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Laboratory Study of the Lightning Attractive Width for Transmission Lines

Thongchai Disyadej and Stanislaw Grzybowski*

High Voltage Laboratory, Department of Electrical and Computer Engineering, Mississippi State University, USA

Abstract: This research focuses on an investigation of the attractive width of high voltage transmission lines to lightning strokes. In order to design the optimal lightning protection, the estimated number of lightning flashes to the line, which is based on its attractive width, needs to be determined. The investigation was performed using experiments with tested models at the Mississippi State University High Voltage Laboratory. For laboratory experiments, a total of 1,900 negative and positive switching impulse voltages were applied to a conducting rod, which represented a lightning downward leader. Different tested models of transmission lines on a scale of 1:100 were used. The effect of overhead ground wires, phase conductors, and the magnitude and polarity of lightning strokes were studied. The attractive width increased gradually with the height of overhead ground wires 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 experimental results satisfactorily coincide with other published works, based on different methods and also with the actual transmission line observations. The new expressions of 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, methodology, experimental results, and analysis were presented in this paper.

Keywords: High voltage, lightning strokes, attractive width, Impulse polarity, Positive Polarity, transmission lines, conducting rod.

1. INTRODUCTION

The protection of transmission lines from lightning flashes has been the significant concern for scientific communities over a period of 100 years. A number of lightning flashes to the transmission lines occurred throughout the service time. It has been found that the line-outage rate is related to the number of lightning flashes to the line. In order to evaluate the lightning performance of transmission lines, a number of parameters are used in computation [1]. The degree of accuracy depends on the availability of data and plays a major role in the calculated performance. One of the parameters that affect 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 [2] still uses the equation for the attractive width, which was primarily derived from empirical data collected from observations of the lightning incidence on practical structures including transmission lines.

Many researchers have developed estimations of this attractive width. Anderson [3] simplified the concept of lightning incidence on the transmission line. The simple model assumed that the transmission line has an electrical shadow width on the ground. Later, Whitehead [4] slightly modified Anderson's model. Eriksson [5] presented an expression, derived from empirical data and an analytical model, and compared to transmission line observations. Nevertheless, the observed data showed dispersion due to recorded uncertainties. Unlike prior methods, Mousa and Srivastava [6] presented a computerized solution to determine the lightning incidence by applying the revised electrogeometric model to transmission lines. Rizk [7] introduced a new model for assessing the exposure of horizontal conductors to lightning strokes. His model started from a developed criterion for positive leaders initiated from a conductor under a negative descending lightning. As compared in [8], most models agreed reasonably up to the range of 30 m of the ground wire height only. Dellera and Garbagnati [9, 10] also introduced a simulation of lightning strokes to transmission lines by means of the leader progression model based on the physics of discharge on long air gaps. Then the model was applied to analysis of the exposure of transmission lines to lightning. The values of attractive width of Dellera and Garbagnati were much lower to that obtained by Eriksson's model and Rizk's model, as presented in [11].

Research results [12-14] have shown certain similarities between the last step of natural downward lightning leader and that of simulated lightning 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. Moreover, extrapolation of laboratory data on sparkover distance for lightning striking distance has been acceptably utilized to analytical studies of transmission line shielding [27, 28]. 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.

*Address correspondence to this author at the Department of Electrical and Computer Engineering, Mississippi State University, Box 9571, Mississippi State, MS 39762 USA; Tel: 662 325-2148; Fax: 662 325-2298;
E-mail: stangrzy@ece.msstate.edu

Knowledge of the attractive width has not been widely studied by using experiments in the laboratory. Some models do not consider realistic factors in practice, such as the combined position of ground wires and phase conductors or the lightning stroke polarity. To solve this problem, a more precise model, one based on the basis of the real phenomena of lightning flashes to the transmission line, needs to be developed.

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 within approximately 100 m above the earth. At that moment, the leader charges create a strong electric field on the transmission line and on the earth' surface. Consequently, the upward leader is initiated from the transmission line and/or the earth and intercepts the tip of the downward leader. The electric field simulation in a high voltage laboratory can be produced by using long-front impulse voltage (several hundreds microseconds) [15]. In practice, the impulse electric field created by a switching impulse has the rate of rise, in average, similar to the time-dependent electric field created by a downward leader.

2. LABORATORY STUDY

2.1. Test System

An experimental study was conducted at the Mississippi State University High Voltage Laboratory. The measurement setup of tests is shown as a diagram in Fig. (**1**). Standard 250/2500 μs switching impulse voltages were applied to the upper rod to represent the lightning downward leader. Switching impulses were obtained from a 3 MV, 57 kJ, 20-stage impulse generator. The increase of the electric field during propagation of a downward leader (stepped leader) is well represented by the switching impulse [15]. Simple models on a scale of 1:100 of typical transmission lines were built in the laboratory by using horizontal conducting wires to represent ground wires and phase conductors. At the ends of the line model, ground wires and phase conductors were connected to the ground (See Appendix). Copper sheets were used on the floor of the laboratory to simulate a conducting ground plane.

