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Backflashover Performance Evaluation of the Partially Grounded Scheme of Overhead Lines with fully Composite Pylons

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***Abstract*— A design of a fully composite pylon has been proposed for new-generation 400 kV transmission towers to save line corridors and to reduce visual impact. Correspondingly, a method of external down-leads is proposed to bring grounding potential to the shield wires, together with a plan that not all pylons are grounded called 'partially grounded transmission lines' (PGTLs). This paper investigates backflashover performance of a partial grounding scheme of overhead lines (OHLs) supported by composite pylons. The transient analysis was carried out in PSCAD based on Monte Carlo method. For OHLs with every pylon grounded, reducing footing resistance and soil resistivity can improve backflashover performance effectively, but for PGTLs, these two methods do not have obvious effect and increasing insulation distance has limited effect. When lightning strikes at PGTLs, overvoltage is mainly dependent on the distance to the nearest grounded pylon and a longer distance will cause overvoltage with larger amplitude and longer wave front duration. Therefore, backflashover rate also increases along with the distance to the nearest grounded pylon until reaching a value limited by the inceptive condition of flashover. A coefficient recommended by CIGRE TB 63 to estimate backflashover rate is discussed and modified when using in PGTLs.**

***Index Terms*—backflashover rate, partially grounded, fully composite pylon, lightning overvoltage, grounding, OHLs**

I. Introduction

IN recent years, usage of overhead lines (OHLs) in transmission system has faced with great challenges, because of the increasing requirement for transmission capacity, along with the public opposing to the erection of more conventional metal lattice towers, which have negative visual impact. A fully composite pylon has been proposed to meet the requirements of compact structure and elegant appearance for new-generation transmission towers[1]. The configuration and dimension of the fully composite pylon is shown in Fig. 1. The pylon is in the shape of a 'Y' geometric configuration. Conductors are fixed by clamps on the surface of the cross-arm, which has an inclined angle of 30° from the horizontal ground plane. Two shield wires are installed at the tips of the two cross-arms. Because the pylon body are made of fiber reinforced plastic (FRP) and the cross-arms are design with sheds of silicon rubber on the surface, the pylon itself cannot conduct lightning current if struck by lightning flashes or when lightning flashes terminate at shield wires. Correspondingly, as one choice of grounding design, two bare-metal conductors downwards outside the pylon are used to conduct the lightning current to ground when shield wires are terminated by lightning flashes, which are shown as red lines in Fig. 1, and they are potential locations to install line surge arresters. An alternative of two conductors downwards inside the cross-arms and pylon body to ground is being considered and studied in [2], but it is not be addressed in present paper.

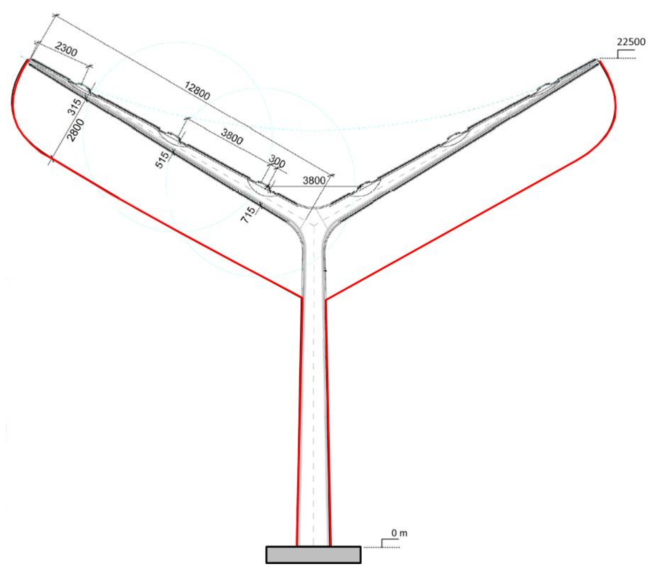

Fig. 1. The design concept of the novel 400 kV fully composite pylon with external grounding down-leads

Out of economic and aesthetic considerations, a scheme where not all pylons are grounded is desirable and investigated in this paper, which is called 'partially grounded transmission lines' (PGTLs). PGTL is designed as a segment of OHLs, which is supported by several ungrounded pylons. At both ends

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of PGTL, it is still necessary to install grounding equipment providing a conducting path when lightning strikes on the shield wires[3]. The grounding equipment can be composite pylons with grounding down-leads, conventional steel transmission towers, or steel tension towers at the corner of PGTLs. According to the travelling wave theory, an overvoltage at a lightning strike location will go on increasing before the negative wave reflected from the ground reaches the striking point[4]. Thus, with a longer distance between the lightning striking point and the grounding point, the lightning overvoltage will become more severe. If the reflection time is shorter than the lightning front time, longer striking distance will cause higher overvoltage amplitude. If the reflection time is longer than the lightning front time, longer striking distance will cause overvoltage with longer duration. Both conditions stress the insulation strength heavily leading to backflashover (BF). Backflashover rate (BFR) is commonly used to evaluate backflashover performance of transmission lines, which is described as the number backflashovers of a transmission lines per 100 km per year.

For conventional OHLs, several papers have studied that the overvoltage with mid-span terminated by lightning is approximately 1.2 to 2.0 times higher than that with tower top terminated by lightning[5-7]. Although the overvoltage at mid-span is higher, the insulation strength of the air gap at mid-span is stronger than the insulator surface on the tower, thus backflashover is less likely to occur at mid-span than at the tower. Therefore, critical lightning current of flashover when lightning strikes at pylon head, I_{c1}, is smaller than critical lightning current of flashover when lightning strikes at mid-span, I_{c2}. Considering this situation, BFR of the entire transmission lines is obtained by the BF probability multiplying a coefficient, which equals to the ratio of the occurring probability of I_{c1} and I_{c2}. For variant spans in conventional OHLs, the ratio according to lightning current probability distribution is in a narrow range from 0.58 to 0.67[7]. Thus, 0.6 is selected as a compromised value.

For PGTL, the distance from lightning location to nearest grounded pylon may be generally longer than most spans in current transmission lines, which will causes overvoltage with higher amplitude and longer duration. On the other hand, insulation strength at cross-arm in ungrounded pylon within PTGL may be generally weaker than mid-span to withstand such severe overvoltage. Therefore, critical lightning current of flashover when lightning strikes at mid-span I_{c2} will be lower, and the ratio of the occurring probability of I_{c1} and I_{c2} increases along with the length of PGTL. The value of the coefficient used in BFR evaluation for PGTL of different length needs to be investigated and revised.

