plane gap with varied rod height, H, from 50-200 cm, were performed as reference values (see Appendix A). Table 5.1 presents the measured CFO voltages for both polarities, which agrees with the published data from other laboratories [11]. So, this agreement assured the accuracy of the generation and measurement system of the MSU High Voltage Laboratory. Test results are also presented in Figure 5.1 as a function of the rod height, H, above ground. In the latter experiments for attractive distance, the magnitude of applied impulse voltages for each specific rod height was 5% higher than the measured CFO voltages of a rod-plane gap.

Table 5.1 Switching Impulse CFO Voltage of Rod-Plane Gap

H (cm)	Negative CFO Voltage (kV)	Positive CFO Voltage (kV)
50	-807	264
60	-876	311
70	-955	360
80	-977	401
90	-1073	423
100	-1141	442
125	-	511
150	-	657
175	-	727
200	-	779

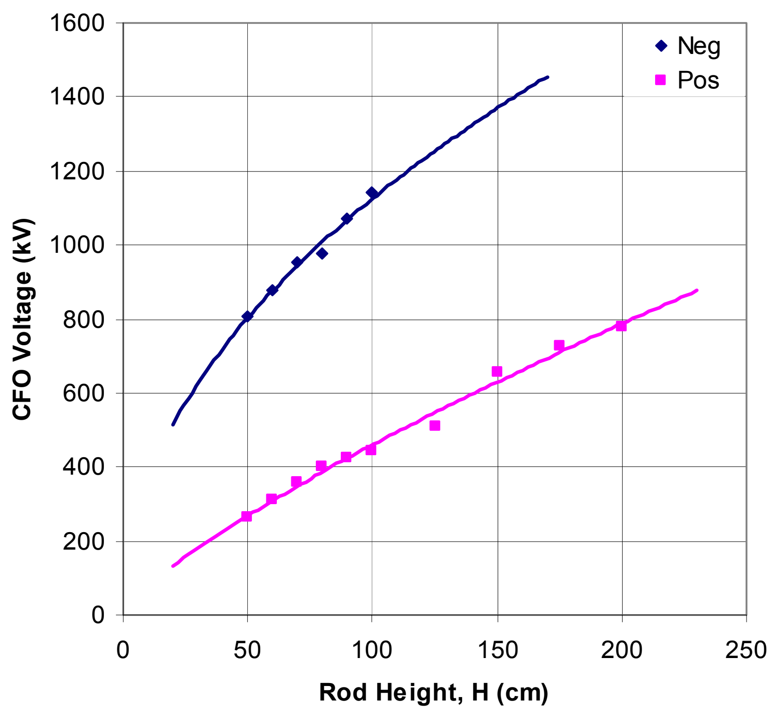


Figure 5.1 Switching Impulse CFO Voltages of Rod-Plane Gap

5.3 Attractive Distance of One Ground Wire

Table 5.2 provides the measured data from tests for one ground wire with H of 73 cm under negative and positive switching impulses (see Appendix B). The attractive distance, X, increased gradually as a function of the ground wire height, h_g.

Table 5.2 Measured Attractive Distance of One Ground Wire

h_g (cm)	X (cm)	
	Negative	Positive
10	48.8	30
20	65	41.7
30	76	52.5
40	80	56.7
50	84	61
60	89	61.7

The results show that the higher ground wire has the larger attractive distance as compared to the lower one. As shown in Figure 5.2, the attractive distance increases with the ground wire height. From these results, it is seen that the ground wire height influences the attractive distance for both polarities, and the attractive distance under positive polarity is approximately 70% of that under negative polarity.

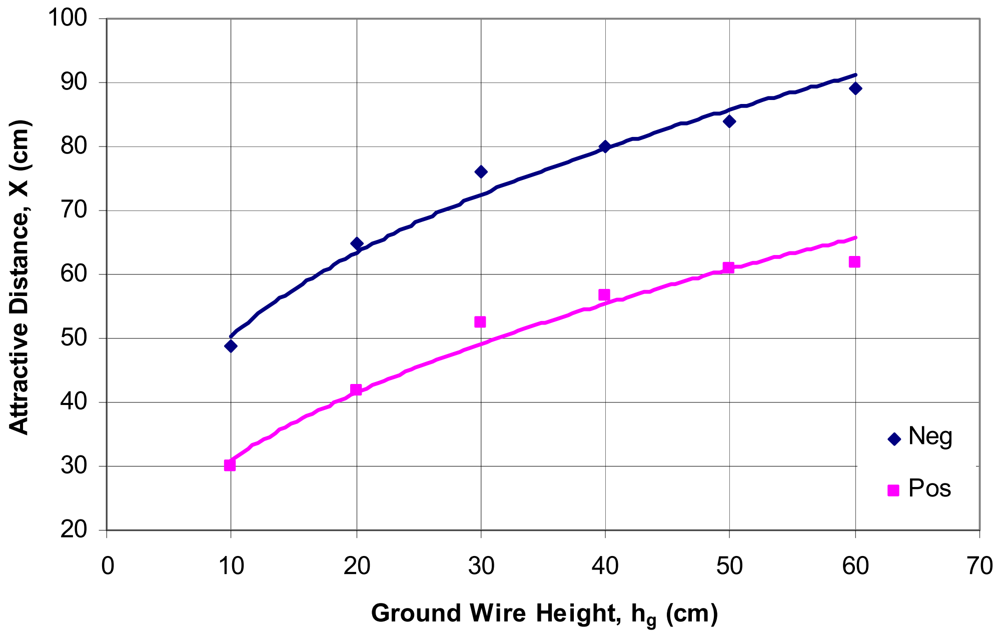


Figure 5.2 Measured Attractive Distance of One Ground Wire

5.4 Attractive Distance of Two Ground Wires

Table 5.3 provides the measured data from tests for two ground wires with H of 73 cm under negative and positive switching impulses (see Appendix C). The attractive distance, X, increased gradually as a function of the ground wire height, h_g, only. The ground wire separation width, b, practically did not show the major impact to the attractive distance. Some deviation of test results with varied ground wire separation width could be the result of statistical error in the experiments, which is a common issue of high voltage testing. Therefore, the attractive distance of one ground wire is reasonably enough to calculate the attractive with of transmission lines with two overhead ground wires by just adding the ground wire separation width.

Table 5.3 Measured Attractive Distance of Two Ground Wires

h_g (cm)	Negative				
	b = 10 cm	b = 20 cm	b = 30 cm	b = 40 cm	b = 50 cm
10	54	-	-	-	
20	66.5	62	-	-	-
30	76.85	71	77	-	-
40	83.5	83	86	82	-
50	83.7	82.3	88	88	86
h_g (cm)	Positive				
	b = 10 cm	b = 20 cm	b = 30 cm	b = 40 cm	b = 50 cm
10	29.3	-	-	-	-
20	43.3	42.5	-	-	-
30	53	52	47	-	-
40	57.5	52.9	55	55.5	-
50	62	62	57.9	60	57

The obtained results show that the higher ground wires have the larger attractive distance as compared to the lower ones. As shown in Figure 5.3, the attractive distance of two ground wires increases with the ground wire height like that of one ground wire. From these results, it is seen that the ground wire height influences the attractive distance for both polarities, and the attractive distance under positive polarity is approximately 70% of that under negative polarity.

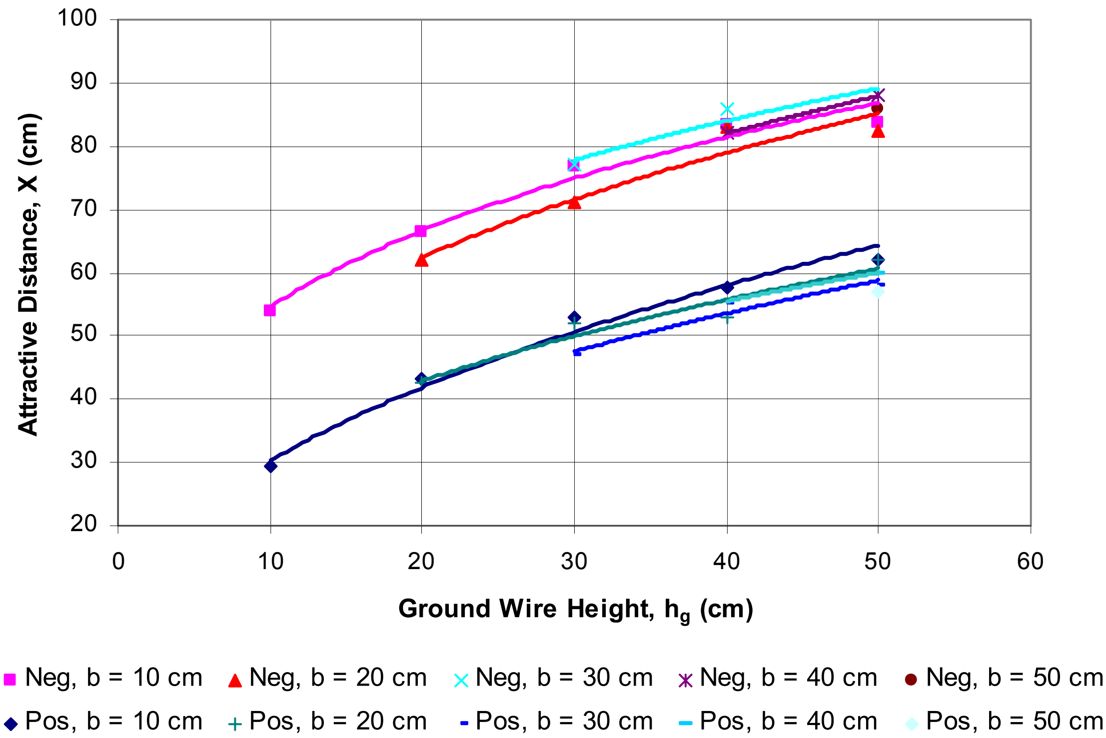


Figure 5.3 Measured Attractive Distance of Two Ground Wires

5.5 Attractive Distance of Single-Circuit Horizontal Transmission Lines

Table 5.4 provides the measured data from tests for single-circuit horizontal line models under negative and positive switching impulses (see Appendix D). The attractive distance, X, increased gradually as a function of the ground wire height, h_g and the rod height, H. There was no impact from the presence phase conductors.

The obtained results show that the higher ground wire has the larger attractive distance as compared to the lower one. As shown in Figure 5.4, the attractive distance increases with the ground wire height and the rod height. From these results, it is seen that the ground wire height and the rod height influence the attractive distance for both polarities, and the attractive distance under positive polarity is approximately 70% of that under negative polarity.

Table 5.4 Measured Attractive Distance of Tested Models of Single-Circuit Horizontal Line Configurations

Transmission Line	h_g (cm)	H (cm)	X (cm), Neg.	X (cm), Pos.
230-kV Line	18	56	55.3	36.3
		73	63.3	42.6
		101.7	82.8	46.2
345-kV Line	22.2	56	58.3	39.3
		73	65.3	50
		101.7	82.6	54.3
500-kV Line	24.3	56	56.2	42.7
		73	71.2	48.9
		101.7	87.7	52.7
765-kV Line	30.7	56	59	47.5
		73	76	53.5
		101.7	89	65
1100-kV Line	40	56	68.1	53.1
		73	83.1	56.9
		101.7	93.1	68.1

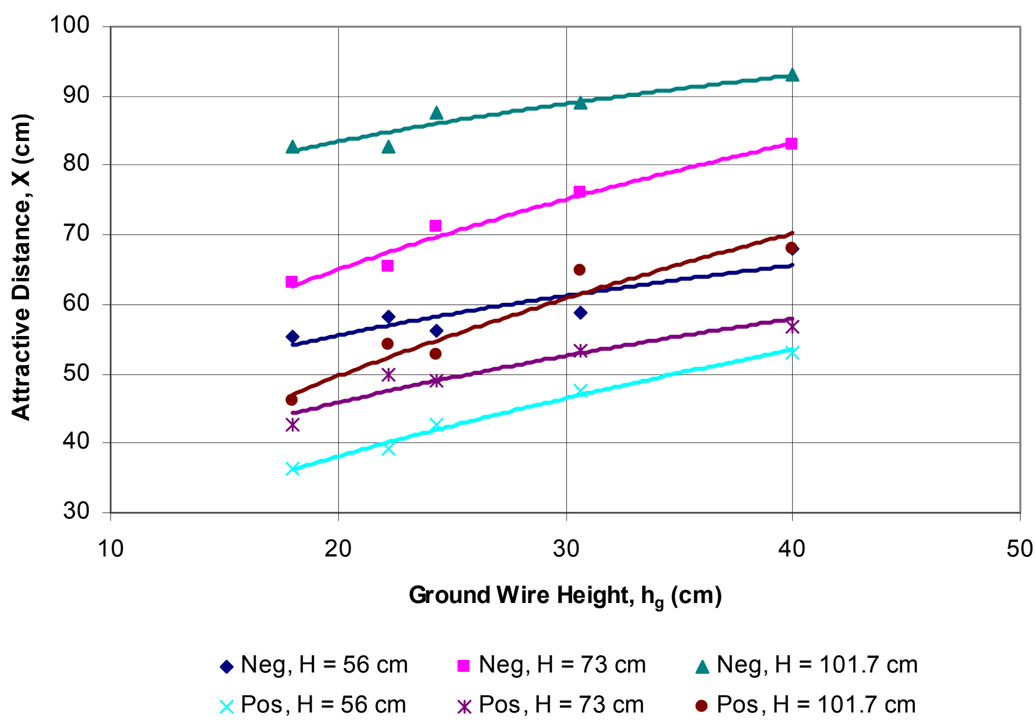
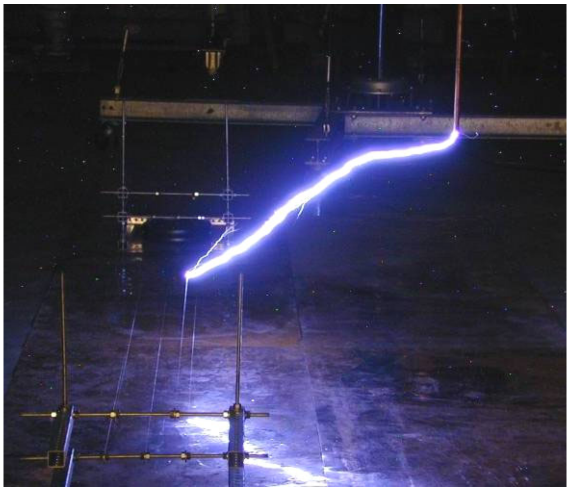
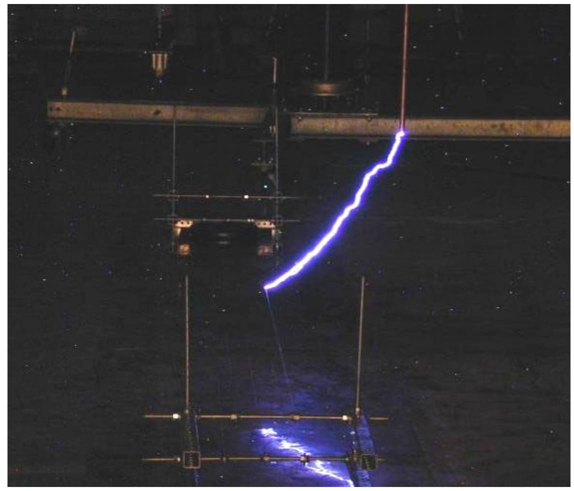