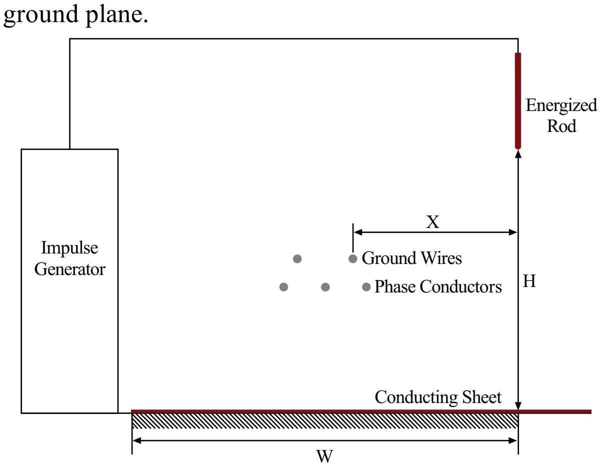


Fig. (1). Diagram of the test system for the study (X: attractive distance; W: attractive width; H: rod height).

The average height of the overhead ground wires, h_g, and the height of the energized rod (simulating the downward leader) above ground, H, were varied in experiments. A capacitive voltage divider connected with a digital oscilloscope was used for monitoring the waveshape and measuring the voltage.

Another challenge in this research is the statistical method for the test procedure on evaluation of the attractive width. Practically, high voltage testing in a laboratory for breakdown of an air gap has a random characteristic [16]. Therefore, the proper number of repeated switching impulses applied to the rod simulating a downward leader must be considered.

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 representing the downward leader. The number of flashes to the ground wire and to the ground plane was counted. As distance X was decreased, more flashes terminated to the ground wire; on the other hand, as the attractive distance X was increased, more flashes terminated to the ground. For each value of h_g and H, the recorded attractive distance X was the distance at which the flashes terminated to the ground wire and to the ground, on the equal probability. The attractive width of transmission lines could be calculated from that specific attractive distance X. The span was 4 m long for all tested transmission line models. Laboratory experiments were conducted under both negative and positive polarities of switching impulses. A total of 1,900 switching impulses were applied in order to obtain the attractive distance, X, of transmission lines. The incidence of flashes was recorded by using a digital camera to help identify the location of flashes, i.e. to the ground wire or to the ground.

2.2. Scale Models

For the first study, models of only one and two overhead ground wires, without phase conductors, were tested. The ground wire height, h_g, was varied from 10 to 50 cm, in a step of 10 cm. The separation width between ground wires, b, was 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 practically not common for typical transmission lines. The purpose of this study is to investigate the effect of varying ground wire separation at each value of the ground wire height. Fig. (**2**) illustrates both configurations of tested models.

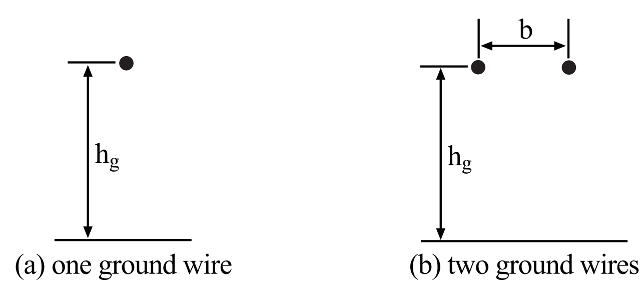


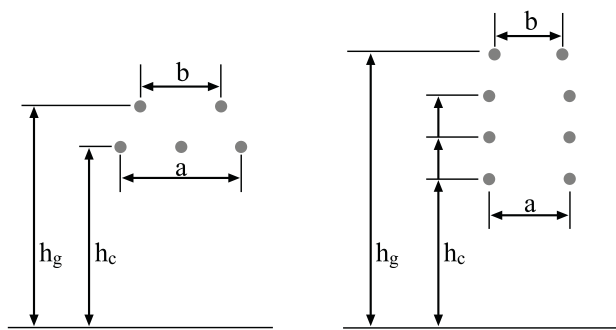
Fig. (2). Models of overhead ground wires.

The height of the energized rod, simulating the lightning downward leader, H, was 73 cm, which correspond to the distance of the final jump to the ground of the median lightning stroke of 30 kA. The striking distance of the final jump to the ground, as a function of lightning current [17], can be approximated by this equation:

$$r_g = \beta 10 I^{0.65} \quad (1)$$

where I is the lightning current in kA and $\beta = 0.8$ was used. Then, r_g is in m and scaled down to H in cm.