This paper deals with backflashover performance evaluation of the PGTLs supported by the novel composite pylons, using the simulation software PSCAD and the Monte Carlo Method (MCM) and it is organized as follows. Chapter II and III describe the modelling details for the backflashover analysis for composite pylons and propose a procedure to evaluate BFR using MCM. Chapter IV analyzes that the distance of PGTLs is the main factor affecting overvoltage, BF probability and BFR, while conventional methods like reducing footing resistance and soil resistivity, or increasing insulation distance do not have substantial effects. Chapter V analyzes the reason and influencing factor of the stabilization of BF probability and BFR with the increasing of distance to the nearest grounded pylon. Then, the equation used in conventional OHLs to estimate BFR is discussed, and modified when it is used for PGTLs.

II. Modelling of Transmission Lines for Backflashover Analysis

A. Lightning current model

There exist several widely used lightning current simulation waveforms. The effect of lightning current waveforms on the backflashover withstand level is studied and summarized in [8]. Among all models, CIGRE lightning current model is used because of its consistency with the waveshape of lightning flashes in nature[9]. Four variables are used to shape the lightning current waveshape of the first stroke of the downward flash as recommended by CIGRE, namely, the lightning current amplitude I_c, the maximum steepness S_m, the front time (from 30% to 90%) t_f, and the tail time t_h. All the parameters yield to log-normal distribution[10]. The median M and log standard deviation β of the variables are shown in Table I.

TABLE I
The Median and Log Standard Deviation of the Lightning Current Parameters[7]

Variable	M, median	β, log std. deviation
I_c [>20 kA, kA]	33.3	0.605
S_m [kA/μs]	24.3	0.599
t_f [μs]	3.83	0.553
t_h [μs]	77.5	0.577

In this paper, I_c and t_f are treated as the inter-related variables to shape the lightning current waveform. t_h is set as constant equal to its median after concluding that it has little effect on overvoltage level. S_m is set as per unit value determined by I_c and t_f and its base value is equal to the quotient by the medians of I_c and t_f.

B. OHL model

The simulated double-circuit OHL is at rated voltage of 400 kV. At one end of the OHL, phase conductors are connected with a three-phase voltage source and shield wires are solidly grounded. At the other end, the OHL is connected to a load. The PGTL under research is set in the middle. At the ends of PGTL segment, two grounded pylons are modelled, then two 50 km OHLs are set from grounded pylons to voltage source and load respectively. The PGTL segment itself is divided into two parts, in order to simulate the lightning striking location with different distance to grounded pylon. The span is 250 m. The distance of PGTL depends on the amount of ungrounded pylons in PGTL. For instance, the shortest PGTL is 500 m within 1 ungrounded pylon. Fig. 2 shows the demonstration of OHL model with PGTL.

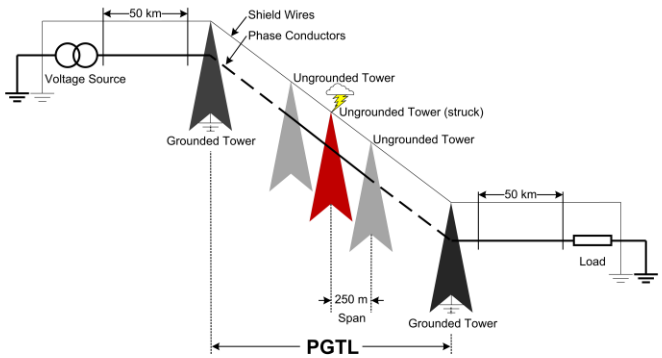

Fig. 2. The demonstration of OHL model within PGTL

C. Down-leads model

The surge impedance of the down-leads varies according to the geometry, as the lightning wave travels from top to ground. To cope with this behavior, the down-leads model is established as a combination of several parts. The 'Bergeron Model' in PSCAD is used to simulate the transient characteristics of each part[11]. The down-lead is regarded as two types of conductors, the part along with pylon body is regarded as a vertical cylindrical conductor whose surge impedance Z_v can be calculated by (1) and the part along with the crossarm is regarded as combination of three horizontal cylindrical conductors whose surge impedance Z_h can be calculated by (2)[12],

$$Z_v = 60(\ln(h_v/r)-1) \tag{1}$$

$$Z_h = 60\ln(2h_h/r) \tag{2}$$

where r is the radius of the down-leads and h is the height of different segment. To be noted, the height of the vertical part h_v is from earth bottom to top and the height of each horizontal segments h_h is from earth bottom to the center of each segment. Fig. 3 shows the demonstration of grounding down-leads and the model in PSCAD. The insulation capacitances are calculated by FEM software.

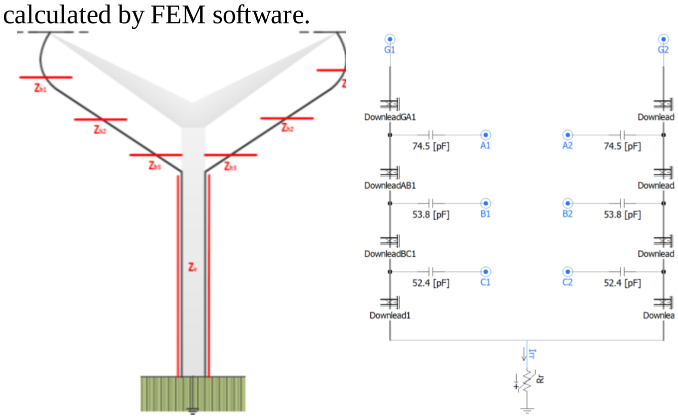

Fig. 3. The demonstration and model of grounding down-leads

D. Tower footing impedance model

After a lightning strike at shield wires of the pylon, the overvoltage waves will travel along the shield wires through the grounding down-leads to ground. A wave in opposite polarity will be reflected after it travels to the pylon base. A concentrated grounding system is selected for modelling pylon base, exhibiting current magnitude dependence from soil ionization[9]. The following current-dependence footing impedance model is used as equation (3) to simulate the footing impedance [13],

$$R_f = \frac{R_0}{\sqrt{1+(I_R/I_g)}} \tag{3}$$

where R_0 is the pylon footing resistance at low frequency and low current, I_R is the lightning current through the footing resistance to ground and I_g is the threshold lightning current initialing the soil ionization described by (4)[14],

$$I_g = \frac{\rho E_0}{2\pi R_0^2} \tag{4}$$

where E_0 is the soil ionization electric field gradient and ρ is the apparent soil resistivity. E_0 can be also related to ρ, in the equation (5)[15],

$$E_0 = 241\cdot\rho^{0.215} \tag{5}$$

E. Leader progression model for flashover

The leader progression method (LPM) considers the physical process of air gap discharge to describe the insulation surface flashover, which mainly consists of two stages: the streamer progression stage T_s and the leader progression stage T_l[16].