Figure 5.4 Measured Attractive Distance of Tested Models of Single-Circuit Horizontal Line Configurations

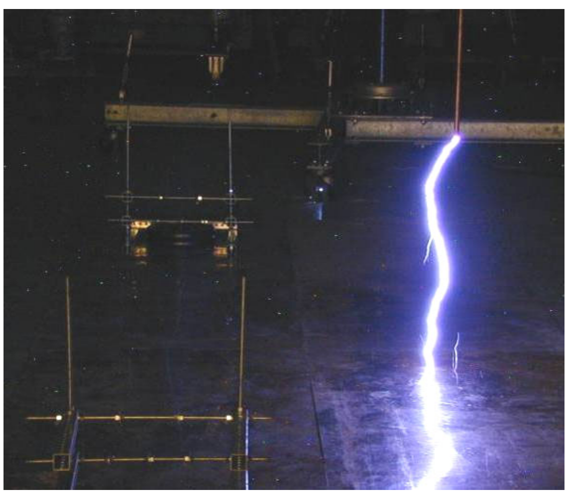
Figure 5.5 shows flashes to a single-circuit horizontal transmission line model, as observed during the laboratory study. For a specific test set-up, with a selected distance X, the flashes attached to the transmission line or to the ground, with equal probability.



(a) Flash to the line, negative polarity
H = 73 cm, h_g = 24.3 cm, X = 87.7 cm



(b) Flash to the line, positive polarity
H = 73 cm, h_g = 24.3 cm, X = 48.2 cm



(c) Flash to the ground, negative polarity
H = 73 cm, h_g = 24.3 cm, X = 87.7 cm

(d) Flash to the ground, positive polarity
H = 73 cm, h_g = 24.3 cm, X = 48.2 cm

Figure 5.5 Flashes to Single-Circuit Horizontal Line Model

5.6 Attractive Distance of Double-Circuit Vertical Transmission Lines

Table 5.5 provides the measured data from tests for double-circuit vertical line models under negative and positive switching impulses (see Appendix E). The attractive distance, X, increased gradually as a function of the ground wire height, h_g and the rod height, H. There was no impact from the presence of phase conductors.

Table 5.5 Measured Attractive Distance of Tested Models of Double-Circuit Vertical Line Configurations

Transmission Line	h_g (cm)	H (cm)	X (cm), Neg.	X (cm), Pos.
230-kV Line	26.3	56	65.6	45.4
		73	67.3	50
		101.7	74.8	50.4
345-kV Line	37.8	56	68	49
		73	73	60.5
		101.7	91	71
500-kV Line	40.7	56	72	49
		73	87	63.8
		101.7	108.7	66.5
765-kV Line	55	56	85.5	49.1
		73	88.8	65.5
		101.7	110.5	75.5

The obtained results show that the higher ground wire has the larger attractive distance as compared to the lower one. As shown in Figure 5.6, the attractive distance for double-circuit vertical line increases with the ground wire height and the rod height like that for single-circuit horizontal line. From these results, it is seen that the ground wire height and the rod height influence the attractive distance for both polarities. The attractive distance under positive polarity is approximately 70% of that under negative polarity.

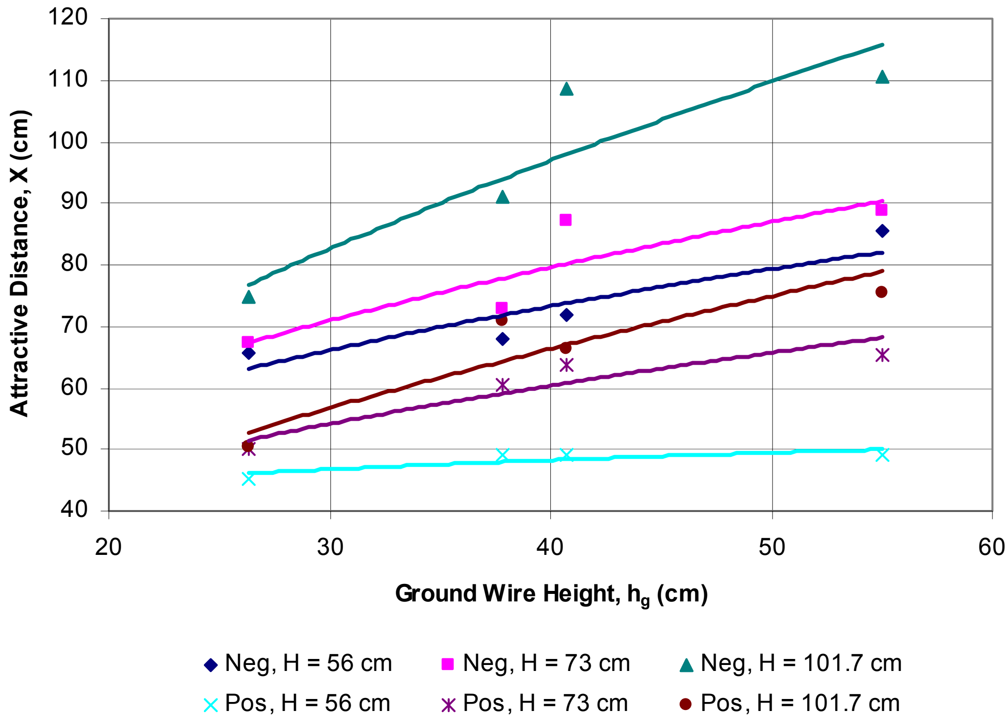
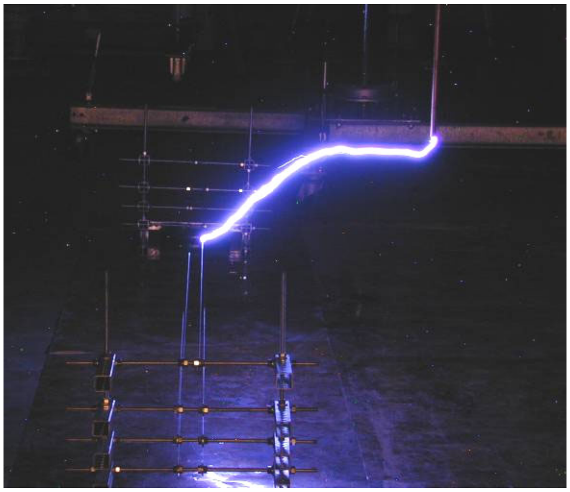
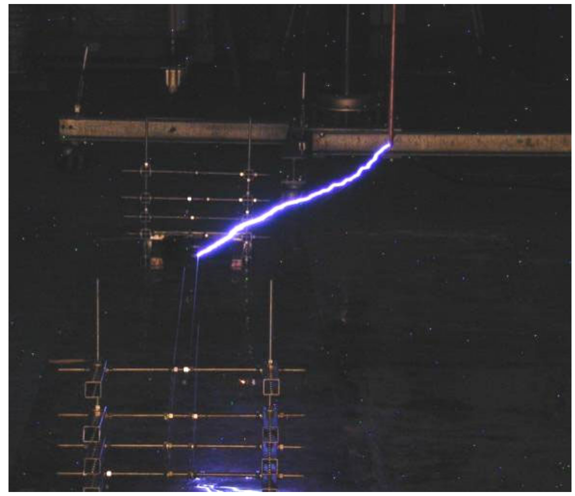


Figure 5.6 Measured Attractive Distance of Tested Models of Double-Circuit Vertical Line Configurations

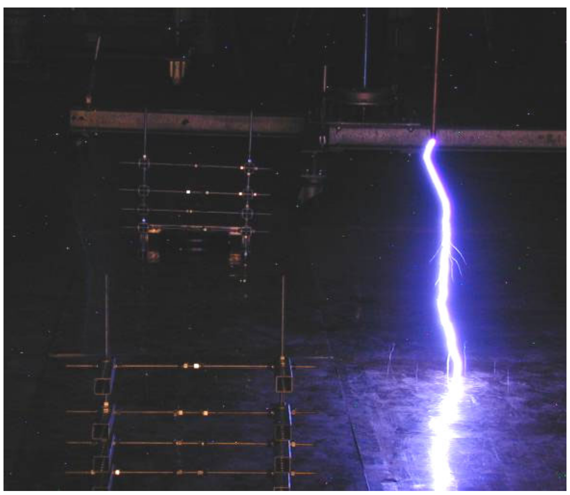
Figure 5.7 shows flashes to a double-circuit vertical transmission line model, as observed during the laboratory study. For a specific test set-up, with a selected distance X, the flashes attached to the transmission line or to the ground, with equal probability.



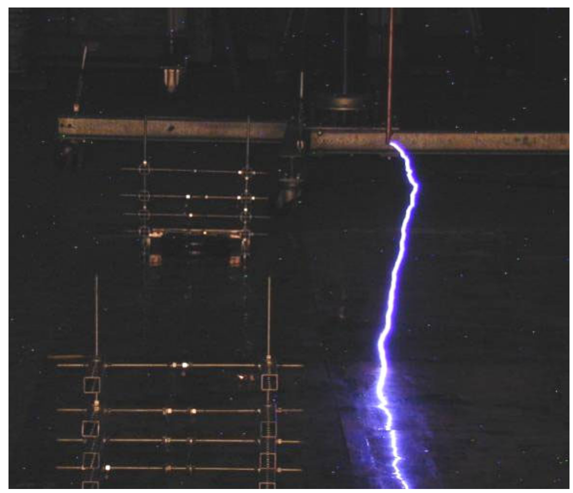
(a) Flash to the line, negative polarity
H = 73 cm, h_g = 37.8 cm, X = 73 cm



(b) Flash to the line, positive polarity
H = 73 cm, h_g = 37.8 cm, X = 62 cm



(c) Flash to the ground, negative polarity
H = 73 cm, h_g = 37.8 cm, X = 73 cm



(d) Flash to the ground, positive polarity
H = 73 cm, h_g = 37.8 cm, X = 62 cm

Figure 5.7 Flashes to Double-Circuit Vertical Line Model

5.7 Attractive Radius of Vertical Rod

Table 5.6 provides the measured data from tests for a vertical rod with H of 73 cm under negative and positive switching impulses (see Appendix F). The attractive radius, R, increased gradually as a function of the rod height, h_r.

Table 5.6   Measured Attractive Radius of Vertical Rod

h_r (cm)	R (cm)	
	Negative	Positive
20	67	40
30	82	45
40	91	49
50	96	52
60	109	54

The obtained results show that the taller rod has the larger attractive radius as compared to the shorter one. As shown in Figure 5.8, the attractive radius increases with the rod height. From these results, it is seen that the rod height influences the attractive radius for both polarities. The attractive radius under positive polarity is approximately 55% of that under negative polarity.