For the second study, complete transmission line models, with the presence of phase conductors, were tested. The different base cases of scaled models for HV, EHV, and UHV transmission lines were selected to study the dimension impact on the attractive width. A number of single and double circuit lines, including horizontal and vertical configurations, were also tested in this study. Fig. (**3**) illustrates both configurations of transmission line models. Table **1** presents parameters of 9 transmission line configurations including 230, 345, 500, 765, and 1100 kV lines [18].



(a) 1-circuit horizontal line (b) 2-circuit vertical line

Fig. (3). Transmission line models (h_g: average ground wire height; h_c: average phase conductor height).

Table 1. Parameters of Base Case Line Configurations [18]

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

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 (final jump) to the ground of the lightning stroke of 20, 30, and 50 kA, respectively. The striking distance of the final jump to the ground, as a function of lightning current, can be approximated by the equation (1).

3. EXPERIMENTAL RESULTS

3.1. Critical Flashover (CFO) Voltage of Rod-Plane Gap

The switching impulse CFO voltage tests for a rod-plane gap with varied rod height, H, from 50-200 cm, were performed as reference values. Fig. (**4**) presents the measured CFO voltages for both polarities, which agrees with the published data from other laboratories [17]. So, this assured the accuracy of the generation and measurement system of the MSU HV Lab.

In the experiments for the attractive width, the magnitude of applied impulse voltages to the rod at the specific height H was 5% higher than the measured CFO voltages of a rod-plane gap in order to cause flashes either to the ground wire or to the ground for all applied impulses. These 5% higher voltages do not play any big role and affect very small difference on the results.

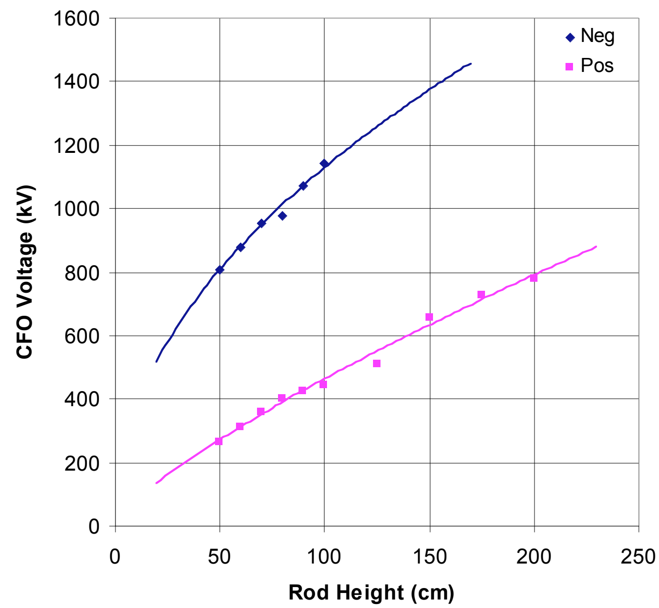


Fig. (4). Switching impulse CFO voltages of a rod-plane gap for negative and positive polarity.

3.2. Test Results of One Ground Wire

Fig. (**5**) presents the measured data from tests for one ground wire under negative and positive switching impulses. The attractive distance, X, increased gradually as a function of the ground wire height, h_g. The obtained results show that the higher ground wire has the larger attractive distance as compared to the lower one. 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.

3.3. Test Results of Two Ground Wires

Fig. (**6**) presents the measured data from tests for two ground wires under negative and positive switching impulses. 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 small impact of the electrical field distribution and the statistical error of experiments. Therefore, the attractive distance of one ground wire is enough to calculate the attractive with of transmission lines with two overhead ground wires by just adding the ground wire separation width. The obtained results show that the higher ground wire has the larger attractive distance as compared to the lower one. 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.

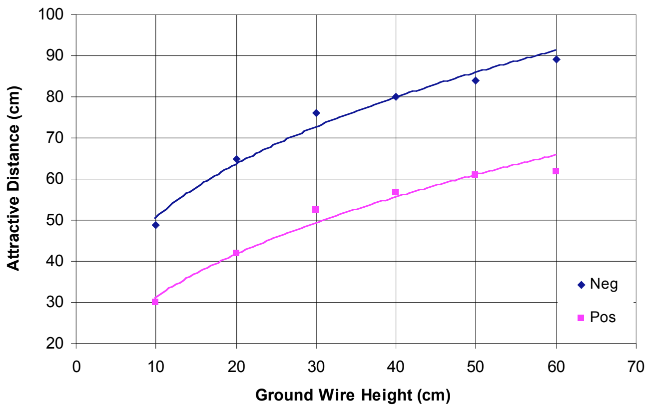


Fig. (5). Attractive distance of one ground wire under negative and positive polarity, H = 73 cm.