The streamer progression time can be calculated by (6)[17],

$$T_s = \frac{1}{k_1(E/E_{50\%})-k_2} \tag{6}$$

where, E is the maximum electric field before insulation flashover and $E_{50\%}$ is the electric field under the 50% flashover voltage. k_1 and k_2 are the factors of streamer progression time, which are recommended to be 1.25 and 0.95 respectively[18].

The leader progression time can be calculated based on its velocity recommended by CIGRE as (7) [10],

$$\frac{dx}{dt} = ku(t)\left(\frac{u(t)}{D-x}-E_l\right) \tag{7}$$

where, x is the length of the leader, $u(t)$ is the voltage at the air gap, D is the length of insulation, E_l is the threshold electric field of leader progression and k is the factor of leader progression speed. E_l and k are related to the type of the insulators and the polarity of lightning impulse voltage, which are obtained from experiments and are shown in Table II.

TABLE II
RECOMMENDED VALUES FOR LEADER PROGRESSION MODEL OF LIGHTNING IMPULSE FLASHOVER

Configuration	Polarity	k [m²/(kV²·μs)]	E_l [kV/m]
Air gaps, post insulators, long-rod polymer insulators	Positive	0.8	600
	Negative	1.0	670
Cap-and-pin porcelain insulators, glass insualtors	Positive	1.2	520
	Negative	1.3	600

For ungrounded pylon, the flashover characteristics between the shield wire and upper phase conductor along the crossarm are more similar to that of a long-rod polymer insulator instead of a cap-and-pin insulator with metallic connecting hardware, thus the parameters of long-rod polymer insulator are selected[19]. For grounded pylon, a flashover is also likely to occur between the down-lead and the phase conductor in the air gap, which uses the same parameters as long-rod polymer insulators. Thus, these two situations can use the same leader progression model.

III. BFR Estimation Procedure

The BFR evaluation procedure based on the Monte Carlo method uses the statistical result of quantities of random lightning surges to evaluate the probability that the backflashover occurs[20]. The procedure consists of three steps: pre-processing step, numerical simulation step and post-processing step.

A. Pre-processing step

In pre-processing step, a large number, N_{total}, of lightning currents were generated. Because the front time of lightning current follows log normal probability distribution, a group of front times were generated using inverse transform sampling. Front time t_f and current amplitude I_c are inter-related. The median of log-normal distribution of I_c can be obtained according to the value of t_f in equation (9)[7],

$$M_I = 19.5 \cdot t_f^{\ 0.39} \tag{9}$$

Then, based on every front time, a group of lightning current amplitudes can be generated based on their medians because of log-normal probability distribution. In this paper, the number of different front times is 100 and the number of different lightning current amplitudes corresponding to every front time is also 100, thus, the number of lightning currents N_{total} is 10000.

B. Numerical simulation step

In numerical simulation step, all lightning currents derived from the previous step were input into the OHLs model established in PSCAD as lightning impulse current source. The overvoltages between down-leads and nearest phase conductors were recorded.

The backflashover probability for every lightning current was estimated considering the operating voltage of the phase conductors. When using LPM to determine the occurrence of backflashover, $u(t)$ in (7) is the voltage at the air gap, which is the difference between the voltages on the down-leads and the operating voltage V on the phase conductors. The operating voltage can be regarded as a constant during the lightning transients because of the relatively extremely short duration of overvoltage. The result after determination of LPM to a certain $u(t)$ is only 1 (flashover) or 0 (not flashover). Hereby, the backflashover probability is related to the probability of the operating voltage in the whole AC cycle when flashover is determined to occur. The different operating voltage values from minimum to maximum are used to determine flashover occurrence with overvoltage together. A critical value of operating voltage V_i can be approached, which means the operating voltage higher than V_i can cause flashover with overvoltage, while the operating voltage lower than V_i cannot. The backflashover probability can be estimated as the ratio of the duration in one cycle when the operating voltage is above V_i for the whole AC period.

C. Post-processing step

In post-processing step, the BFR is calculated after processing the results of backflashover probability of all lightning currents.

The BFR can be expressed in equation (10)[10],

$$BFR = K \cdot N_d \cdot \frac{\sum P(I_C)}{N_{total}} \tag{10}$$

where $\Sigma\ P(I_C)$ is the sum of the backflashover probability of every lightning current and N_{total} is the total number of lightning currents. N_d is the estimated number of lightning strikes that terminate on the 100-km line, which can be calculated by (11)[21],

$$N_d = N_g \cdot (D + 28H^{0.6}) / 10 \tag{11}$$

where N_g is the ground flash density describing the number of flashes that terminate on the ground per year per square kilometers. H is the pylon height and D is the horizontal distance between shield wires. K is a coefficient less than 1, considering that overvoltage at the shield wire caused by lightning flashes striking within the span is lower than that caused by lightning striking at the pylon head. Consequently, the BFR is reduced if lightning flashes striking within the span is considered. In conventional OHLs supported by steel towers, $K = 0.6$ is usually applied in the BFR estimation recommended by CIGRE TB 63 [10, 20, 22-24]. The value of K used in PGTLs is discussed in Chapter V.

IV. Results

A. BFR of different footing resistance and soil resistivity in OHLs with every pylon grounded

For OHLs with every pylon grounded, after lightning strikes at shield wires, the reflections of travelling waves from the tower base through the down-leads arrive at the pylon top much faster than those reflections from adjacent pylons[25]. According to (4) and (5), it can be found that two parameters, the soil resistivity and the footing resistance at low current determine the performance of tower footing impedance. Thus, the BFR of OHLs with every pylon grounded is influenced by these two parameters. The soil resistivity depends on local soil type. Hereby, the Danish soil conditions are selected as case study. The soil of Denmark can be classified into three major types, namely sand in the western and northern region, sandy clay or clayey sand in the center and clay in the southeastern region. The soil resistance and the soil ionization electric field gradient of different soil types are shown in the Table III[26].