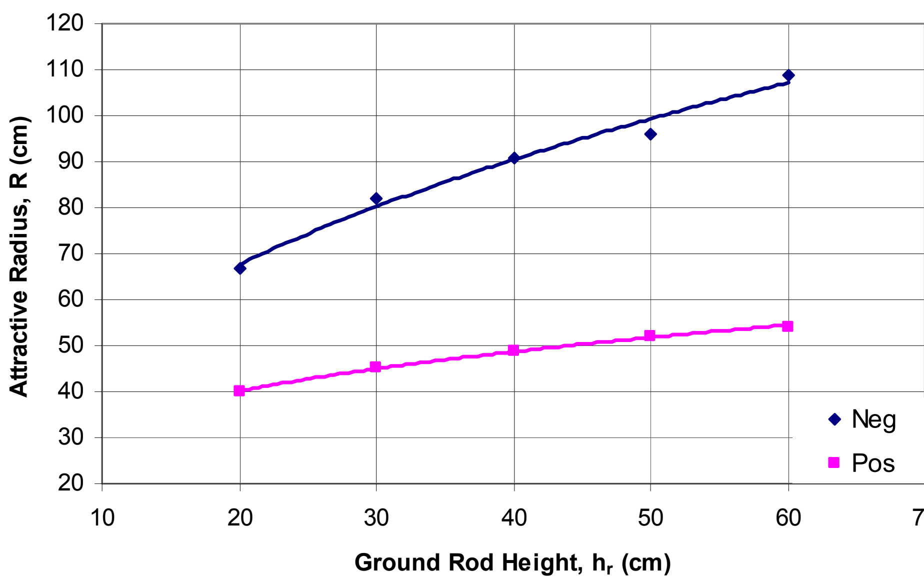


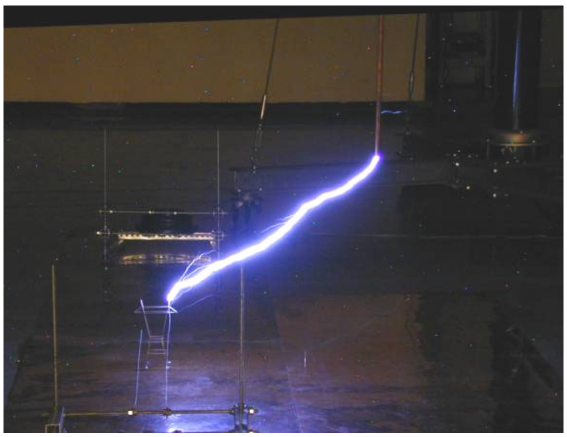
Figure 5.8   Measured Attractive Radius of Vertical Rod

5.8 Attractive Distance of Transmission Line Towers

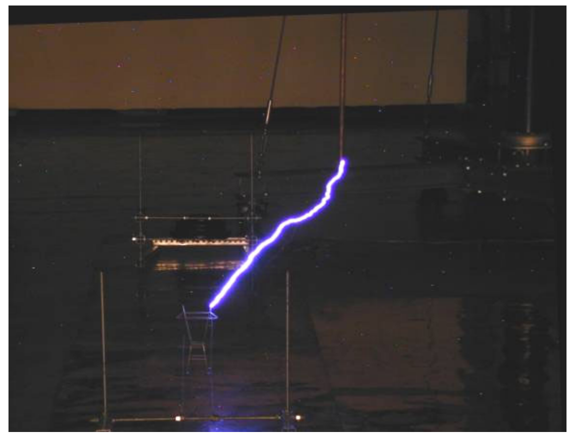
Table 5.7 provides the measured data from tests for transmission line towers with H of 73 cm under negative and positive switching impulses (see Appendix G). The attractive distance, X, increased gradually as a function of the tower height h_t. The obtained results show that the taller tower has the larger attractive distance as compared to the shorter one. Figure 5.9 shows flashes to the model of a 230-kV single-circuit transmission tower, as observed during the experiments.

Table 5.7 Measured Attractive Distance of Transmission Line Towers

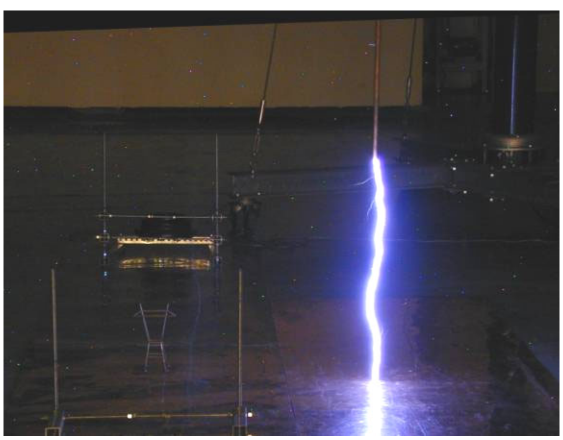
Case	Transmission Line Tower	X (cm)	
		Negative	Positive
1	1-cct horizontal 230-kV Line	69.8	45
2	2-cct vertical 765-kV Line	104	62.5



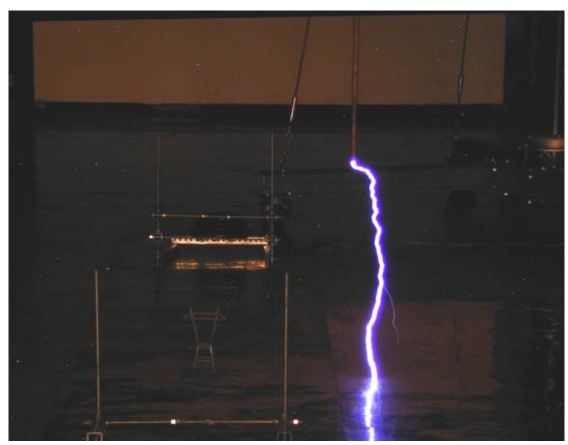
(a) Flash to the tower, negative polarity
$H = 73$ cm, $h_t = 23.5$ cm, $X = 69.8$ cm



(b) Flash to the tower, positive polarity
$H = 73$ cm, $h_t = 23.5$ cm, $X = 45$ cm



(c) Flash to the ground, negative polarity
$H = 73$ cm, $h_t = 23.5$ cm, $X = 69.8$ cm



(d) Flash to the ground, positive polarity
$H = 73$ cm, $h_t = 23.5$ cm, $X = 45$ cm

Figure 5.9 Flashes to Model of 230-kV Single-Circuit Transmission Tower

For a specific test set-up, with a selected distance X, the flashes attached to the tower or to the ground with equal probability. The attractive distance under positive polarity is approximately 60% of that under negative polarity.

5.9 Distribution of Flashes to Transmission Lines

Table 5.8 provides the measured data from tests for the models of transmission lines with H* of 91.2 cm under negative and positive switching impulses (see Appendix H). The lengthwise attractive distance, Y, (see Figure 4.8) increased gradually with the increase of the tower height, h_t. The percentage ratio of total attractive distance (twice of Y) per span length was calculated and presented in the bracket in order to show the contribution of towers and overhead ground wires on flash distribution to a transmission line.

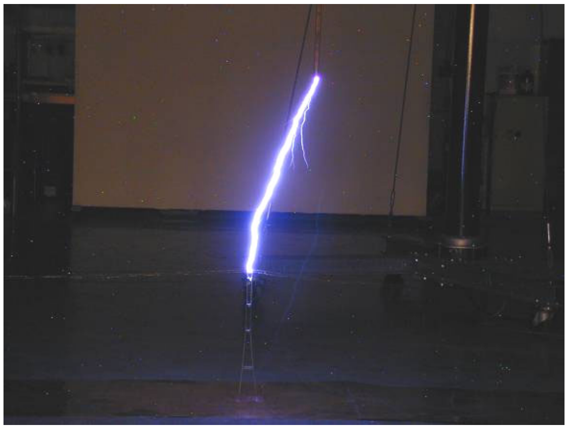
For the case of a single-circuit horizontal 230 kV transmission line under positive polarity, the attractive distance was not available because flashes rarely occurred on the tower. As shown in Table H.5, Appendix H, which is the case that the energized rod was exactly above the tower, less than 50% of flashes occurred on the tower. Thus, unlike all other experiments, the lengthwise attractive distance, Y, could not be evaluated.

Table 5.8 Measure Lengthwise Attractive Distance of Towers and Distribution of Flashes

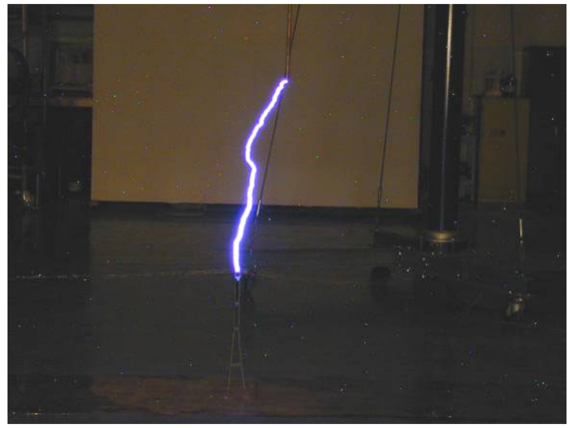
Case	Transmission Line	Y (cm)	
		Negative	Positive
1	1-cct horizontal 230-kV Line	20 (*16%)	N/A
2	2-cct vertical 765-kV Line	29 (*19%)	15 (*10%)

* Represents the percentage ratio of total attractive distance per span length

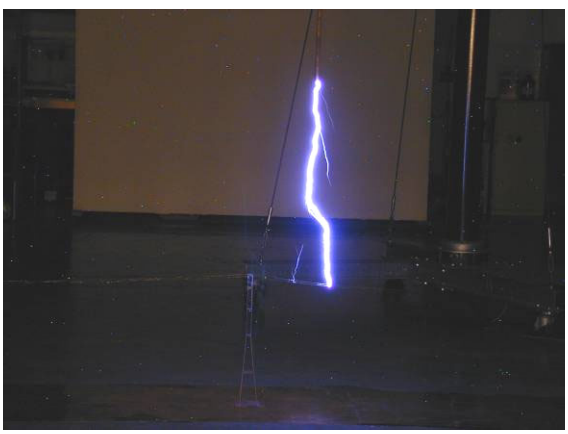
The obtained results showed that the taller tower had the larger lengthwise attractive distance as compared to the shorter one. This also means the taller tower has more effect on the distribution of lightning flashes. Figure 5.10 shows flashes to the model of a 765-kV double-circuit vertical transmission line, as observed during the laboratory study.



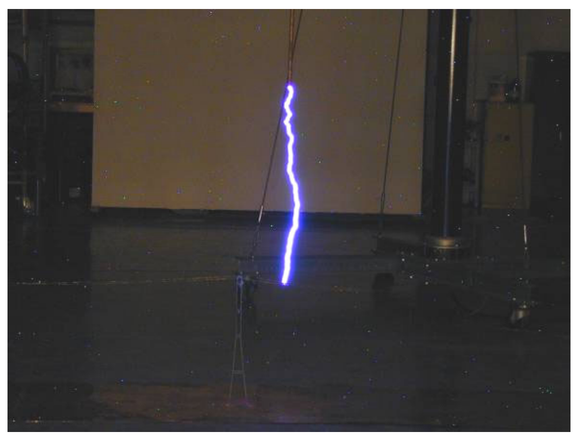
(a) Flash to the tower, negative polarity
$H^* = 91.2$ cm, $h_t = 61$ cm, $Y = 29$ cm



(b) Flash to the tower, positive polarity
$H^* = 91.2$ cm, $h_t = 61$ cm, $Y = 15$ cm



(c) Flash to the ground wire, negative polarity
$H^* = 91.2$ cm, $h_t = 61$ cm, $Y = 29$ cm



(d) Flash to the ground wire, positive polarity
$H^* = 91.2$ cm, $h_t = 61$ cm, $Y = 15$ cm

Figure 5.10 Flashes to Model of 765-kV Double-Circuit Transmission Line

5.10 Summary

All of the experimental results for attractive distance have been presented. The attractive distance increased gradually with the height of overhead ground wires or towers as well as the energized rod, corresponding to the magnitude of the lightning stroke current. Impulse polarity had an impact, and the attractive distance for negative polarity was larger than that for positive polarity. This was clearly observed in recorded photographs of flashes. The ground wire separation width and phase conductors practically did not show a major impact, so the attractive distance of one ground wire could be used to calculate the attractive width of transmission lines with one or two overhead ground wires. The taller tower had more effect on flash distribution to transmission lines than the shorter one.

CHAPTER VI

ANALYSIS AND DISCUSSION

6.1 Introduction

The experimental results are analyzed and discussed in this chapter. The observed impact of the ground wire height, the tower height, the energized rod height, and the polarity of impulses are individually analyzed by using the concept of the electric field and lightning discharge. According to the results, mathematical expressions for the attractive width are developed for practical use of electric power utilities. The attractive width based on this study is verified with the one based on different methods by other researchers. Finally, the estimation of the attractive width is validated with the published transmission line observations.

6.2 Ground Wire Height

At the final step of lightning attachment, the electric field distribution around the overhead ground wire, induced by an approaching downward leader, is the vital part of this impact. If the induced electric field varying with the ground wire height reaches the critical value, an upward leader initiates and propagates toward the downward leader. Therefore, the ground wire height affects the criterion needed for the inception of an upward leader.

As seen from the experimental results, the presence of another ground wire practically did not have a significant impact. Thus, the experimental results of one ground wire, with the energized rod height equal to 73 cm that corresponds with the median lightning stroke of 30 kA, yield the following expressions for negative and positive polarity, respectively:

$$X = 23.58 h_g^{0.33} \qquad (6.1)$$

$$X = 11.85 h_g^{0.42} \qquad (6.2)$$

The estimated attractive distances found by using these expressions are presented in Figure 6.1 and compared to the combined experimental results of the attractive distances for both single-circuit horizontal and double-circuit vertical transmission line models, using only conducting wires without towers. For negative polarity, the attractive distance from expression 6.1 is very close to that from experimental results of both line configurations. For positive polarity, the attractive distance from expression 6.2 has some deviation from that of the experimental results of both line configurations. Again, this could be the result of the statistical error in laboratory experiments.