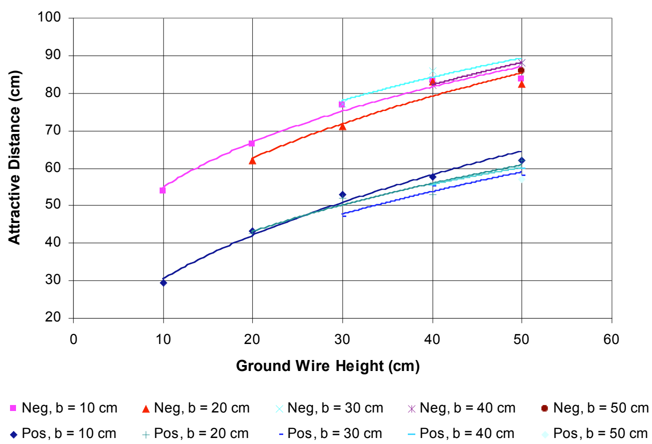


Fig. (6). Attractive distance of two ground wires for different ground wire separation width under negative and positive polarity, H = 73 cm.

3.4. Test results of Single-Circuit Horizontal Lines

Fig. (**7**) presents the measured data from the tests of 5 single-circuit horizontal lines using negative and positive switching impulses, respectively. The attractive distance, X, increased gradually as a function of the ground wire height, h_g. From the test 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. The impact from the presence of phase conductors was not observed. Fig. (**9a**, **b**) show flashes at negative polarity of switching impulses, as observed during the laboratory study. Fig. (**9c**, **d**) show flashes at positive polarity of switching impulses. For a specific test set-up, with a selected attractive distance X, the flashes attached to the transmission line or to the ground with equal probability.

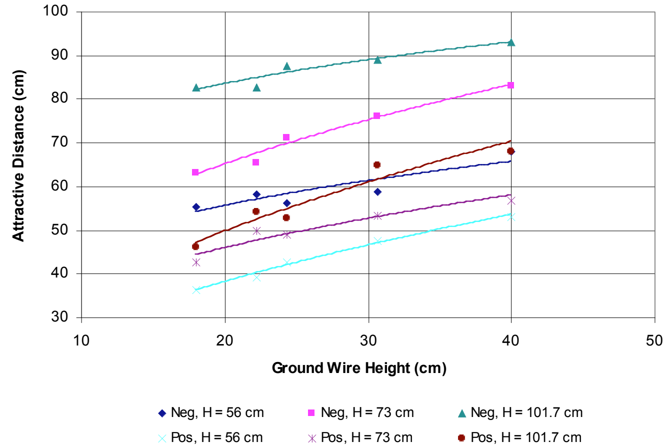


Fig. (7). Attractive distance of single-circuit horizontal lines for different rod heights under negative and positive polarity.

3.5. Test Results of Double-Circuit Vertical Lines

Fig. (**8**) presents measured data from the tests of 4 double-circuit vertical lines using negative and positive switching impulses, respectively. Similar to the previous results, the attractive distance, X, increased gradually as a function of the ground wire height, h_g. The obtained results show that the higher transmission line has the larger attractive distance as compared to the lower one. From these results, it is seen that the ground wire height influences the attractive distance for both polarities. The impact from the presence of phase conductors was not observed. For a specific test set-up, with a selected attractive distance X, the flashes attached to the transmission line or to the ground with equal probability.

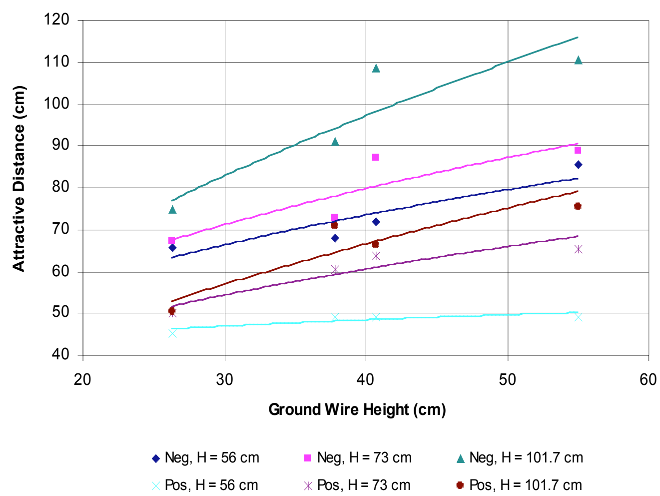
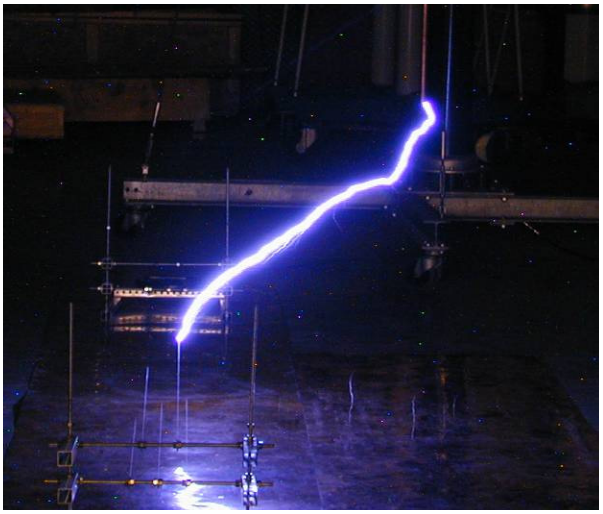