TABLE III
The Soil Resistivity and Soil Ionization Electric Field Gradient of Different Soil Types in Denmark

Soil type	Soil resistivity ρ [Ωm]	Soil ionization E-field E_0 [kV/m]
Sand	200-300	752.90-821.48
Sandy clay / clayey sand	50-500	558.85-916.84
Clay	100-200	648.66-752.90

Pylon footing resistance is set as 5Ω, 10 Ω, 20 Ω, and 50 Ω. The BFR of OHLs supported by grounded composite pylons with different combination of pylon footing resistance and soil resistivity is summarized in Fig. 4.

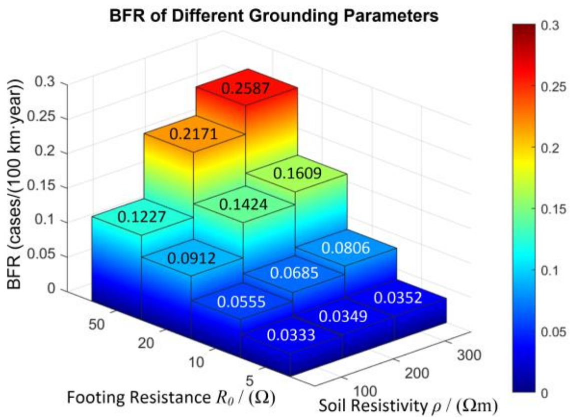

Fig. 4. BFR of OHLs with every pylon grounded of different grounding parameters

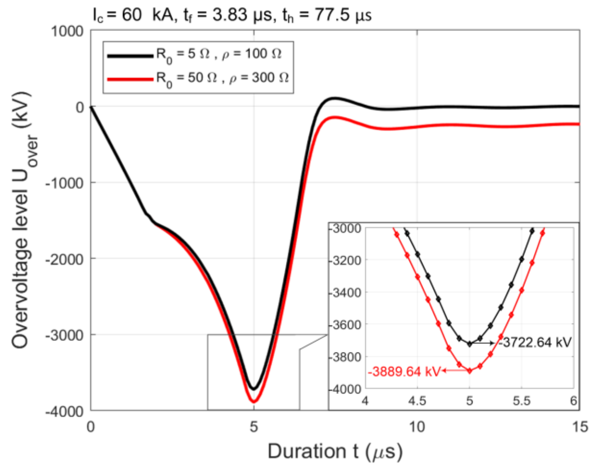

Fig. 5. Overvoltage wave fronts of two combinations of grounding parameters

It can be summarized that for OHLs supported by grounded composite pylons, reducing footing resistance and soil resistivity of grounded pylons can improve backflashover performance effectively, which is identical to the case of OHLs supported by steel lattice towers. When pylon footing resistance is low enough, the effect of reducing soil resistivity is limited.

B. Overvoltage of different footing resistance and soil resistivity in PGTLs

Reducing footing resistance and soil resistivity of grounded pylons can improve backflashover performance effectively in the OHLs where every pylon is grounded. However, for PGTLs neither of the methods are effective.

The wave fronts of overvoltages of different grounding parameters are studied. Hereby, an example under the same lightning strike is shown in Fig. 5, where the PGTLs is 500 m long including only one ungrounded pylon in the middle. The lightning flash with the amplitude of 60 kA (3.83/77.5 μs) strikes in the middle. The maximum overvoltage when the grounded pylons are of lower footing resistance and soil resistivity is -3722.64 kV, which is only 4.5 % lower than when the grounded pylons are of higher footing resistance and soil resistivity, which is -3889.64 kV. For the span of 250 m, the 500 m PGTL with one ungrounded pylon is the shortest scheme. Along with the increasing of PGTL length, the effect of reducing footing resistance and soil resistivity will become even more limited. The differences of the maximum overvoltage on the PGTLs of 1000 m, 1500 m and 2000 m and a strike at the middle of the span are 89.69 kV, 1.85 kV and 0 kV. Moreover, the small differences in overvoltage cannot influence the BFR results obviously.

In summary, when the lightning strikes at the ungrounded pylon, reducing footing resistance and soil resistivity of grounded pylons at the both ends of PGTLs has limited effect on the amplitude of overvoltage and so as to the BFR.

C. Overvoltage of lightning location in PGTLs

Because the pylons within PGTLs are not grounded, when lightning flashes terminate at the shield wires, the overvoltage wave will travel to both ends in opposite directions on the shield wires and go into ground through the grounded pylons. The travelling distances to the two ends are different except when lightning strikes at right middle. Hereby, D_{near} is termed as the nearer travelling distance from lightning location to one of the grounded pylon while D_{far} is termed as the longer one.

The overvoltage at lightning location in PGTLs with different distance to grounded pylons can be seen in Fig. 6 and Fig. 7. The lightning surge is 35 kA (3.83/77.5 μs). If the D_{near} is the same, the overvoltage waveforms with different D_{far} are similar, especially in the wave front duration. The maximum values of overvoltage range from -2289.55 kV to -2708.74 kV, increasing by 18.31 %. If lightning current amplitude is lower, the dispersion is even smaller. However, if D_{far} is the same, the overvoltage waveforms with different D_{near} are obviously different. The maximum values of overvoltage range from -2708.74 kV to -4182.65 kV, increasing by 54.41%. The discrepancy among the overvoltage waveshapes becomes also larger. Along with the increasing of D_{near}, the waveshape of the overvoltage changes from a 'V' shape to a 'U' shape, forming a flat bottom. This is because the time for the overvoltage at the striking point to reach its peak is shorter than that for the reflection wave from ground to reach the striking point. Before the arrival of the reflection wave, the waveshape of the overvoltage is consistent with the shape of the lightning current. After the arrival of reflection wave, the overvoltage wave is chopped by superimposing the reflection wave. During the propagation of overvoltage wave on shield wires after lightning striking, corona will damp the energy, which will reduce overvoltage amplitude. Along with the increase of travelling distance, damping effect of corona will become larger[27].