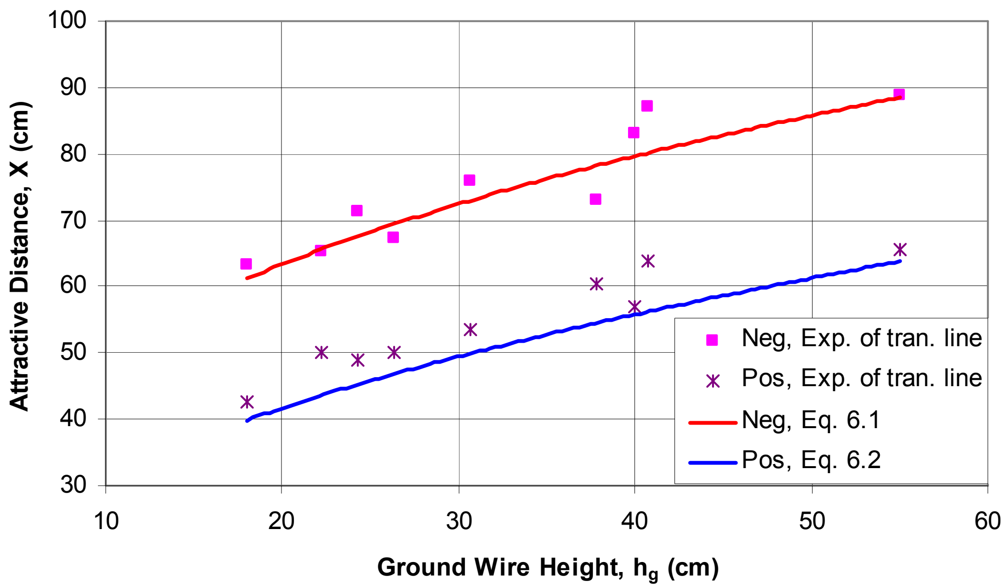


Figure 6.1 Attractive Distance by Expressions and Experimental Results of Both Transmission Line Configurations

Figure 6.2 shows the attractive distances for both single-circuit horizontal and double-circuit vertical transmission line models with different rod heights corresponding to the lightning stroke current. It is seen that the attractive distance of transmission lines increases with the ground wire height for all cases of the lightning stroke current. Along with the ground wire height, the lightning stroke current also has an impact, and this is discussed later.

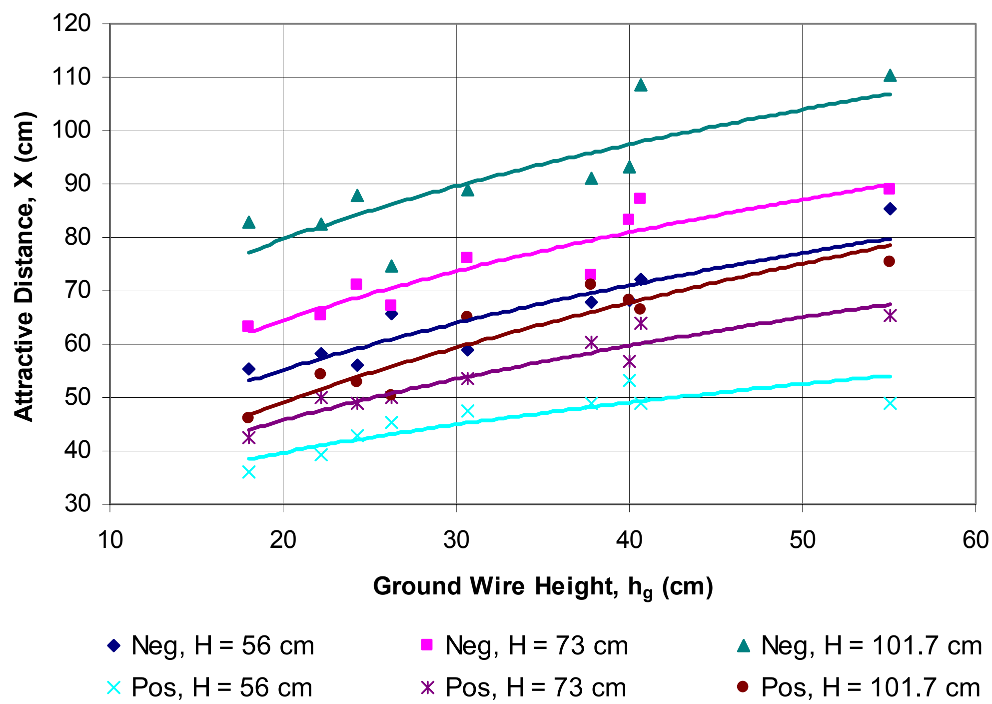


Figure 6.2 Attractive Distance from Experimental Results of Both Transmission Line Configurations with Different Rod Height

For verification purposes, the estimated attractive distance from this study is compared to those based on different methods by other researchers [15, 26], as shown in Figure 6.3. Values of the attractive distance and ground wire height are scaled up into meters. Only the attractive distance under negative polarity, which is the frequent polarity of lightning strokes, is used for comparison. It is seen that the attractive distance evaluated from this study reasonably correlates with the others, especially Mousa and Srivastava's model [22].

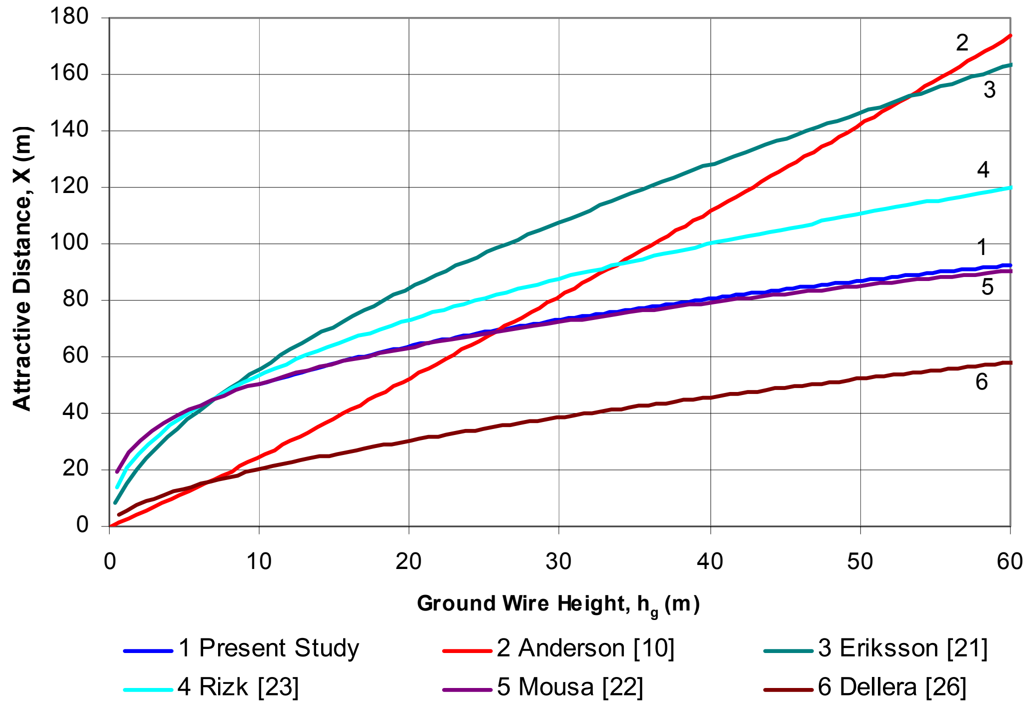


Figure 6.3 Attractive Distance from Different Methods

6.3 Tower Height

Similar to the case of the ground wire height, the electric field distribution around the tip of a tower, induced by an approaching downward leader, is the vital part of this impact. If the induced electric field varying with the tower height reaches the critical value, an upward leader initiates and propagates toward the downward leader. Therefore, the tower height affects the criterion needed for the inception of an upward leader. However, the electric field at a tower tip, which has the shape of a protruding sharp point, is different than one around an overhead ground wire, which has a smoother shape. This will cause a different impact on the attractive distance of a tower and a ground wire.

From the experimental results, the attractive radius of a rod is compared to the attractive distance of a ground wire, as presented in Figure 6.4. For negative polarity, the attractive radius is larger than the attractive distance, but for positive polarity, the attractive radius is smaller than the attractive distance. The percentage ratio of the attractive distance and the attractive radius drops from 97% to 82% for negative polarity and that of the attractive radius and the attractive distance drops from 96% to 88% for positive polarity.

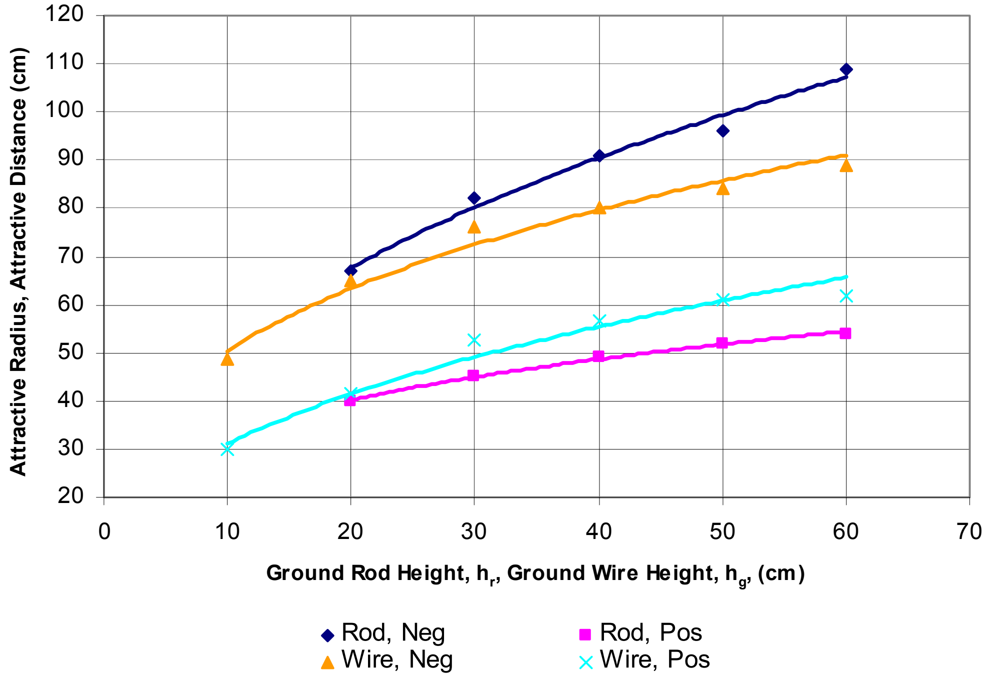


Figure 6.4 Attractive Radius of Rod and Attractive Distance of Wire

Thus, the experimental results of a vertical rod, with the energized rod height equal to 73 cm that corresponds with the median lightning stroke of 30 kA, yield the following expressions for negative and positive polarity, respectively:

$$R = 19.33 h_r^{0.42} \quad (6.3)$$

$$R = 17.56 h_r^{0.28} \quad (6.4)$$

Moreover, the estimated attractive radius found by using expressions 6.3 and 6.4 and the estimated attractive distance found by using expressions 6.1 and 6.2 are compared to the measured attractive distances of two transmission tower models from the experimental results, presented in Figure 6.5. It is seen that for negative polarity the attractive distances of tower models correlates with the values estimated by expression 6.3, and for positive polarity the attractive distances of tower models do not correlate with expression 6.4; they correlate with expression 6.2 instead. It is interesting to note that for a complex structure like a tower tip, from which an overhead ground wire is suspended, a tower has more contribution for negative polarity, but a ground wire has more contribution for positive polarity.

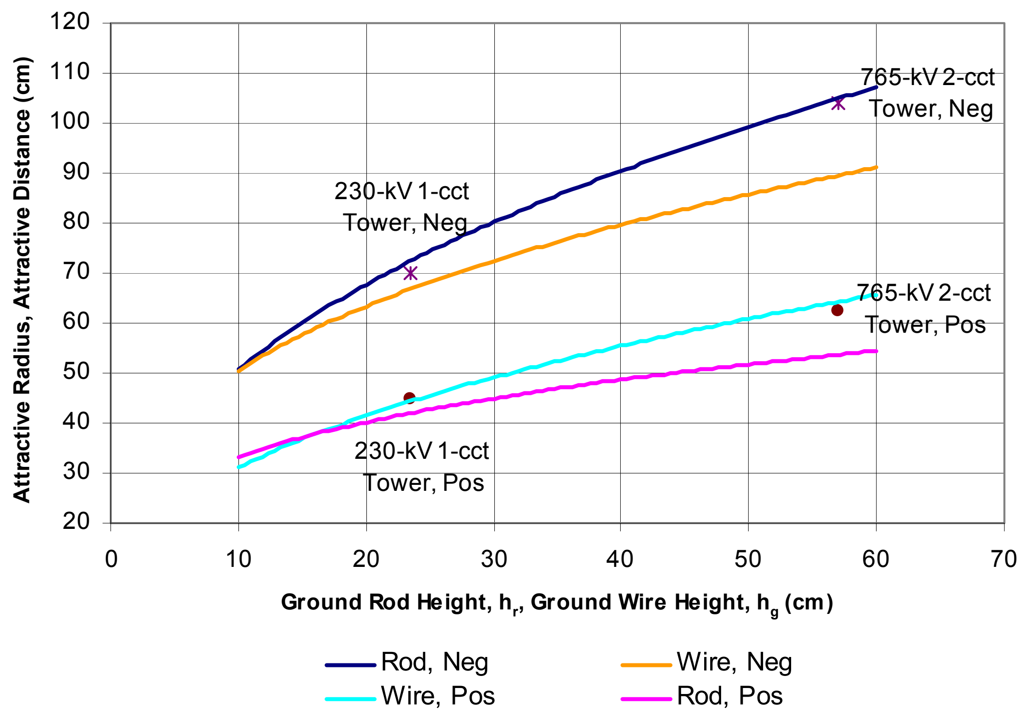


Figure 6.5 Attractive Radius of Rod, Attractive Distance of Wire, and Attractive Distance of Tower Models

For verification purposes, the estimated attractive radius from this study is compared to those based on different methods by other researchers [26], as shown in Figure 6.6. Values of the attractive radius and rod height are scaled up into meters. Only the attractive radius under negative polarity, which is the frequent polarity of lightning strokes, is used for comparison. It is seen that the attractive radius evaluated in this study reasonably correlates with the others.