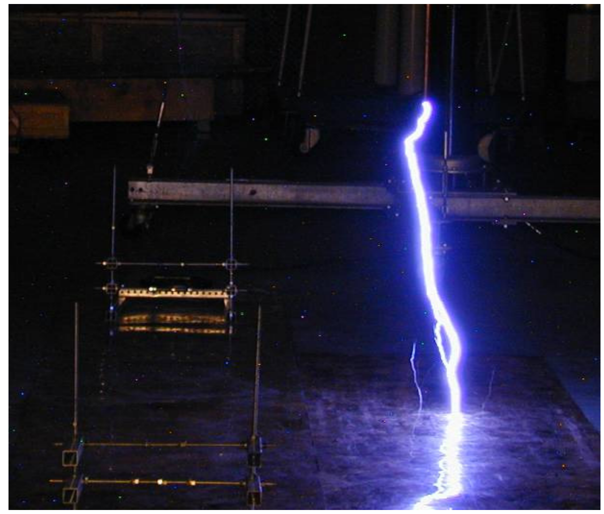
Fig. (8). Attractive distance of double-circuit vertical lines for different rod heights under negative and positive polarity.

4. ANALYSIS AND DISCUSSION

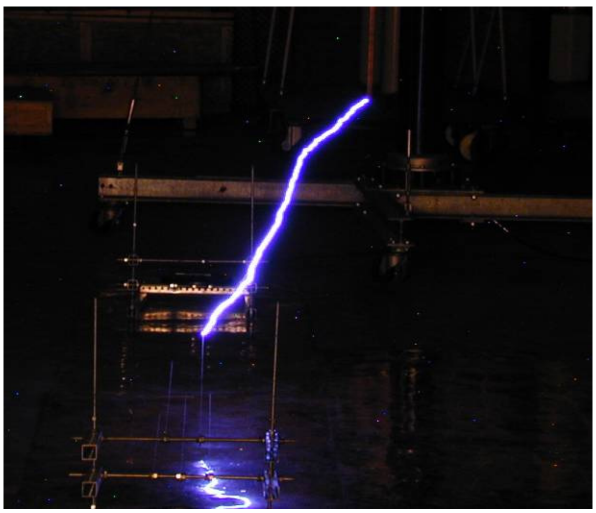
As observed in laboratory experiments, the process of leader attachment to the ground wire or to the ground is quite closely simulated by switching impulse voltages. An upward leader, in response to an approaching downward leader,



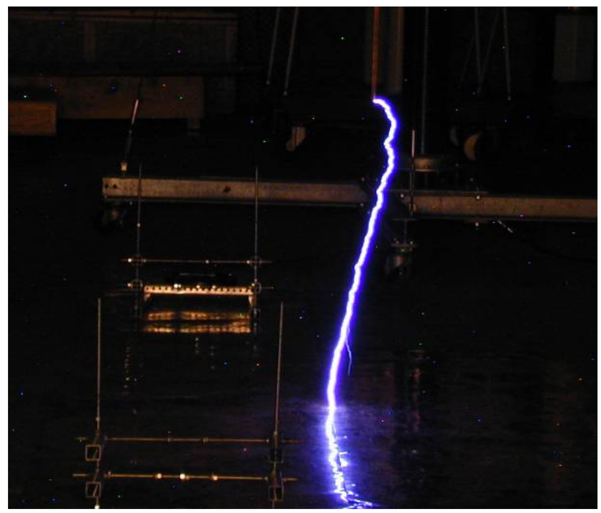
(**a**) Flash to the line, negative polarity.
H: 101.7 cm; h_g: 22.2 cm; X: 82.6 cm.



(**b**) Flash to the ground, negative polarity.
H: 101.7 cm; h_g: 22.2 cm; X: 82.6 cm.



(**c**) Flash to the line, positive polarity.
H: 101.7 cm; h_g: 22.2 cm; X: 54.3 cm.



(**d**) Flash to the ground, positive polarity.
H: 101.7 cm; h_g: 22.2 cm; X: 54.3 cm.

Fig. (9). Photographs of flashes to the single-circuit horizontal transmission line model during experiments.

which is initiated from ground and finally makes contact, is somewhat similar to the natural cloud-to-ground lightning discharge.

All test results for different line configurations, rod heights (correspond to lightning current), and impulse polarities are analyzed in this section. According to the laboratory experiments of the study, the lightning flashes inside the attractive width will strike the transmission line (strike the overhead ground wire), while lightning flashes outside the attractive width will not strike the line; they will strike the ground instead. The effects of ground wire height, rod heights, and impulse polarities are observed.