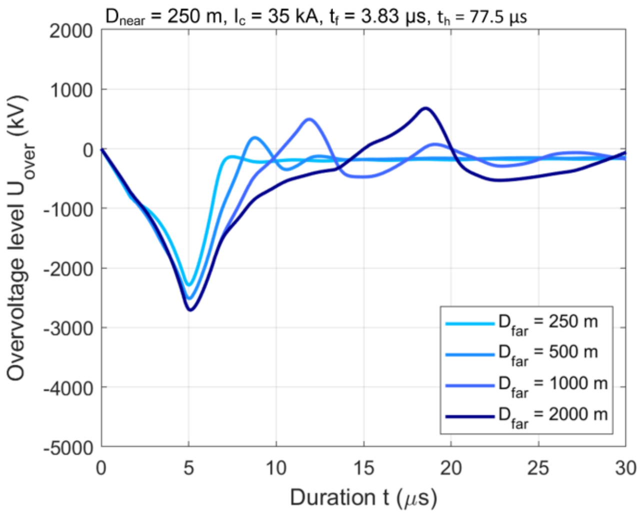

Fig. 6. Overvoltage wave fronts of same D_{near} and different D_{far}

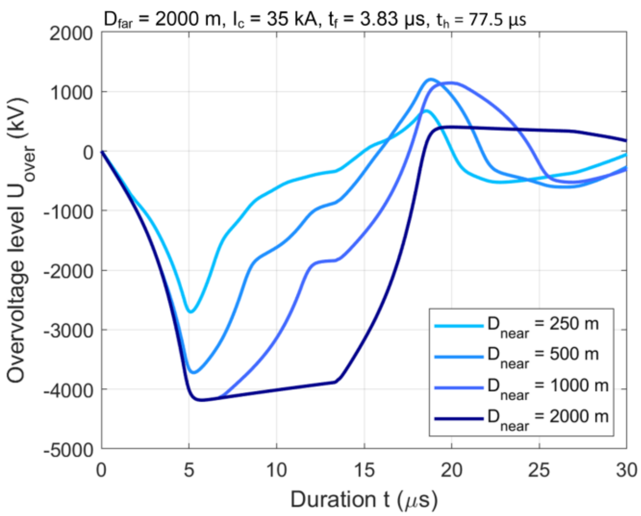

Fig. 7. Overvoltage wave fronts of same D_{far} and different D_{near}

In summary, in PGTLs, lightning overvoltage is mainly dependent on the distance to the nearest grounded pylon. Longer distance to the nearest grounded pylon will cause overvoltage with larger amplitude and longer wave front.

D. BFR of different distances of PGTLs

According to (10), BFR is the product of the amount of lightning flashes terminating on 100 km lines per year and the backflashover probability caused by lightning flashes, based on MCM procedure. Backflashover probability is resulted from lightning overvoltage which is mainly dependent on the distance to the nearest grounded pylon as elaborated in the last section.

The backflashover withstand levels of the ungrounded pylons after lightning striking with different distances to nearest grounded pylons is shown in Fig. 8. For a grounded pylon, its BF withstand level is 83 kA. After After the nearest distance increases to exceed 750 m, the BF withstand level stabilizes at 28 kA. The backflashover probability when lightning strikes at the PGTLs for different distances to nearest grounded pylon is shown in the Fig. 9. When the distance from the lightning location to the nearest grounded pylon increases, the BF probability also increases, because of the increase of the overvoltage amplitude and wave front duration. After the nearest distance increases to exceed 750 m, the BF probability stabilizes at 0.6149.

Lightning flashes may not only strike at pylons, but also strike in span. The overvoltage at the pylon caused by lightning flashes striking within the span is lower than that caused by the same lightning strike at the pylon head. Therefore, a coefficient K is considered which is less than 1. For PGTLs, the analysis of the value of K is discussed in next chapter. Hereby, K increases and approaches to 1, along with the increasing of the distance between ungrounded pylon and grounded pylon. Therefore, BFR can be calculated by equation (10). The BFR of different length of PGTL is shown in the Fig. 10, which increases and approaches to 17.3161 cases per 100 km per year along with the increase in the length of PGTL. To be noted, because the span is 250 m, the length of 250 m means the pylons in OHL are all grounded. A PGTL of 500m has 1 ungrounded pylon, a PGTL of 750 m has 2 ungrounded pylon inside, and so on.

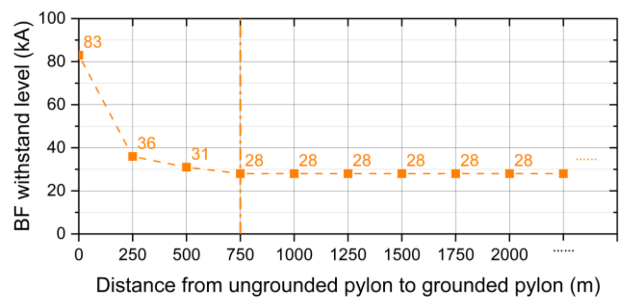

Fig. 8. BF withstand level of different distances to nearest grounded pylon

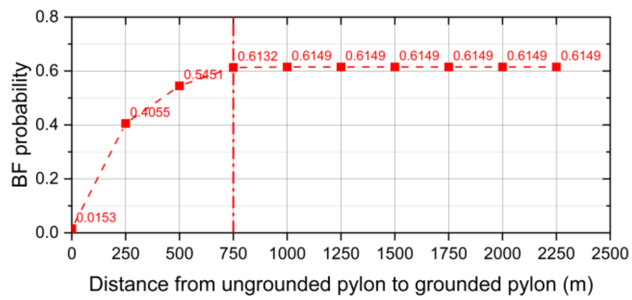

Fig. 9. BF probability of different distances to nearest grounded pylon

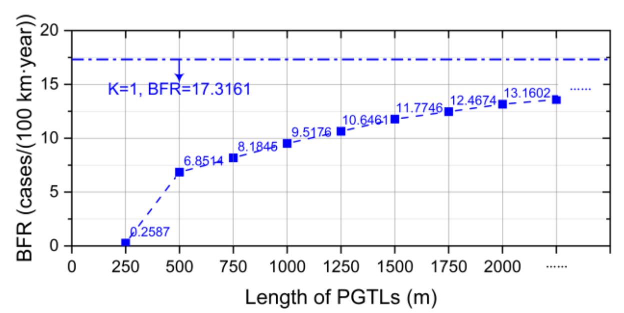

Fig. 10. BFR of different length of PGTLs

In Section IV.B, the ineffectiveness of reducing footing resistance and soil resistivity to improve backflashover performance of PGTLs was summarized. Another alternative method is increasing the insulation distance between the shield wire and the upper phase conductor. To be noted from equation (11), increasing insulation distance will increase the pylon height and shield wires corridor width, which means the OHLs will attract more lightning flashes. The BFRs along with different distance between ungrounded pylon and grounded pylon provided by different insulation distances are shown in following Fig. 11. It can be seen that increasing insulation distance has limited effect for practical application.