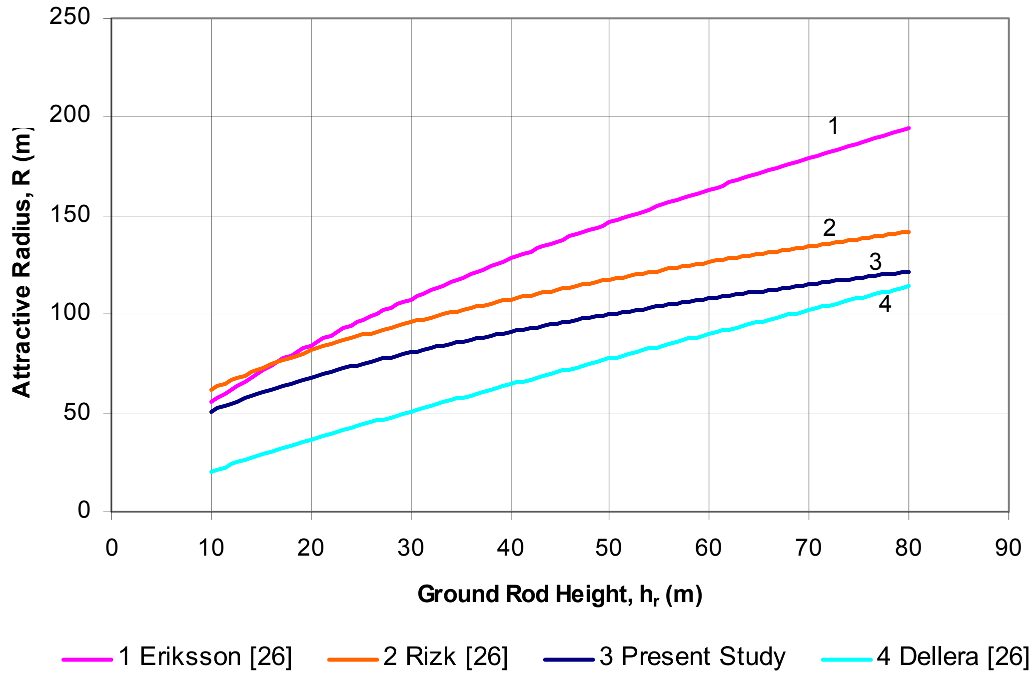


Figure 6.6 Attractive Radius from Different Methods

6.4 Contribution of Tower and Overhead Ground Wire

As for the different attractiveness to lightning, the contribution or proportion of overhead ground wires and towers to the attractive width of a transmission line is now considered. The experimental result of the distribution of flashes to transmission line models has given some indications in order to evaluate the probable lightning flashes to various parts of a transmission line. The ratios of the total lengthwise attractive distance of towers per span length from the experimental results (Table 5.8) are compared to the published information for observations [37-39] of the ratio of lightning flashes to the towers per total lightning flashes to the lines, presented in Table 6.1. Only the values of the experimental results under negative polarity are used for comparison. It is observed that the experimental results from this study are in satisfactory agreement with observational results of actual transmission lines. In Figure 6.7, experimental data are also compared to observational data with the approximated trend line.

Table 6.1 Distribution of Flashes to Transmission Line Towers

Source	Tower Height (m)	Percentage Ratio
Experiment 1 (230 kV Tower)	23.5	16%
Experiment 2 (765 kV Tower)	61	19%
HV Lines [37]	22.2	14%
345 kV Line [38]	45	20%
500 kV Line [39]	100	17%
UHV Line [39]	140	25%

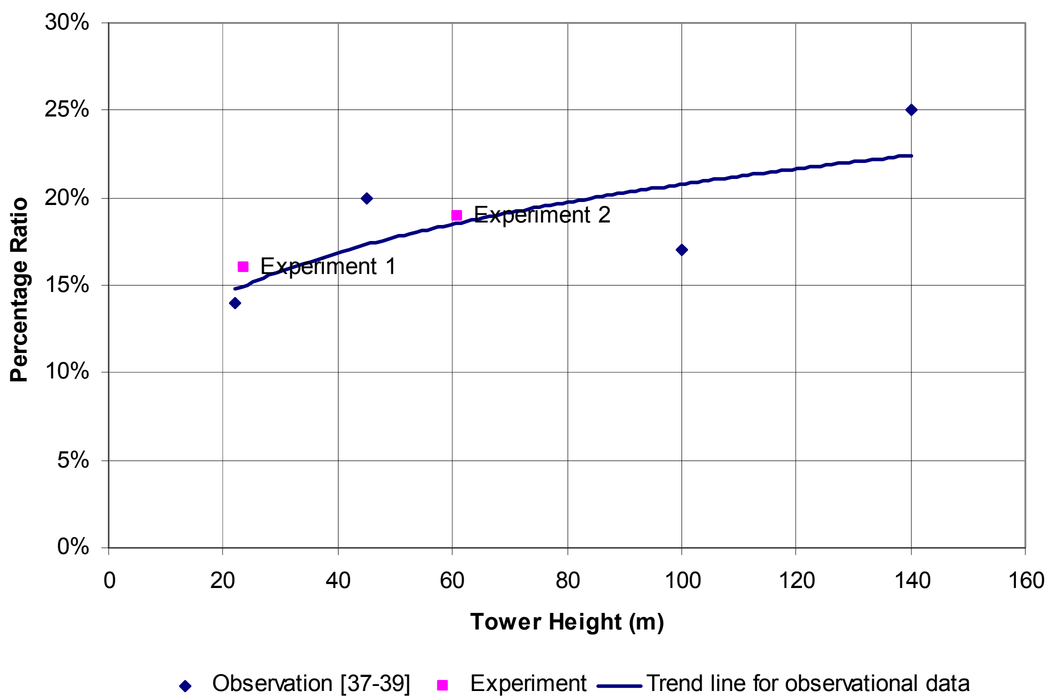


Figure 6.7 Percentage of Lightning Flashes to Towers from Observations and Experiments

As shown in the figure 6.7, the percentage ratio of lightning flashes to towers tends to increase with tower height, but the number of observations is not enough to draw conclusions. Therefore, the simplified percentage values of 20% for towers and 80% for overhead ground wires can be used for practical calculation of the attractive width. Also, because of the lack of enough data, the conclusion for positive polarity could not be drawn. However, the approximated values of 10% for towers and 90% for overhead ground wires may be used.

6.5 Polarity of Lightning Strokes

As for the difference in the breakdown mechanism of air in a long gap under different polarities, it is expected that the results under positive polarity will differ from those under negative polarity [6]. According to the experimental results for ground wires and towers, the attractive distance of transmission lines for negative polarity is larger than that for positive polarity. Therefore, a transmission line encounters a much lower number of positive lightning strokes compared to negative lightning strokes. This is explained by the polarity effect on the breakdown mechanisms. For the case of negative lightning, when a negative downward leader approaches a transmission line, a positive upward leader initiates from the tower or the ground wire. Then, both leaders meet at some position in the final jump of lightning attachment, called the striking distance. For the case of positive lightning, the breakdown mechanism is different. A positive downward leader approaches a transmission line and propagates mostly across the striking distance.

The foregoing analysis for polarity effects on the attractive distance can be applied to the results of the distribution of flashes as well. For the case of negative lightning, an approaching negative downward leader induces positive polarity on the tower tip and the overhead ground wire. If the induced electric field reaches the critical value, the positive upward leaders will initiate from the tower tip and the overhead ground wire. At this moment, the positive upward leader from the tower competes with the one from the overhead ground wire, and the winning leader intercepts the negative downward leader and completes the lightning attachment. For the case of positive lightning, the mechanism is again different. The space charges caused by an approaching positive downward leader smooth the electric field around the tower tip and consequently reduce the probability of lightning flashes to the tower. This concept is widely discussed in the research on lightning physics and lightning protection [29, 35, 40].

6.6 Lightning Return Stroke Current

Eventually, the magnitude of the lightning return stroke current is the most significant factor for the attractive distance of ground wires and towers. The return stroke current, which is proportional to the charge and also potential at the downward leader tip, mainly has an impact on the final jump of lightning attachment [17]. The extrapolated trend lines for the experimental results of transmission line models, each with different rod height corresponding to lightning return stroke currents, are presented again in Figs. 6.8 and 6.9 in order to show a clear picture of the impact of the lightning stroke current. It is seen that the attractive distance of a transmission line increases not only with the ground wire height but also with the lightning stroke current. Therefore, a transmission line with the route through a region with the higher lightning stroke current (median value = 30 kA) will have the larger attractive distance. This point has never been considered by transmission line designers.

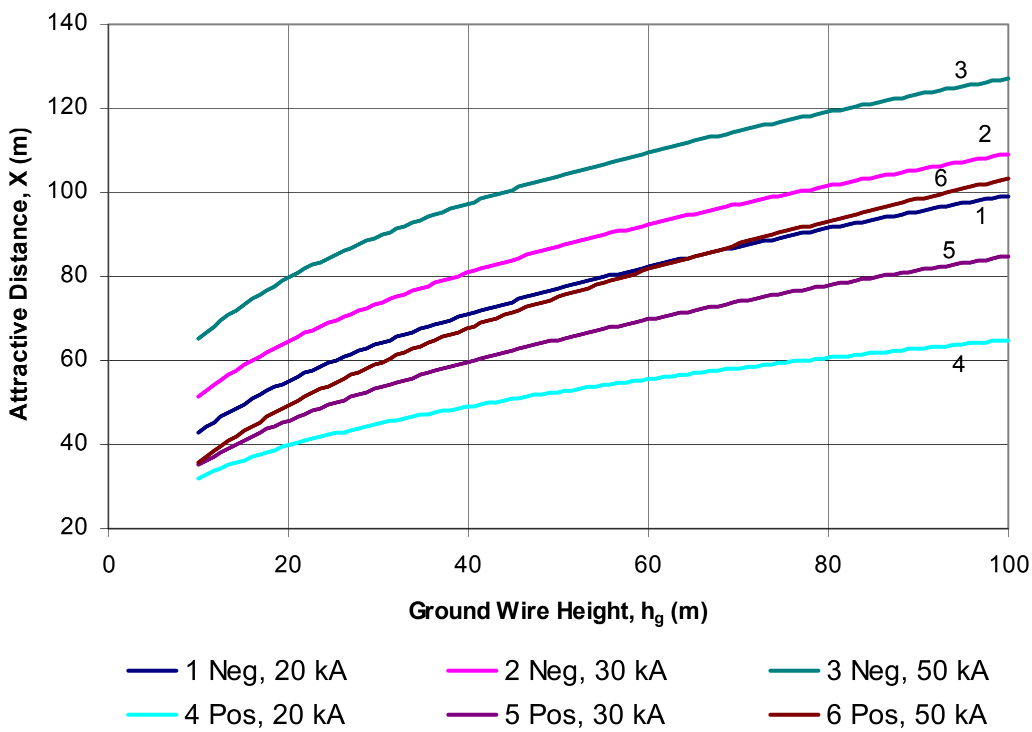


Figure 6.8 Attractive Distance of Transmission Line with Different Lightning Stroke Current

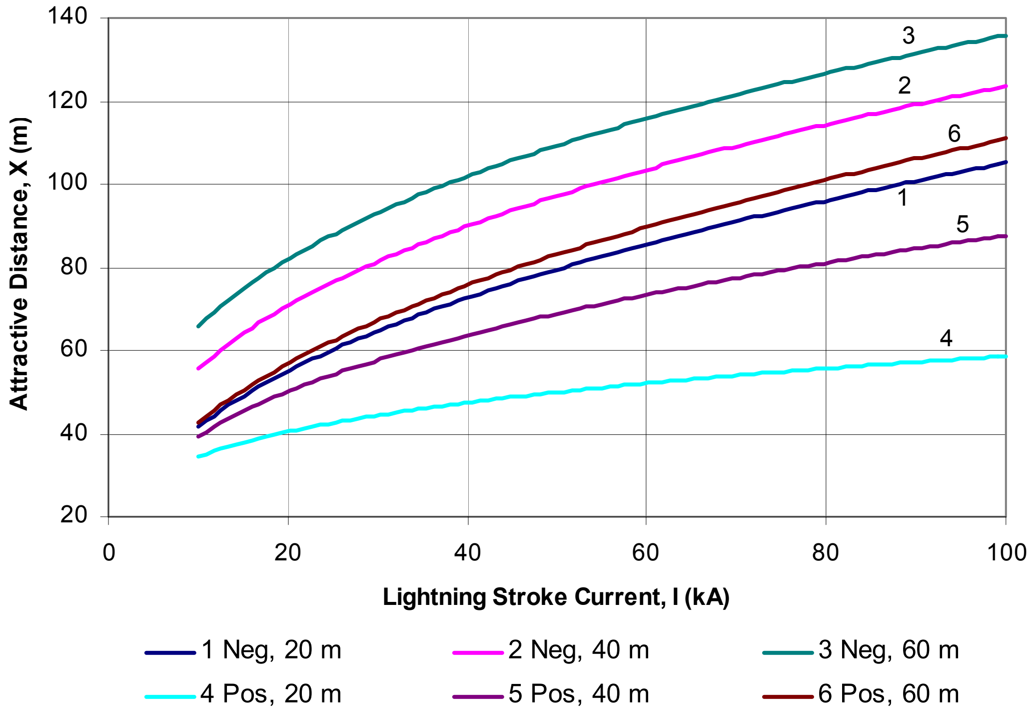


Figure 6.9 Attractive Distance of Transmission Line with Different Ground Wire Height

6.7 Lightning Attractive Width

According to the laboratory experiments of the study, the lightning flashes inside the attractive width strike the transmission line (strike the overhead ground wire), while lightning flashes outside the attractive width do not strike the line; they strike the ground instead. The more realistic attractive width of a transmission line, W, can be estimated by using the attractive width of overhead ground wires, W_g, the attractive width of towers, W_t, and the ground wire separation width, b. The attractive width of a transmission line consists of 20% contribution from that of towers and 80% contribution from that of overhead ground wires. The attractive width of a tower can be estimated by using the expression for a vertical rod. The expressions for the lightning attractive width based on 2,100 applied impulses are presented next.