4.1. Overhead 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 on this impact. If the induced electric field varying with the ground wire height reaches the critical value, an upward leader will initiate and propagate 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 much impact. Thus, the experimental results of one ground wire, with the energized rod equals to 73 cm that corresponds with the median lightning stroke of 30 kA, yield the following expressions for negative and positive polarity, respectively:

$$X = 23.58h_g^{0.33} \tag{2}$$

$$X = 11.85h_g^{0.42} \tag{3}$$

For verification purposes, the estimated attractive distance from this study is compared to that based on different methods by other researchers [8, 11], as shown in Fig. (**10**). Values of the attractive distance, X, and ground wire height are scaled up into m. Only the attractive distance under negative polarity, which is the frequent polarity of lightning strokes, is used for comparison. It can be seen that the attractive distance, X, evaluated in this study reasonably agrees with the others, especially Mousa and Srivastava's model.

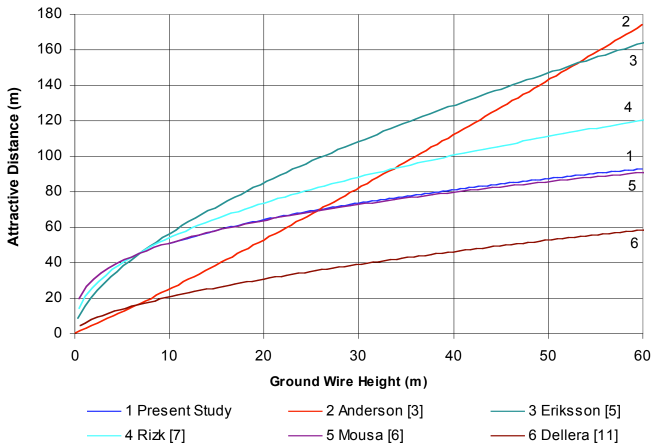


Fig. (10). Attractive distance from this study and other different methods.

4.2. 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 [12, 13]. According to the experimental results for ground wires and transmission line models, the attractive distance for the negative polarity is larger than that for the positive polarity. Therefore, a transmission line will encounter a much lower number of positive lightning strokes compared to negative lightning strokes. This can be explained by the polarity effect on the breakdown mechanisms. For the case of negative lightning, when a negative downward leader approaches to 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.

Note that 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. It also has some negative upward leader, but very short length, from the tower or the ground wire because, according to the field data [9, 25], the velocity of the positive downward leader increases with the propagation of the leader toward the ground while the velocity of the negative downward leader decreases. The characteristic of the positive downward leader appears to be faster than other types of stepped leaders and without distinct steps.

4.3. Lightning Stroke Current

Eventually, the magnitude of a lightning stroke current is the most significant factor for the attractive distance of transmission lines. The return stroke current, which is proportional to the charge and also potential at the downward leader tip, mainly has the impact on the final jump of lightning attachment. The experimental results of transmission line models, with different rod height (H = 56, 73, and 101.7 cm) corresponding to different lightning stroke current (I = 20, 30, and 50 kA), are re-presented in Figs. (**11**, **12**) in order to show the clear picture on the impact of lightning stroke current. It can be 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 higher lightning stroke current (median value = 30 kA) will have the larger attractive distance. This point has not been considered by transmission line designers.

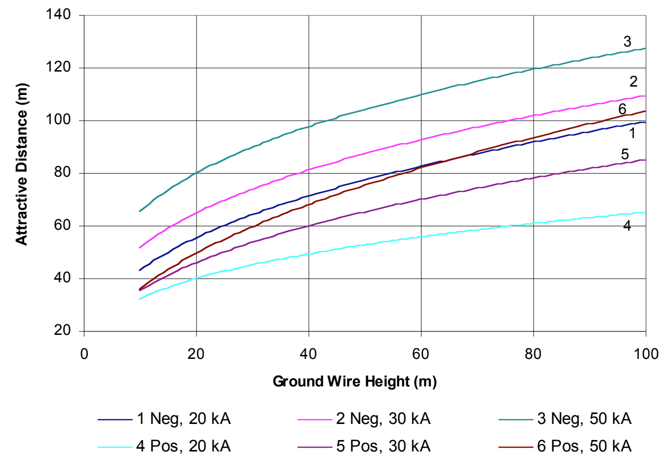


Fig. (11). Attractive distance as a function of ground wire height for different lightning stroke current.