In summary, the BFR of PGTLs increases along with the distance to the nearest grounded pylon, until it reaches a limit value. Besides reducing footing resistance and soil resistivity, increasing insulation distance has limited effect for practical application either.

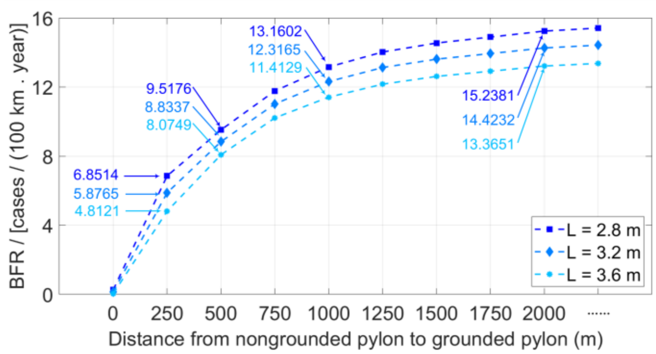

Fig. 11. Effect of increasing insulation distance L on BFR of different PGTLs distances

V. Discussion

A. Discussion on the stabilization of BF probability of long-distance PGTLs

The reason for the stabilization of the BF probability is explained and the determining factor is discussed in this chapter. The stabilization of the BF probability results from the stabilization of the maximum value of overvoltages along with the increase of the distance to the nearest grounded pylon. A distance over 750 m corresponds to a reflection wave travelling time that exceeds 5.36 μs, which is longer than the front time of 72.83% of the lightning currents, according to the cumulative distribution function of lightning current parameters. Therefore, the maximum value of overvoltages is not influenced by the majority of lightning impulses when travelling time exceeds 5.36us. As a result, the BF probability stabilizes when distance to the nearest grounded pylon exceeds around 750 m.

The value of the maximum BF probability 0.6149 is limited by the threshold electric field of leader progression development E_l in (7). Based on the mechanism of leader progression, it is necessary for flashover occurrence that the electric field exceeds E_l and keeps over E_l continuously during the development of leader progression. When distance to the nearest grounded pylon increase over 750 m, the wave front of the overvoltage is long enough for the leader progression to develop as flashover. Once the inceptive condition of leader progression is satisfied, the longer duration of the 'U' shape bottom may ensure the occurrence of flashover. Thus, as the inceptive condition for leader progression, the threshold electric field E_l is significant to evaluate the flashover.

At present, the value of threshold electric field E_l is recommended by CIGRE when using leader progression model to determine the occurrence of flashover, which was derived from the results of experiments in [17]. Catering to the industrial demand, line post insulators and suspension insulators were tested and their E_l were analyzed under different impulse polarities. Given the lacking of experimental data, threshold electric field E_l of composite crossarm, one can refer to that of polymer insulators, because of similarity in electrical design. They both have sheds made of silicon rubber and composite material.

Despite this, a sensitivity analysis based on the different values of threshold electric field E_l, which were derived in experiments under different conditions. Among all, the values obtained by Motoyama[28] and Xi[29] present the highest and lowest under the negative lightning impulse. The tested models and conditions are summarized in Table IV. The sensitivity analysis results are shown in Fig. 12. When the value of E_l changes ±10%, the deviation of BF probability is around ±5%. The sensitivity coefficient is -0.52, whose absolute value less than 1. In summary, firstly, the stabilized BF probability is closely related to E_l. Secondly, although there is no such experimental data to provide exact value of E_l for crossarm, the simulating BF probability is also convincing considering the uncertainty of E_l in a probable range.

TABLE IV
THE TEST CONDITIONS AND FITTED THRESHOLD ELECTRIC FIELD

Scholar	Gap type	Waveform	Polarity	E_l [kV/m]
Pigini 1989[17] & CIGRE 1991[10]	line post insulator	1.6/50	+	600
		0.5/50	−	670
Motoyama 1996[28]	rod-rod air gap	1.2/3.2	±	750
Xi 2014[29]	composite insulator	1.45/11	+	620
		1.56/49.2	−	570

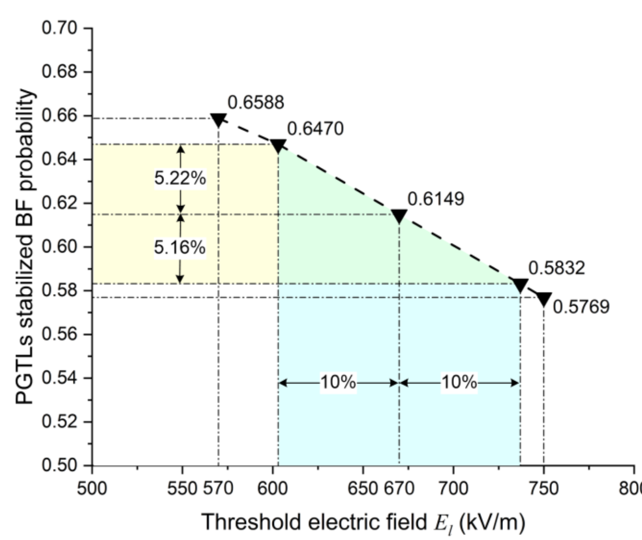

Fig. 12. Sensitivity analysis result of PGTLs stabilized BF probability to the threshold electric field E_l

However, there still exist some differences between crossarm and polymer insulators. For instance, the air gap of crossarm is much longer than that of line post insulator and the E_l of insulators was tested under standard lightning impulse voltage[16, 17, 29]. From [28], for short tail lightning impulse, the value of E_l might be higher. In a word, the threshold electric field of leader progression used for crossarm is higher than the practical value recommended by CIGRE, which is necessary to be revised in experiments in further research. Thus, the actual BF performance might not be worse than simulating results.

B. Discussion on span flashover coefficient K of long-distance PGTLs

In this section, the value of K is analyzed and discussed. In the past, most researchers used (10) to estimate BFR and $K=0.6$ is recommended[7].

For PGTLs, the overvoltage caused by lightning flashes striking at the ungrounded pylon head in the middle of PGTLs is higher than at mid-span and at other pylon heads. Therefore, the backflashover probability at the ungrounded pylon in the middle of PGTLs is the highest. From middle to the grounded pylons, BF probability decreases. The value of K can be estimated by the unitization of BF probability.