The estimation of attractive width for negative polarity, which is the frequent polarity of lightning strokes, is presented. For practical use, it yields the following expression:

$$W = 0.8W_g + 0.2W_t \tag{6.5}$$

where

$$W_g = b + 2X_g = b + 47.16h_g^{0.33}$$
$$W_t = b + 2X_t = b + 38.66h_t^{0.42}$$

The estimation of attractive width for positive polarity, which is the infrequent polarity of lightning strokes, is also found using the similar way. For practical use, it yields the following expression:

$$W = 0.9W_g + 0.1W_t \tag{6.5}$$

where

$$W_g = b + 2X_g = b + 23.7h_g^{0.42}$$
$$W_t = b + 2X_t = b + 35.12h_t^{0.28}$$

Moreover, for validation purposes, the attractive width from this study is compared to derived attractive width, by using equation 3.1, from transmission line observations published in literature, as shown in Table 6.2 [21, 39]. The average ground wire height, assumed to be 90% of the tower height, is used. For the lower transmission lines, data nos. 1 and 4 have the most reliability because they are derived from more observations and longer km years than others [37, 45]. For the higher transmission lines, data no. 8 derived from 4-year observations is more reliable than data no. 9 derived from 2-year observations [39]. As seen in the table, the attractive width from this study correlates with the transmission line observations. The configurations and operating voltage of transmission lines from nine observations are given in Figure 6.10.

For a better understanding, nine observational data from table 6.2 are also depicted in Figure 6.11, with the estimation line from the developed expression. According to the expression, the attractive width is a function of the transmission line height and the separation width of overhead ground wires. Therefore, for an appropriate comparison, only one side attractive distance is presented.

Table 6.2 Attractive Width Derived from Transmission Line Observations Compared to Attractive Width Estimated from This Study

	h_t (m)	h_g (m)	b (m)	Observed Strokes	km years	W (m) Observation	W (m) Experiment
1	22	20	0	1077	3454	124	130
2	22	20	0	253	331	234	130
3	22	20	3.3	190	257	240	133
4	25	23	12.7	698	1182	186	149
5	33	30	18.6	365	419	266	168
6	44	40	0	44	32	294	165
7	44	40	0	38	50	160	165
8	100	90	22.6	121	104	264	243
9	140	126	38	126	54	350	286

NOTE: Data no. 1 are from [37], data nos. 2-5 are from [18, 45, 48], data nos. 6-7 are from [46], and data nos. 8-9 are from [39].

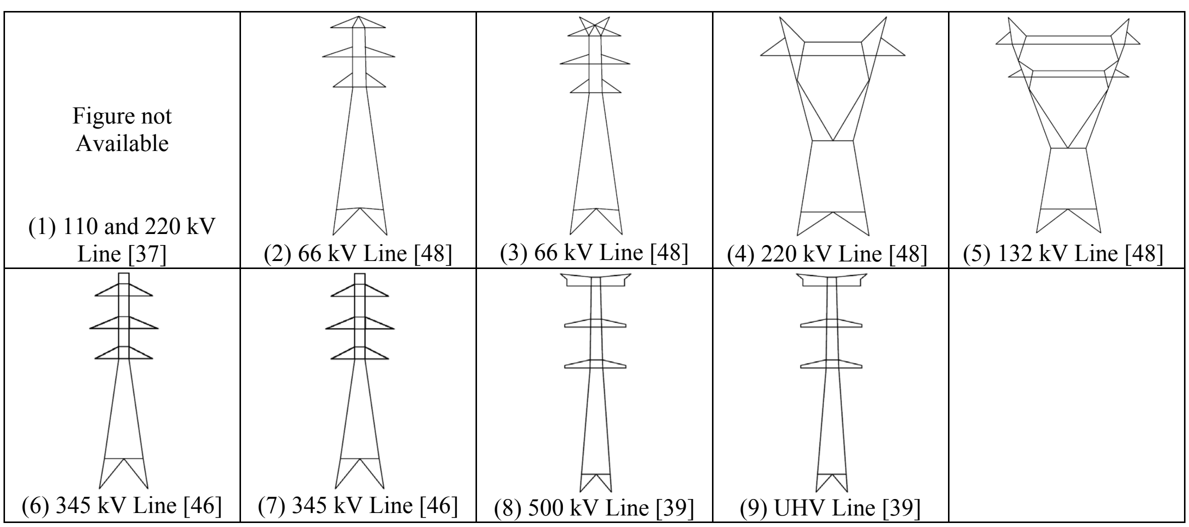


Figure 6.10 Configurations of Transmission Lines from 9 Observations

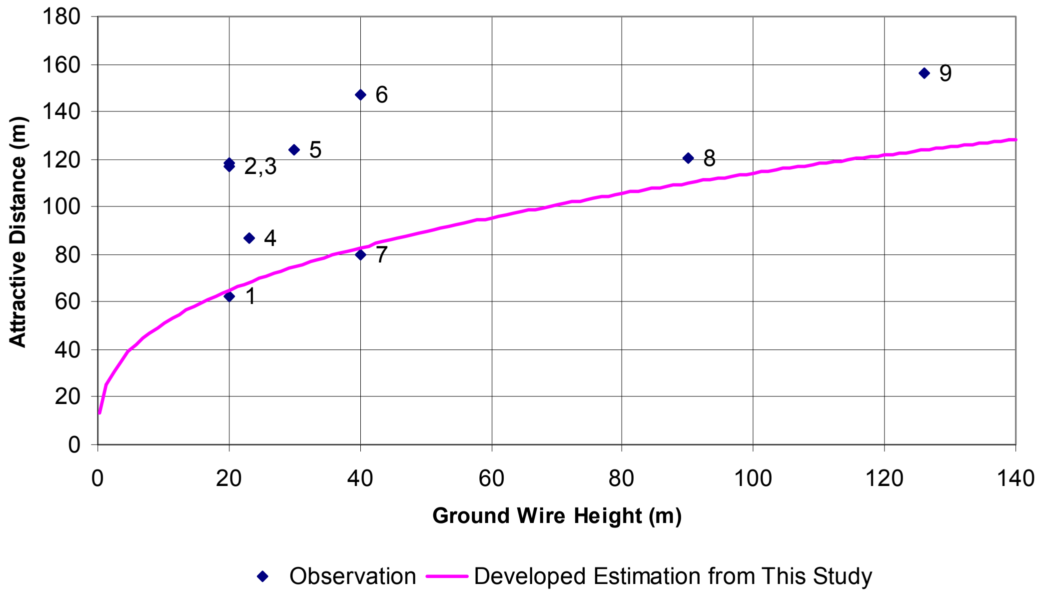


Figure 6.11 Attractive Distance Derived from Observations and Estimated from Expressions

As shown above, the estimation from this study correlates well with the most reliable observation, data no. 1, but deviates from data nos. 2, 3, 5, 6, and 9. The latter could be analyzed to find out the cause and effect. Observational data was collected from three regions, including the United States, Czechoslovakia, and Japan, by a number of researchers using different methods. The number of observed lightning strokes to the transmission lines, the length of transmission lines equipped with instruments, and the time period also have an impact on the reliability of data.

Data nos. 2, 3, and 5 were collected from the very short length of observed transmission lines [45]. It has been presented that the distribution of lightning flashes occurs at random, and there are great variations from area to area. Data nos. 6 and 7 had the least reliability among the others because they were collected from only one year each [46]. Lightning flash is the phenomenon that varies from year to year, so obtaining average values requires long-term observations over many years [3-5]. However, the developed estimation of the attractive distance falls between those two data. Data no. 9 was collected over a two-year period, which also was the short-time observation [39].

Another factor which cannot be ignored is the height of the transmission lines and landscape. This transmission line has the tower height of 140 m, which is vey rare for typical transmission lines, and can have two impacts. First, upward lightning, which is not in the scope of the research, can become significant at structures having heights above 100 m [21]. This will cause an increase in the number of observed lightning flashes to the line and the derived attractive distance to become larger. Second, according to Figure 6.7, the actual percentage of lightning flashes to towers for this transmission line is 25%, but because of the reason previously presented, 20% was used for calculation. Whenever more observational data becomes available, the developed expressions can be calibrated, and the research will be at the finest level.

6.8 Summary

The electric field distribution and the polarity of lightning have an impact on the final step of lightning attachment. Because of the differences in configuration, overhead ground wires and towers have different attractiveness to lightning strokes. The attractive distance of a ground wire and the attractive radius of a rod from the present study correlate with other methods from published research. The attractive widths estimated from the presented expressions agree with the actual transmission line observations.

CHAPTER VII

CONCLUSIONS

In this dissertation, the results from the research on the estimation of the lightning attractive width of high voltage transmission lines are presented. The ground wire separation width practically did not have a major impact, so the attractive distance of one ground wire can be used to calculate the attractive width of transmission lines with one or two overhead ground wires. Thus, the separation width only has a geometrical impact and not an electrical impact. Phase conductors did not have an impact on the attractive width either. The attractive width increased gradually with the height of overhead ground wires or towers and the magnitude of the lightning stroke current. Impulse polarity had an impact, and the attractive width for negative polarity was larger than that for positive polarity. This is clearly observed in the photographs of flashes. The taller tower had more effect on lightning flash distribution to transmission lines than the shorter one.

The electric field distribution and the polarity of lightning had an impact on the final step of lightning attachment. Because of the differences in shape, overhead ground wires and towers have different attractiveness to lightning strokes. The attractive distance of a ground wire and the attractive radius of a rod from the present study correlate with the methods from other research. Based on the experimental results, the mathematical expressions for the attractive width were developed. The attractive widths estimated from the presented expressions agree with the actual transmission line observations.

When investigating the lightning performance of transmission lines, many relevant parameters must be considered. Shielding of phase conductors, which was not in the scope of this research, could be interesting for further investigation. In order to avoid direct strokes to the phase conductors, a good design of shielding configurations must be accomplished. As seen in Figure 3.1, the attractive width is related to the striking distance to the overhead ground wire, the phase conductor, and the ground. Usually, the shielding failure rate will decrease by increasing the separation width between two overhead ground wires. However, by doing that, the number of lightning flashes to the line will increase, and the backflashover rate may also increase. There will be only one optimized location of ground wires, which causes the minimum lightning outage rate (from backflashover and shielding failure). Along with the modern knowledge for positive lightning [31, 32], which can penetrate the protection zone designed by a conventional method, suggestions are made as for further investigations. This can be performed by methods including, but not limited to, laboratory experiments, analytical methods, computer simulations, or statistical observations.

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APPENDIX A

CRITICAL FLASHOVER VOLTAGE OF ROD-PLANE GAP

Table A.1 Critical Flashover (CFO) Voltage of Rod-Plane Gap at Various Gap Distances Under Negative Switching Impulses

	H = 50 cm		H = 60 cm		H = 70 cm		H = 80 cm	
Shot No.	Voltage (kV)	Result	Voltage (kV)	Result	Voltage (kV)	Result	Voltage (kV)	Result
1	-596	F	-711	F	-1022	W	-898	F
2	-869	W	-840	F	-675	F	-998	W
3	-754	F	-912	W	-1050	W	-883	F
4	-740	F	-912	W	-1064	W	-1013	W
5	-869	W	-883	F	-980	F	-1027	W
6	-740	F	-912	W	-967	F	-1070	W
7	-855	W	-941	W	-855	F	-1113	W
8	-883	W	-769	F	-1050	W	-1085	F
9	-869	F	-927	W	-841	F	-783	F
10	-898	W	-955	W	-1050	W	-898	F
Avg.	-807		-876		-955		-977	

	H = 90 cm		H = 100 cm	
Shot No.	Voltage (kV)	Result	Voltage (kV)	Result
1	-1027	F	-1041	F
2	-883	F	-1228	W
3	-1099	W	-1257	W
4	-1128	W	-1156	F
5	-1156	W	-984	F
6	-1185	W	-1214	W
7	-1214	W	-1257	W
8	-1199	F	-1070	F
9	-912	F	-1243	W
10	-927	F	-955	F
Avg.	-1073		-1141	

Note: F = Flash and W = Withstand

Table A.2 Critical Flashover (CFO) Voltage of Rod-Plane Gap at Various Gap Distances Under Positive Switching Impulses