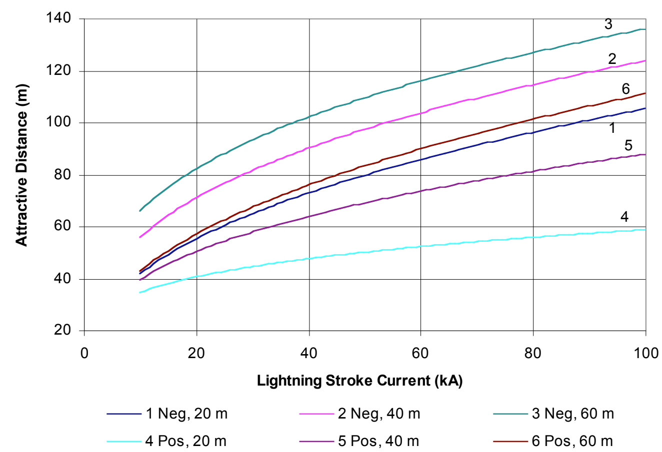


Fig. (12). Attractive distance as a function of lightning stroke current for different ground wire height.

4.4. Validation of the Attractive Width

The attractive width of a transmission line, W, can be estimated by using the attractive distance of overhead ground wires, X, and the ground wire separation width, b. Based on 1,900 applied impulses in total, the estimation of the attractive width for the median lightning current of 30 kA is presented. For a practical use, it yields the following expressions for negative and positive, respectively:

$$W = b + 2X = b + 47.16h_g^{0.33} \tag{4}$$

$$W = b + 2X = b + 23.7h_g^{0.42} \tag{5}$$

Moreover, for validation purposes, the attractive width from this study is compared with derived attractive width, from transmission line observations published in literature [5, 19], as shown in Table **2**. The average ground wire height assumed to be 90% of the tower height is used. For the lower transmission lines, data no. 1 and 4 have the most reliability because they are derived from more observations and longer km years than others. 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. As seen in the table, the attractive width from this study agrees with the transmission line observations.

For a better understanding, 9 observational data from Table **2** are also depicted in Fig. (**13**), together 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 instead.

As shown, the estimation agrees well with the most reliable observation, data no. 1, but deviates from the data nos. 2, 3, 5, 6, and 9. The latter could be analyzed to find out the cause and effect. Observational data were collected from three regions including, the United States, Czechoslovakia, and Japan, by different 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 have the impact on the reliability of data also.

Data nos. 2, 3, and 5 were collected from the very short length of observed transmission lines [22]. It was presented that the distribution of lightning flashes occurs at random, and there are great variations from area to area. Data nos. 6 and 7 have the least reliability among others because they were collected from only one year each [24]. Lightning flash is the phenomenon that varies from year to year, so obtaining average values requires long-term observations over many years [25, 26]. However, the developed estimation of the attractive distance falls between those two data. Data no. 9 were collected over a two-year period, which also was the effect of short-time observations [19].

Moreover, another factor that cannot be ignored is the height of transmission lines. This transmission line has the tower height of 140 m which is vey rare for typical transmission lines and can have an impact. Indeed, upward lightning, which is not in the scope of the research, can become significant at structures having heights above 100 m [5]. This will cause the increasing number of observed lightning flashes to the line, and the derived attractive distance to become larger. Whenever more observational data becomes available, the developed expressions can be calibrated, and the research will be at the finest level.

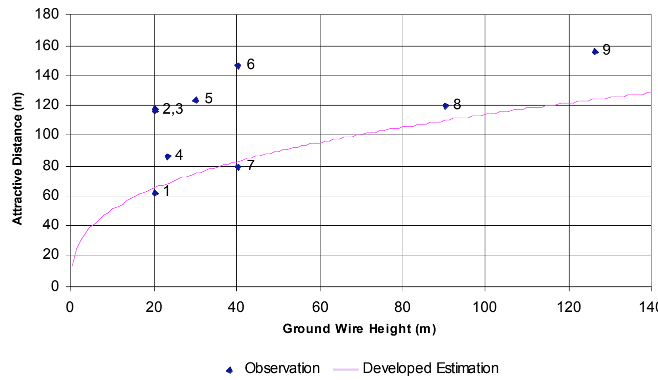


Fig. (13). Attractive distance derived from observations and estimated from the developed expression.

Lightning is an atmospheric discharge which is composed of many processes but the only two processes considered for this research are the process of leaders and attachment. When the downward leader approaches ground, the electric field at the ground and at the grounded objects increase. If the electric field exceeds the critical value, the upward leader will initiate in response to the downward leader. Finally, two leaders making contact ends the attachment process. These mechanisms were similarly observed on laboratory discharges during experiments for model tests, i.e. streamer, leader, and spark. The height of the energized rod corresponds to the striking distance of lightning stroke current, which has been scaled down. Moreover, extrapolation of laboratory data on sparkover distance for lightning striking distance has been acceptably utilized to analytical studies of transmission line shielding [27]. The obtained experimental results, which agree with

Table 2. Attractive Width Derived from Transmission Line Observations Compared to Attractive Width Estimated from This Study

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

NOTE: Data no. 1 are from [20], data no. 2-5 are from [21-23], data no. 6-7 are from [24], and data no. 8-9 are from [19].

the actual transmission line observations from many sources, present the validity of the model test technique.