The following Fig. 13 shows the estimation of K for the PGTLs of different distance for example. At the ends of the PGTLs, there are two grounded pylons. Within the PGTLs, there locate ungrounded pylons with the span of 250 m. The PGTLs length of 500 m, 1000 m, 1500 m, and 2000 m means the number of ungrounded pylons within PGTLs is 1, 3, 5, and 7 correspondingly. The origin of horizontal axis is where the middle ungrounded pylon locates. The first step is the unitization of BF probability, which means the highest BF probability is regarded as 1, and the unitized BF probability of other ungrounded pylons equals to the ratio of their BF probability to the highest BF probability. Thus, the unitized BF probability of the middle ungrounded pylon is 1 and the BF probability at grounded pylons are extremely low compared with that of middle pylon which can be regard as 0. From the middle ungrounded pylon to the grounded pylon, the unitized BF probability decreases from 1 to 0 and the height of every pylon is its unitized probability. The second step is the probability average. As a result of the first step, the blue region in Fig. 12 is the unitized BF probability distribution of every pylon in PGTLs. The red region is in the same area of the blue region, which averages the unitized BF probability of pylon to the entire line. Because of unitization, the height of red region is the value of K. Finally, the product of K multiplying the highest BF probability of pylon in PGTL is the BF probability of the entire line.

It can be derived that the value of K increases and approaches to 1 but always less than 1, along with the increasing of the distance of PGTLs. In this case, the K for PGTLs with different lengths, represented by the amount of ungrounded pylons N within PGTLs, can be induced in following equation (11). When N ranges from 1 to 4, K is from 0.5 to 0.65. To be concise in equation, before the amount of ungrounded pylons N increases to the critical amount for stabilization, K is compromised and unified as 0.6 here referring to the value recommended by CIGRE. When N exceeds 5, the BF probability starts to stabilize and the value of K is formulated by N.

$$K = \begin{cases} 0.6 & (1 \le N \le 4) \\ 1 - \dfrac{1.9}{N+1} & (N \ge 5) \end{cases} \tag{11}$$

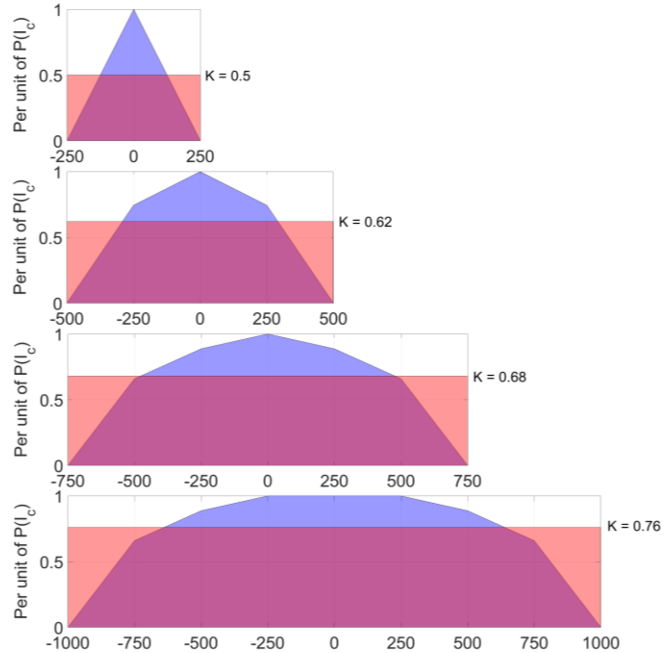

Fig. 13. Demonstration of the BF probability unitization and estimation of K

VI. CONCLUSIONS

This paper investigated the backflashover performance of a partial grounding scheme of OHLs supported by a novel fully composite pylon. The OHLs was established and the transient analysis was carried out in PSCAD based on Monte Carlo method. A coefficient used in the equation estimating backflashover rate is discussed and modified when it is used in partial grounding OHLs. The following conclusions can be drawn:

(1) For common OHLs supported by composite pylons without using PGTLs, reducing footing resistance and soil resistivity of grounded pylons can improve backflashover performance effectively according to the local soil characteristics in Denmark.

(2) For PGTLs supported by composite pylons, when the lightning strikes at the ungrounded pylon, reducing footing resistance and soil resistivity of grounded pylons at the both ends of PGTLs does not have obvious effect. Increasing insulation distance has limited effect to some extent. Future emphasis may lie in the application and coordination of surge arresters.

(3) For PGTLs supported by composite pylons, lightning overvoltage is mainly dependent on the distance to the nearer grounded pylon and longer distance to the nearest grounded pylon will cause overvoltage with larger amplitude and longer wave front duration. Future research will consider corona effect during the propagation of overvoltage on shield wires.

(4) For PGTLs supported by composite pylons, BF probability and BFR increase along with the longer distance of PGTLs, but are limited to a certain value, which is determined by the lightning current probability distribution in the nature and the threshold electric field of leader progression development.

(5) The value of the coefficient *K* to estimate BFR considering the lightning striking in mid-span of shield wire has been examined for PGTLs. *K* increases and approaches to 1, along with the increasing of the distance of PGTLs supported by composite pylons.

References

[1] BYSTRUP. "THE COMPOSITE PYLON." https://www.powerpylons.com/composite-pylon (accessed.

[2] T. Jahangiri, Q. Wang, C. L. Bak, F. F. d. Silva, and H. Skouboe, "Electric stress computations for designing a novel unibody composite cross-arm using finite element method," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 6, pp. 3567-3577, 2017, doi: 10.1109/TDEI.2017.006802.

[3] C. Hu *et al.*, "Investigation on 110kV composite material pole: Effects of grounding methods on insulation of conductor-pole gaps," in *2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, 19-22 Sept. 2016 2016, pp. 1-5, doi: 10.1109/ICHVE.2016.7800782. [Online]. Available: https://ieeexplore.ieee.org/ielx7/7784673/7800563/07800782.pdf?tp=&arnumber=7800782&isnumber=7800563&ref=

[4] J. Li, *Measurement and Analysis of Overvoltages in Power Systems*. Wiley Online Library, 2018.

[5] T. Udo, "Estimation of lightning shielding failures and mid-span back-flashovers based on the performance of EHV double circuit transmission lines," *IEEE Transactions on Power Delivery*, vol. 12, no. 2, pp. 832-836, 1997, doi: 10.1109/61.584393.

[6] N. Rugthaicharoencheep, W. Thansiphraserth, and A. Phayomhom, "Comparison voltage across insulator strings of 69 kV and 24 kV lines due to lightning strokes to top pole and mid span," in *2012 47th International Universities Power Engineering Conference (UPEC)*, 4-7 Sept. 2012 2012, pp. 1-5, doi: 10.1109/UPEC.2012.6398426. [Online]. Available: https://ieeexplore.ieee.org/document/6398426/

[7] A. R. Hileman, *Insulation Coordination for Power Systems* (POWER ENGINEERING). Taylor & Francis Group, 1999.