	H = 50 cm		H = 60 cm		H = 70 cm		H = 80 cm	
Shot No.	Voltage (kV)	Result	Voltage (kV)	Result	Voltage (kV)	Result	Voltage (kV)	Result
1	281	F	302	F	374	W	399	W
2	281	F	334	W	345	F	378	F
3	245	W	299	F	374	W	406	W
4	281	F	334	W	381	F	417	F
5	241	W	324	F	342	F	406	W
6	266	F	302	F	360	W	370	F
7	245	W	302	W	356	F	406	W
8	273	F	306	F	370	W	450	W
9	270	W	299	W	374	W	392	F
10	255	W	309	W	327	F	388	F
Avg.	264		311		360		401	
	H = 90 cm		H = 100 cm		H = 125 cm		H = 150 cm	
Shot No.	Voltage (kV)	Result	Voltage (kV)	Result	Voltage (kV)	Result	Voltage (kV)	Result
1	442	F	446	F	560	F	690	F
2	385	F	468	F	460	W	682	W
3	446	W	410	W	524	F	589	F
4	464	W	432	F	575	F	675	W
5	446	F	410	W	417	W	690	W
6	385	F	446	W	467	W	718	W
7	410	F	432	W	532	W	733	W
8	410	W	457	F	589	F	690	F
9	453	W	468	W	524	F	589	F
10	385	F	457	F	460	W	517	F
Avg.	423		442		511		657	
	H = 175 cm		H = 200 cm					
Shot No.	Voltage (kV)	Result	Voltage (kV)	Result				
1	668	F	862	W				
2	747	F	747	F				
3	718	W	718	F				
4	754	W	697	F				
5	697	F	790	W				
6	754	W	776	F				
7	769	W	804	W				
8	740	F	819	W				
9	668	F	840	W				
10	754	W	733	F				
Avg.	727		779					

Note: F = Flash and W = Withstand

APPENDIX B

EXPERIMENTAL DATA FOR ATTRACTIVE DISTANCE OF ONE GROUND WIRE

Table B.1 Experimental Data of One Ground Wire under Negative Polarity, H = 73 cm, h_g = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 50 cm	G	W	W	G	G	G	W	G	G	W	3/7
X = 45 cm	W	W	W	W	W	G	W	G	W	W	8/2

Table B.2 Experimental Data of One Ground Wire under Negative Polarity, H = 73 cm, h_g = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 60 cm	W	W	W	W	G	G	W	W	W	W	8/2
X = 65 cm	G	G	W	W	G	W	G	G	W	W	5/5

Table B.3 Experimental Data of One Ground Wire under Negative Polarity, H = 73 cm, h_g = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 80 cm	G	G	W	G	G	W	G	G	G	G	2/8
X = 75 cm	W	W	G	W	G	W	G	W	G	W	6/4

Table B.4 Experimental Data of One Ground Wire under Negative Polarity, H = 73 cm, h_g = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 80 cm	G	W	G	G	W	W	W	G	W	G	5/5

Table B.5 Experimental Data of One Ground Wire under Negative Polarity, H = 73 cm, h_g = 50 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 84 cm	G	W	G	G	W	G	W	G	W	W	5/5

Table B.6 Experimental Data of One Ground Wire under Negative Polarity, H = 73 cm, h_g = 60 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 89 cm	G	W	G	W	G	W	W	W	G	G	5/5

Table B.7 Experimental Data of One Ground Wire under Positive Polarity, H = 73 cm, h_g = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 30 cm	G	W	G	G	W	G	G	W	W	W	5/5

Table B.8 Experimental Data of One Ground Wire under Positive Polarity, H = 73 cm, h_g = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 45 cm	G	W	G	G	W	W	G	G	G	G	3/7
X = 40 cm	W	W	W	W	W	G	G	W	G	G	6/4

Table B.9 Experimental Data of One Ground Wire under Positive Polarity, H = 73 cm, h_g = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 55 cm	W	G	G	G	G	G	W	W	G	G	3/7
X = 50 cm	W	G	G	W	W	W	G	W	W	W	7/3

Table B.10 Experimental Data of One Ground Wire under Positive Polarity, H = 73 cm, h_g = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 65 cm	G	G	G	G	G	G	G	G	G	G	0/10
X = 55 cm	W	G	W	G	W	W	W	W	W	G	7/3

Table B.11 Experimental Data of One Ground Wire under Positive Polarity, H = 73 cm, h_g = 50 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 64 cm	G	W	G	G	G	G	G	G	G	W	2/8
X = 60 cm	W	G	W	W	W	W	G	W	G	G	6/4

Table B.12 Experimental Data of One Ground Wire under Positive Polarity, H = 73 cm, h_g = 60 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 64 cm	G	G	G	G	W	G	W	G	W	G	3/7
X = 60.5 cm	G	G	W	G	G	W	W	W	W	W	6/4

Note: W = Wire and G = Ground

APPENDIX C

EXPERIMENTAL DATA FOR ATTRACTIVE DISTANCE OF TWO GROUND WIRES

Table C.1 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 10 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 54 cm	G	W	G	W	W	G	W	W	G	G	5/5

Table C.2 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 20 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 64 cm	G	W	G	W	W	W	W	W	W	W	8/2
X = 69 cm	G	G	G	W	G	W	G	G	G	G	2/8

Table C.3 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 20 cm, b = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 65 cm	G	G	G	G	G	G	W	W	G	G	2/8
X = 60 cm	W	G	W	W	G	W	W	W	G	W	7/3

Table C.4 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 30 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 76 cm	W	G	W	W	W	W	W	W	G	G	7/3
X = 81 cm	G	G	G	G	G	W	G	G	G	G	1/9

Table C.5 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 30 cm, b = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 76 cm	G	G	W	G	G	G	G	W	W	G	3/7
X = 71 cm	W	W	G	G	W	G	W	G	G	G	4/6

Table C.6 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 30 cm, b = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 71 cm	W	W	W	W	G	W	W	W	G	W	7/3
X = 81 cm	G	W	G	G	W	G	W	G	G	G	3/7

Table C.7 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 40 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 83.5 cm	W	W	G	G	W	W	W	G	G	G	5/5

Table C.8 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 40 cm, b = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 83 cm	G	W	G	W	W	W	G	G	G	W	5/5

Table C.9 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 40 cm, b = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 81 cm	W	W	W	W	G	G	G	W	W	W	7/3
X = 88.5 cm	W	W	W	G	G	G	G	G	G	W	4/6
X = 83 cm	G	W	G	W	W	W	G	G	G	W	5/5

Table C.10 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 40 cm, b = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 88 cm	G	W	G	G	G	G	G	W	G	G	2/8
X = 78 cm	W	W	W	W	G	W	G	G	W	W	7/3

Table C.11 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 50 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 87 cm	W	G	G	G	G	G	G	G	W	W	3/7
X = 82 cm	W	W	W	W	G	G	W	W	G	G	6/4

Table C.12 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 50 cm, b = 20 cm,

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 86 cm	G	G	G	G	W	G	G	W	G	G	2/8
X = 80.5 cm	W	W	W	G	G	G	W	W	W	G	6/4

Table C.13 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 50 cm, b = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 88 cm	W	W	G	W	G	W	G	W	W	G	6/4

Table C.14 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 50 cm, b = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 88 cm	W	W	G	G	G	W	W	G	W	G	5/5

Table C.15 Experimental Data of Two Ground Wires under Negative Polarity, H = 73 cm, h_g = 50 cm, b = 50 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 86 cm	G	G	G	W	W	W	W	G	G	W	5/5

Table C.16 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 10 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 35 cm	G	W	G	G	G	G	G	G	G	G	1/9
X = 25 cm	W	G	G	W	W	W	W	W	W	W	8/2

Table C.17 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 20 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 45 cm	G	W	G	G	G	G	W	G	G	W	3/7
X = 40 cm	W	W	W	W	G	W	W	W	W	W	9/1

Table C.18 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 20 cm, b = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 40 cm	W	W	W	G	G	W	W	W	G	W	7/3
X = 45 cm	W	G	W	G	G	W	G	G	G	G	3/7

Table C.19 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 30 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 53 cm	W	G	G	W	G	W	G	W	G	W	5/5

Table C.20 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 30 cm, b = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 50 cm	W	G	W	G	W	W	G	W	W	W	7/3
X = 55 cm	G	G	W	G	G	G	G	W	G	G	2/8

Table C.21 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 30 cm, b = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 52.5 cm	G	G	G	G	G	W	G	G	W	G	2/8
X = 47.5 cm	G	W	G	W	G	G	W	G	G	W	4/6

Table C.22 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 40 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 62.5 cm	G	W	G	G	G	G	W	G	W	G	3/7
X = 57.5 cm	W	G	W	G	G	W	G	W	G	W	5/5

Table C.23 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 40 cm, b = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 55 cm	G	G	W	G	G	G	W	G	G	G	2/8
X = 50 cm	W	W	W	W	W	G	W	W	W	W	9/1

Table C.24 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 40 cm, b = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 53 cm	W	G	G	W	W	W	W	G	W	W	7/3
X = 58 cm	G	W	G	G	G	G	G	G	W	G	2/8

Table C.25 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 40 cm, b = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 53 cm	G	G	W	W	G	W	W	W	W	W	7/3
X = 58 cm	W	G	G	G	G	G	G	W	W	G	3/7

Table C.26 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 50 cm, b = 10 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 63 cm	W	G	W	G	W	W	G	W	W	W	7/3
X = 68 cm	G	G	G	G	G	G	G	G	G	G	0/10

Table C.27 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 50 cm, b = 20 cm,

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 58 cm	G	W	W	W	W	W	W	W	W	G	8/2
X = 63 cm	G	G	W	W	W	W	G	G	G	W	5/5

Table C.28 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 50 cm, b = 30 cm,

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 56 cm	G	G	W	W	W	W	W	W	W	W	8/2
X = 61 cm	W	G	G	G	G	G	G	G	G	G	1/9

Table C.29 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 50 cm, b = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 58 cm	G	W	W	W	G	W	W	W	W	W	8/2
X = 63 cm	G	G	G	G	G	G	W	G	G	G	1/9

Table C.30 Experimental Data of Two Ground Wires under Positive Polarity, H = 73 cm, h_g = 50 cm, b = 50 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 63 cm	G	G	G	G	W	W	W	G	G	G	3/7
X = 58 cm	W	G	G	W	W	G	G	G	W	G	4/6

Note: W = Wire and G = Ground

APPENDIX D

EXPERIMENTAL DATA FOR ATTRACTIVE DISTANCE OF SINGLE-CIRCUIT HORIZONTAL TRANSMISSION LINES

Table D.1 Experimental Data of 1-cct Horizontal 230-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 55.25 cm	W	G	W	G	G	G	W	W	G	W	5/5

Table D.2 Experimental Data of 1-cct Horizontal 230-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 78.8 cm	G	G	G	G	G	G	G	G	G	G	10/0
X = 66.3 cm	G	G	G	G	G	G	G	W	W	G	2/8
X = 61.3 cm	G	G	W	W	G	W	W	W	W	W	7/3

Table D.3 Experimental Data of 1-cct Horizontal 230-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 82.75 cm	W	W	W	G	G	W	W	G	G	G	5/5

Table D.4 Experimental Data of 1-cct Horizontal 345-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 58.3 cm	W	W	W	G	G	G	G	G	W	W	5/5

Table D.5 Experimental Data of 1-cct Horizontal 345-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 65.3 cm	G	W	G	G	G	W	W	G	W	W	5/5

Table D.6 Experimental Data of 1-cct Horizontal 345-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 89.3 cm	W	W	G	G	G	G	G	W	G	G	3/7
X = 79.3 cm	W	W	G	G	G	W	W	W	W	G	6/4

Table D.7 Experimental Data of 1-cct Horizontal 500-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 62.2 cm	G	G	W	G	G	G	G	G	W	G	2/8
X = 52.2 cm	G	W	W	W	G	W	G	W	W	W	7/3

Table D.8 Experimental Data of 1-cct Horizontal 500-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 78.7 cm	W	G	G	G	W	G	G	G	G	G	2/8
X = 73.7 cm	G	G	W	G	W	G	G	G	G	W	3/7
X = 68.7 cm	G	W	W	W	W	G	W	G	W	W	7/3

Table D.9 Experimental Data of 1-cct Horizontal 500-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 87.7 cm	W	W	G	W	G	W	G	G	G	W	5/5

Table D.10 Experimental Data of 1-cct Horizontal 765-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 69 cm	G	G	G	G	W	G	G	G	G	G	1/9
X = 59 cm	W	W	G	W	W	W	G	G	G	G	5/5

Table D.11 Experimental Data of 1-cct Horizontal 765-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 95 cm	G	G	G	G	G	G	G	G	W	G	1/9
X = 85 cm	G	G	G	W	W	G	G	G	G	G	2/8
X = 80 cm	G	G	G	G	G	G	W	W	W	G	3/7
X = 70 cm	W	W	W	W	W	W	G	G	W	W	8/2

Table D.12 Experimental Data of 1-cct Horizontal 765-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 89 cm	W	W	G	W	W	G	G	G	G	W	5/5

Table D.13 Experimental Data of 1-cct Horizontal 1100-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 73.1 cm	W	W	G	G	W	W	G	G	G	G	4/6
X = 68.1 cm	W	G	W	G	G	W	W	W	G	G	5/5

Table D.14 Experimental Data of 1-cct Horizontal 1100-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 73.1 cm	G	W	W	W	W	W	W	W	G	W	8/2
X = 78.1 cm	G	W	W	W	G	G	W	W	W	G	6/4
X = 83.1 cm	G	G	W	G	W	W	G	W	G	W	5/5

Table D.15 Experimental Data of 1-cct Horizontal 1100-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 93.1 cm	G	G	G	G	W	G	W	W	W	W	5/5

Table D.16 Experimental Data of 1-cct Horizontal 230-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 36.3 cm	G	W	W	G	W	G	W	G	G	W	5/5

Table D.17 Experimental Data of 1-cct Horizontal 230-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 69.3 cm	G	G	G	G	G	G	G	G	G	G	0/10
X = 59.3 cm	G	G	G	G	G	G	G	G	G	G	0/10
X = 49.3 cm	G	G	G	W	G	G	G	G	G	G	1/9
X = 44.3 cm	G	G	G	G	W	G	G	W	W	W	4/6