5. CONCLUSIONS

In this paper, the results from the research on the lightning attractive width were presented. The ground wire separation width practically did not show the 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. Thus, the separation width is increasing the attractive width of the transmission line. The attractive width increased gradually with the height of overhead ground wires as well as the magnitude of lightning stroke current. Impulse polarity had an impact, and the attractive width for negative polarity was larger than that for positive polarity. This was clearly observed in the photographs of flashes.

The electric field distribution and the polarity of lightning play a role on the final step of lightning attachment. The attractive distance, X, of an overhead ground wire from the present study agrees with the other methods from many researches. Based on the experimental results, the mathematical expressions for the attractive width were developed. The attractive width estimated from the presented expressions satisfactorily coincides with the actual transmission line observations. Assuming similarities between the breakdown mechanism for the striking distance (final jump) in a laboratory and the natural lightning phenomena in the final stage, a study of striking distance under lightning condition can be another methodology to investigate the lightning incidence to transmission lines.

CONFLICT OF INTEREST

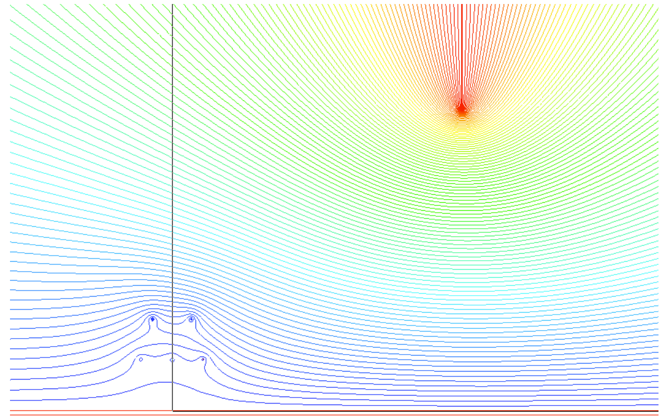
None declared.

ACKNOWLEDGEMENT

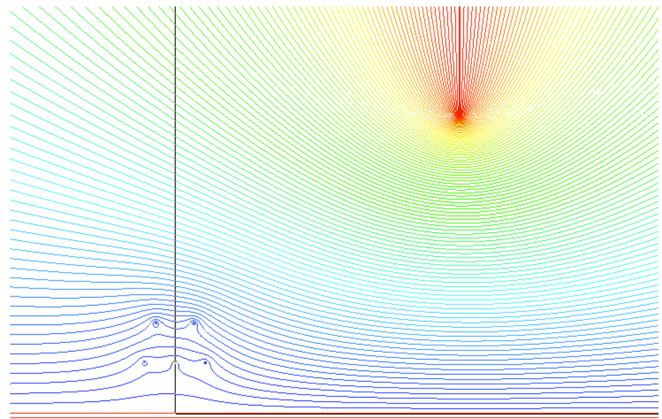
None declared.

APPENDIX

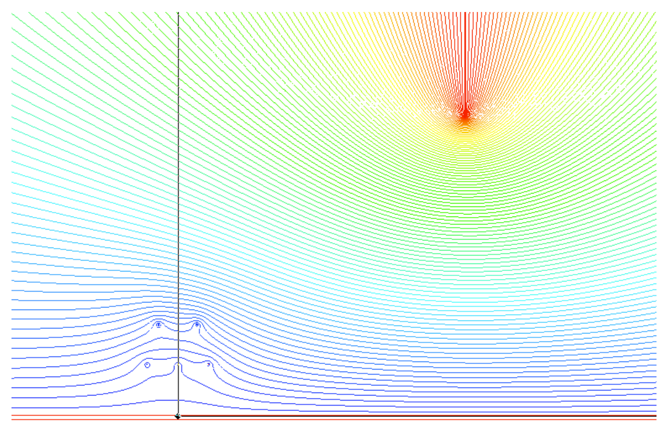
Before starting laboratory experiments, a computer analysis of electric field distribution around transmission lines, in the pre-breakdown stage, also have been performed. The computer analysis was performed by using the electromagnetic field simulation software based on the Finite Element Method (FEM). Transmission lines and lightning leader were modeled in the software and then simulated for visualization of electric fields. An example of electric field distribution for the study using this software, with phase conductors energized and not energized, is shown in Fig. (**14**). The simulation results did not show major differences between each case because the voltage on phase conductors (in the range of kV) is much lower than the voltage on the lightning leader (in the range of MV). This does not affect the electric field distribution around transmission lines. Therefore, phase conductors were not energized and connected to the ground for all experiments.



(**a**) Phase conductors with 0 voltage.



(**b**) Phase conductors with positive voltage.



(**c**) Phase conductors with negative voltage.

Fig. (14). Computer analysis of electric field distribution.

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