[8] Y. Han, L. Li, H. Chen, and Y. Lu, "Influence of Modeling Methods on the Calculated Lightning Surge Overvoltages at a UHVDC Converter Station Due to Backflashover," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1090-1095, 2012, doi: 10.1109/TPWRD.2012.2190306.

[9] M. S. Banjanin and M. S. Savić, "Some aspects of overhead transmission lines lightning performance estimation in engineering practice," *International Transactions on Electrical Energy Systems*, vol. 26, no. 1, pp. 79-93, 2016/01/01 2016, doi: 10.1002/etep.2069.

[10] W. S. 33, "Guide to procedures for estimating the lightning performance of transmission lines," CIGRE 1991, vol. 63.

[11] J. A. Martinez and F. Castro-Aranda, "Tower modeling for lightning analysis of overhead transmission lines," in *IEEE Power Engineering Society General Meeting, 2005*, 16-16 June 2005 2005, pp. 1212-1217 Vol. 2, doi: 10.1109/PES.2005.1489355.

[12] T. Hara and O. Yamamoto, "Modelling of a transmission tower for lightning-surge analysis," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 143, no. 3, pp. 283-289, 1996, doi: 10.1049/ip-gtd:19960289.

[13] T. Hara, Y. Yasuda, Y. Hirakawa, N. Hayanose, K. Nomura, and K. Kawabata, "Flashover analyses of 500 kV transmission towers with nonlinear and capacitive grounding impedance model," in *1999 Eleventh International Symposium on High Voltage Engineering*, 27-23 Aug. 1999 1999, vol. 2, pp. 292-295 vol.2, doi: 10.1049/cp:19990650.

[14] A. M. Mousa, "The soil ionization gradient associated with discharge of high currents into concentrated electrodes," *IEEE Transactions on Power Delivery*, vol. 9, no. 3, pp. 1669-1677, 1994, doi: 10.1109/61.311195.

[15] F. E. Asimakopoulou, I. F. Gonos, and I. A. Stathopulos, "Methodologies for determination of soil ionization gradient," *Journal of Electrostatics*, vol. 70, no. 5, pp. 457-461, 2012/10/01/ 2012, doi: https://doi.org/10.1016/j.elstat.2012.07.003.

[16] T. Shindo and T. Suzuki, "A New Calculation Method of Breakdown Voltage-Time Characteristics of Long Air Gaps," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 6, pp. 1556-1563, 1985, doi: 10.1109/TPAS.1985.319172.

[17] A. Pigini, G. Rizzi, E. Garbagnati, A. Porrino, G. Baldo, and G. Pesavento, "Performance of large air gaps under lightning overvoltages: experimental study and analysis of accuracy predetermination methods," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1379-1392, 1989, doi: 10.1109/61.25625.

[18] X. Chen, X. Wen, and L. Lan, "Application of the Leader Progression Model in the Insulation Flashover Criterion for Lightning Performance Calculation," in *Proceedings of the Second International Conference on Mechatronics and Automatic Control*, Cham, W. Wang, Ed., 2015// 2015: Springer International Publishing, pp. 459-466.

[19] D. Filipović-Grčić, B. Filipović-Grčić, D. Brezak, I. Uglešić, and A. Tokić, "Leader progression model application for calculation of lightning critical flashover voltage of overhead transmission line insulators," in *2012 International Conference on Lightning Protection (ICLP)*, 2-7 Sept. 2012 2012, pp. 1-8, doi: 10.1109/ICLP.2012.6344266.

[20] P. Sarajcev, "Monte Carlo method for estimating backflashover rates on high voltage transmission lines," *Electric Power Systems Research*, vol. 119, pp. 247-257, 2015/02/01/ 2015.

[21] A. J. Eriksson, "An Improved Electrogeometric Model for Transmission Line Shielding Analysis," *IEEE Transactions on Power Delivery*, vol. 2, no. 3, pp. 871-886, 1987, doi: 10.1109/TPWRD.1987.4308192.

[22] F. H. Silveira, S. Visacro, and R. E. Souza, "Lightning performance of transmission lines: Assessing the quality of traditional methodologies to determine backflashover rate of transmission lines taking as reference results provided by an advanced approach," *Electric Power Systems Research*, vol. 153, pp. 60-65, 2017/12/01/ 2017, doi: https://doi.org/10.1016/j.epsr.2017.01.005.

[23] F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and A. Santarpia, "An ATP-EMTP Monte Carlo procedure for backflashover rate evaluation: A comparison with the CIGRE method," *Electric Power Systems Research*, vol. 113, pp. 134-140, 2014/08/01/ 2014, doi: https://doi.org/10.1016/j.epsr.2014.02.031.

[24] F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and A. Santarpia, "An ATP-EMTP Monte Carlo procedure for backflashover rate evaluation," in *2012 International Conference on Lightning Protection (ICLP)*, 2-7 Sept. 2012 2012, pp. 1-6, doi: 10.1109/ICLP.2012.6344362.

[25] J. A. G. R *et al.*, "Nonuniform transmission tower model for lightning transient studies," *IEEE Transactions on Power Delivery*, vol. 19, no. 2, pp. 490-496, 2004, doi: 10.1109/TPWRD.2003.823210.

[26] K. Adhikari, "Soil Mapping in Denmark Using Digital Soil Mapping Techniques," PhD, AArhus University, 2013.

[27] X. Liu, J. Yang, G. Liang, and L. Wang, "Modified field-to-line coupling model for simulating the corona effect on the lightning induced voltages of multi-conductor transmission lines over a lossy ground," *IET Generation, Transmission & Distribution*, vol. 11, no. 7, pp. 1865-1876. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/iet-gtd.2016.1340

[28] H. Motoyama, "Experimental study and analysis of breakdown characteristics of long air gaps with short tail lightning impulse," *IEEE Transactions on Power Delivery*, vol. 11, no. 2, pp. 972-979, 1996, doi: 10.1109/61.489359.

[29] X. Wang, Z. Yu, and J. He, "Breakdown Process Experiments of 110- to 500-kV Insulator Strings Under Short Tail Lightning Impulse," *IEEE Transactions on Power Delivery*, vol. 29, no. 5, pp. 2394-2401, 2014, doi: 10.1109/TPWRD.2014.2306688.