Table D.18 Experimental Data of 1-cct Horizontal 230-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 48.3 cm	W	G	G	G	G	G	G	G	G	W	2/8
X = 43.3 cm	W	W	W	W	W	W	G	W	W	W	9/1

Table D.19 Experimental Data of 1-cct Horizontal 345-kV Line under Positive Polarity, H = 56 cm,

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 44.3 cm	G	G	G	G	G	G	W	G	G	G	1/9
X = 34.3 cm	W	W	W	W	W	W	W	G	W	W	9/1

Table D.20 Experimental Data of 1-cct Horizontal 345-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 43.3 cm	W	W	W	W	W	W	W	W	G	W	9/1
X = 48.3 cm	W	W	W	G	W	W	G	W	G	G	6/4

Table D.21 Experimental Data of 1-cct Horizontal 345-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 54.3 cm	G	W	G	W	W	G	W	W	G	G	5/5

Table D.22 Experimental Data of 1-cct Horizontal 500-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 45.2 cm	G	G	G	G	G	W	G	G	G	W	2/8
X = 40.2 cm	W	G	W	W	G	W	W	W	W	W	8/2

Table D.23 Experimental Data of 1-cct Horizontal 500-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 45.2 cm	W	G	W	W	W	W	W	W	W	W	9/1
X = 50.2 cm	W	G	W	G	G	G	W	G	G	G	3/8
X = 48.2 cm	W	W	G	W	W	W	G	W	G	G	6/4

Table D.24 Experimental Data of 1-cct Horizontal 500-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 62.7 cm	G	G	G	G	G	G	W	G	G	G	1/9
X = 52.7 cm	W	G	W	G	G	G	W	G	W	W	5/5

Table D.25 Experimental Data of 1-cct Horizontal 765-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 49 cm	G	G	W	G	W	G	G	W	W	G	4/6
X = 46 cm	W	W	W	W	G	W	W	G	G	G	6/4

Table D.26 Experimental Data of 1-cct Horizontal 765-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 58 cm	G	G	G	W	G	G	W	G	G	G	2/8
X = 55 cm	G	G	W	G	G	G	W	W	G	W	4/6

Table D.27 Experimental Data of 1-cct Horizontal 765-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 59 cm	W	W	W	W	G	W	G	W	W	W	8/2
X = 69 cm	G	W	G	G	W	G	G	G	G	W	3/7

Table D.28 Experimental Data of 1-cct Horizontal 1100-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 48.1 cm	W	W	G	W	G	W	W	W	W	W	8/2
X = 53.1 cm	G	G	W	W	W	W	G	G	W	G	5/5

Table D.29 Experimental Data of 1-cct Horizontal 1100-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 58.1 cm	G	G	W	G	W	G	G	W	W	G	4/6
X = 53.1 cm	W	W	W	G	G	W	W	W	W	W	8/2

Table D.30 Experimental Data of 1-cct Horizontal 1100-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 73.1 cm	G	G	G	W	G	G	W	G	G	W	3/7
X = 68.1 cm	W	W	G	W	G	W	G	W	G	G	5/5

Note: W = Wire and G = Ground

APPENDIX E

EXPERIMENTAL DATA FOR ATTRACTIVE DISTANCE OF DOUBLE-CIRCUIT VERTICAL TRANSMISSION LINES

Table E.1 Experimental Data of 2-cct Vertical 230-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 46.8 cm	W	G	W	W	W	W	G	W	W	W	8/2
X = 54.3 cm	W	G	G	W	G	W	W	W	W	W	7/3

Table E.2 Experimental Data of 2-cct Vertical 230-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 67.25 cm	G	W	W	W	G	G	G	W	W	G	5/5

Table E.3 Experimental Data of 2-cct Vertical 230-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 77.25 cm	W	G	G	W	G	W	W	G	G	G	4/6
X = 72.25 cm	W	W	W	W	W	G	G	G	W	G	6/4

Table E.4 Experimental Data of 2-cct Vertical 345-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 73 cm	G	G	G	W	W	W	W	G	G	G	4/6
X = 68 cm	G	G	G	W	W	G	G	W	W	W	5/5

Table E.5 Experimental Data of 2-cct Vertical 345-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 93 cm	W	W	G	G	G	G	G	G	G	G	2/8
X = 83 cm	G	G	G	G	W	G	W	G	G	W	3/7
X = 73 cm	W	G	G	W	G	W	W	G	G	W	5/5

Table E.6 Experimental Data of 2-cct Vertical 345-kV Line under Negative Polarity, H = 101.7 cm,

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 85 cm	W	W	W	W	W	W	G	G	W	W	8/2
X = 95 cm	W	W	W	G	G	G	G	G	G	G	3/7

Table E.7 Experimental Data of 2-cct Vertical 500-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 67 cm	G	G	W	G	W	W	G	W	W	W	6/4
X = 72 cm	G	W	G	G	W	W	W	G	G	W	5/5

Table E.8 Experimental Data of 2-cct Vertical 500-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 72 cm	G	W	W	W	G	W	W	W	W	W	8/2
X = 82 cm	G	W	G	G	W	W	W	W	G	W	6/4

Table E.9 Experimental Data of 2-cct Vertical 500-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 102 cm	W	W	W	G	W	G	G	W	W	W	7/3
X = 112 cm	W	G	W	G	G	G	W	W	G	G	4/6

Table E.10 Experimental Data of 2-cct Vertical 765-kV Line under Negative Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 70.5 cm	W	W	W	W	W	W	W	G	W	W	9/1
X = 75.5 cm	G	W	W	W	W	W	G	W	W	W	8/2

Table E.11 Experimental Data of 2-cct Vertical 765-kV Line under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 85.5 cm	W	W	W	G	G	W	W	W	G	G	6/4
X = 95.5 cm	G	W	G	W	G	G	G	G	W	G	3/7

Table E.12 Experimental Data of 2-cct Vertical 765-kV Line under Negative Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 110.5 cm	W	G	W	G	G	G	W	G	W	W	5/5

Table E.13 Experimental Data of 2-cct Vertical 230-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 47.25 cm	G	G	G	G	G	W	W	G	G	G	2/8
X = 37.25 cm	W	W	W	W	W	W	W	W	W	W	10/0

Table E.14 Experimental Data of 2-cct Vertical 230-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 57.25 cm	G	G	G	G	G	G	W	G	G	G	1/9
X = 47.25 cm	W	G	W	W	W	W	W	G	W	G	7/3

Table E.15 Experimental Data of 2-cct Vertical 230-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 67.25 cm	W	G	G	G	G	G	G	G	G	G	1/9
X = 57.25 cm	G	W	G	W	G	G	G	G	W	G	3/7

Table E.16 Experimental Data of 2-cct Vertical 345-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 49 cm	G	W	W	G	G	W	G	G	W	W	5/5

Table E.17 Experimental Data of 2-cct Vertical 345-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 53 cm	W	W	W	G	W	W	W	W	G	W	8/2
X = 63 cm	W	W	G	G	G	G	G	G	W	W	4/6

Table E.18 Experimental Data of 2-cct Vertical 345-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 63 cm	G	W	W	W	W	W	W	W	W	W	9/1
X = 73 cm	G	G	G	G	W	G	W	W	G	W	4/6

Table E.19 Experimental Data of 2-cct Vertical 500-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 49 cm	G	G	G	W	G	G	W	W	W	W	5/5

Table E.20 Experimental Data of 2-cct Vertical 500-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 62 cm	W	W	G	W	W	W	W	W	G	W	8/2
X = 72 cm	G	G	G	G	G	G	G	G	G	G	0/10

Table E.21 Experimental Data of 2-cct Vertical 500-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 69 cm	G	G	G	G	W	W	G	W	G	G	3/7
X = 64 cm	W	W	W	G	G	W	W	W	W	G	7/3

Table E.22 Experimental Data of 2-cct Vertical 765-kV Line under Positive Polarity, H = 56 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 50.5 cm	G	G	G	W	G	W	G	G	W	G	3/7
X = 45.5 cm	W	W	W	W	W	W	W	W	W	W	10/0

Table E.23 Experimental Data of 2-cct Vertical 765-kV Line under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 75.5 cm	G	G	G	G	G	G	G	G	G	G	0/10
X = 65.5 cm	W	W	G	G	W	G	W	W	G	G	5/5

Table E.24 Experimental Data of 2-cct Vertical 765-kV Line under Positive Polarity, H = 101.7 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	W/G
X = 70.5 cm	W	W	W	G	W	G	W	W	W	G	7/3
X = 75.5 cm	G	G	W	W	G	W	W	W	G	G	5/5

Note: W = Wire and G = Ground

APPENDIX F

EXPERIMENTAL DATA FOR ATTRACTIVE RADIUS OF VERTICAL ROD

Table F.1 Experimental Data of Vertical Rod under Negative Polarity, H = 73 cm, h_r = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 72 cm	G	G	G	G	G	G	R	G	G	G	1/9
R = 62 cm	R	R	R	R	G	R	R	R	R	R	9/1

Table F.2 Experimental Data of Vertical Rod under Negative Polarity, H = 73 cm, h_r = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 82 cm	R	R	G	G	R	R	G	G	R	G	5/5

Table F.3 Experimental Data of Vertical Rod under Negative Polarity, H = 73 cm, h_r = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 91 cm	G	R	G	R	R	G	G	G	R	R	5/5

Table F.4 Experimental Data of Vertical Rod under Negative Polarity, H = 73 cm, h_r = 50 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 106 cm	G	R	G	R	R	G	G	G	G	G	3/7
R = 96 cm	R	G	R	R	G	R	G	G	R	G	5/5

Table F.5 Experimental Data of Vertical Rod under Negative Polarity, H = 73 cm, h_r = 60 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 109 cm	G	R	R	G	G	R	R	R	G	G	5/5

Table F.6 Experimental Data of Vertical Rod under Positive Polarity, H = 73 cm, h_r = 20 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 40 cm	R	R	G	G	G	R	G	R	G	R	5/5

Table F.7 Experimental Data of Vertical Rod under Positive Polarity, H = 73 cm, h_r = 30 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 40.2 cm	R	G	R	R	G	R	R	G	R	R	7/3
R = 45.1 cm	G	R	R	R	G	G	G	R	R	G	5/5

Table F.8 Experimental Data of Vertical Rod under Positive Polarity, H = 73 cm, h_r = 40 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 49 cm	G	R	R	G	G	R	G	R	G	R	5/5

Table F.9 Experimental Data of Vertical Rod under Positive Polarity, H = 73 cm, h_r = 50 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 52 cm	G	R	G	R	R	G	G	R	R	G	5/5

Table F.10 Experimental Data of Vertical Rod under Positive Polarity, H = 73 cm, h_r = 60 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	R/G
R = 76.3 cm	G	G	G	G	G	G	G	G	G	G	0/10
R = 66.3 cm	G	G	G	G	G	G	G	G	G	G	0/10
R = 56.3 cm	R	G	R	G	R	R	G	G	G	G	4/6

Note: R = Rod and G = Ground

APPENDIX G

EXPERIMENTAL DATA FOR ATTRACTIVE DISTANCE OF TRANSMISSION LINE TOWERS

Table G.1 Experimental Data of 1-cct Horizontal 230-kV Tower, under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/G
X = 73.5 cm	G	T	G	T	G	G	T	G	G	G	3/7
X = 66 cm	T	G	T	T	T	T	T	T	T	G	8/2
X = 71 cm	G	G	G	T	G	T	T	T	G	G	4/6

Table G.2 Experimental Data of 1-cct Horizontal 230-kV Tower, under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/G
X = 45 cm	G	T	T	T	T	G	G	G	T	G	5/5

Table G.3 Experimental Data of 2-cct Vertical 765-kV Tower, under Negative Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/G
X = 104 cm	G	G	T	T	T	G	T	G	T	G	5/5

Table G.4 Experimental Data of 2-cct Vertical 765-kV Tower, under Positive Polarity, H = 73 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/G
X = 50 cm	T	T	T	T	T	T	T	T	T	T	10/0
X = 55 cm	T	G	T	T	T	G	T	T	T	T	8/2
X = 60 cm	T	T	G	G	T	G	T	G	T	T	6/4

Note: T = Tower and G = Ground

APPENDIX H

EXPERIMENTAL DATA FOR DISTRIBUTION OF FLASHES TO TRANSMISSION LINES

Table H.1 Experimental Data of 1-cct Horizontal 230-kV Line, under Negative Polarity, H* = 91.2 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/W
Y = 34 cm	W	W	W	W	W	W	W	W	W	W	0/10
Y = 20 cm	W	W	T	W	T	T	T	W	W	T	5/5
Y = 10 cm	W	T	W	T	T	T	T	W	W	T	6/4

Table H.2 Experimental Data of 1-cct Horizontal 230-kV Line, under Positive Polarity, H* = 91.2 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/W
Y = 10 cm	W	W	W	W	W	W	T	T	W	W	2/8
Y = 0 cm	W	W	W	T	W	W	W	T	W	T	3/7

Table H.3 Experimental Data of 2-cct Vertical 765-kV Line, under Negative Polarity, H* = 91.2 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/W
Y = 32 cm	W	W	T	T	W	W	T+W	W	W	T	3.5/6.5
Y = 27 cm	W	T	T	T	W	T	T	W	W	T	6/4

Table H.4 Experimental Data of 2-cct Vertical 765-kV Line, under Positive Polarity, H* = 91.2 cm

Shot No.	1	2	3	4	5	6	7	8	9	10	T/W
Y = 0 cm	T	T	T	T	T	T	T	T	T	T	10/0
Y = 10 cm	W	T	T	T	T	T	W	W	T	W	6/4
Y = 20 cm	T	W	W	W	T	W	T	W	T	W	4/6

Note: T = Tower and W = Wire