Quantifying the Shielding Effect of Trees against Lightning Strikes for Power Transmission Lines

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***Abstract*—Power transmission lines are often built along terrains where trees surround the right-of-way in British Columbia, Canada. These trees provide natural shielding against direct lightning strokes to transmission lines. In this paper, a new method is proposed to quantify the shielding effect of trees based on LiDAR survey data. This method takes as input the statistical parameters for the trees around the edge of the right-of-way such as heights, distance to centerline, and density per span. LiDAR survey data are collected for transmission line corridors in BC Hydro's system. Calculation results are shown for a new transmission line project in British Columbia.**

***Index Terms*—Lightning performance, shielding effect of trees.**

I. Introduction

Transmission lines are usually shielded to protect the phase conductors against direct lightning strokes. Shield wires provide a path for the lightning current to discharge to ground through the structures and their associated grounding. If the transmission line is not shielded, a transient over-voltage appears in the struck phase(s), and if the voltage is high enough, a flashover will occur across the insulators. The arc across insulator strings will be sustained by the power frequency current, causing a ground fault. If no damage is made to the insulator strings, a breaker re-closing action usually restores the line. The discharge of lightning current in the ground causes a voltage rise, usually referred to as ground potential rise (GPR). In the case of a shielded transmission line, if the GPR is higher than the basic insulation level (BIL) of the insulator strings, a back-flashover will occur. To avoid this problem, the structure grounding resistance is reduced. A minimum grounding resistance can be calculated to minimize the risk of back-flashovers, though it cannot be totally eliminated due to the tower surge impedance. Due to the particular circumstances in the province of British Columbia, transmission lines are not shielded, except for a short section outside the substations.

The soil resistivity in BC is relatively high due to the rocky terrain. In order to minimize the risk of back-flashover on shielded structures, the structure grounding resistance should be sufficiently small. In a high soil resistivity area, this translates into prohibitive cost figures.

In summary, the following three factors have driven BC Hydro not to fully shield the transmission lines:

- Relatively low ground flash density
- Natural shielding by trees
- Rocky terrains and high soil resistivity

The average ground flash density for Western Canada can be obtained from Environment and Climate Change Canada's website [1]. BC has the lowest keraunic level compared to the neighboring provinces and states. Most of the long transmission lines in BC were built in terrains surrounded by trees. Trees provide natural shielding against lightning for transmission lines. The shielding effect from trees is quantified in this study using simulations with a commercial software (SESShield-3D). This program adopts the electro-geometric model (EGM), based on the proposed methods by Mousa [2] and Eriksson [3].

Although full shielding of transmission lines is not BC Hydro's practice, short sections outside the substations are typically shielded. In particular, 1 km for 230 kV and 287 kV, and 1.6 km for 345 kV and 500 kV lines are shielded outside the substations at both ends of the lines. This practice is to reduce the rate of rise of the lightning-initiated transient over-voltage (TOV) traveling along a struck phase conductor towards the substations. Surge arresters may not be able to operate for very fast TOV waves. Those cases are usually encountered when the lightning flash terminates on the lines very close to the substations. As the TOV wave travels down the line, its rate of rise and peak attenuate, as shown in [4]. The approximate distances provided, i.e. 1km and 1.6km, have been calculated based on the rate of rise tolerance of station surge arresters for lightning-initiated TOVs.

At the design stage, the lightning performance of transmission lines is analyzed and compared against the acceptable design criterion. For unshielded critical lines, BC Hydro adopted the industry-accepted guideline of 1 flashover/100km/year. The line performance over a few spans is studied and the result is generalized to the entire length of the line. In this paper, a methodology is proposed for evaluating the shielding effect of trees using statistical methods. In BC Hydro, Light Detection and Ranging (LiDAR) data is usually collected for new transmission corridors to assist the overhead designers determine the optimal path and the required clearances. This set of data contains the coordinates of the objects on the ground, such as trees, and their heights. This data set is used to create a statistical database for trees and is subsequently used for lightning performance analysis.

The shielding effect of trees has been studied in [5] and the detailed calculation method was described therein. Although the method is comprehensive, it is rather complicated to be implemented for each new transmission line, various tree densities, heights, and distances to centerline. It was deemed necessary to develop a new method that works based on statistical calculations and takes into account the actual effect of trees for a given transmission line using LiDAR data.

II. Shielding Effect of Trees

Occasionally, transmission line corridors are located within naturally-grown forests. In those cases, tree clearing is carried out to create a sufficient right-of-way (ROW) for building a transmission line. The level of shielding provided by trees depends on several factors, such as distance to centerline, tree height, and tree density (measured by average number of trees per span). This information can be obtained from the LiDAR survey data.

The proposed method for estimating the shielding effect of trees is explained here through an actual case study for a new 287 kV line in BC Hydro. As an example, the statistical analysis done on a set of LiDAR data collected for a transmission corridor around the North West area in BC showed that the average tree height is about 23m with a standard deviation of 31%. The histogram of the tree heights and their distances to the centerline is shown in Fig. 2. The frequency of occurrence is referred to as $P^{HD}(H, D)$, where H and D are the tree heights and distances to the centerline, respectively.

The base case results on the shielding effect of trees were obtained using SESShield-3D software. Three factors are studied here: tree height, tree density (number of trees per span), and distance to centerline. The results of this analysis are shown in Figs. 3 and 4. In this analysis, ten spans were built in the program and the results are the average of the ten spans. The number of flashes terminated on the conductors and structures is calculated separately. Note that no shield wire is assumed. The parameters used for the simulations are defined in Fig. 1. Ground flash density was assumed 1 flashes/km^2/year.

In case of no trees, the number of flashes collected by the conductors in one span is about twice as many as the flashes collected by each structure. For the case of one tree per span, a tree is placed in the middle of the span on each side, which explains the negligible impact on the number of flashes collected by the structures in this case. Additional trees are placed uniformly within each span on both sides. When trees are taller, closer to the centerline, and more dense, the shielding impact against lightning strokes is greater. For instance, 5 trees per span, 40m tall, 40m away from the centerline substantially reduce the number of strokes terminating on the line, as shown in Figs. 3(a) and 3(b). The results in Fig. 4 were obtained assuming a fixed tree height of 25m and a fixed density of 8 trees per span (4 on each side).

In order to calculate the overall lightning performance of a transmission line taking into account the shielding effect of trees, a statistical approach is used here. The statistical

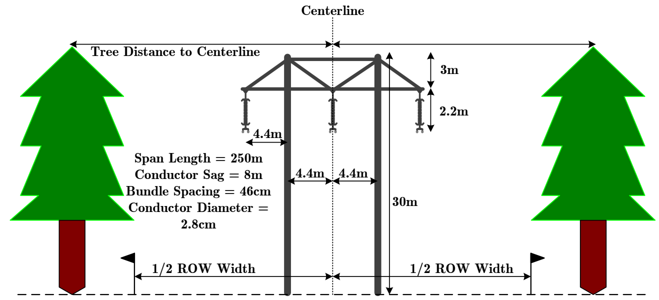


Fig. 1. Transmission line ROW surrounded by naturally-grown trees.

distribution of tree heights and distances to centerline is shown in Fig. 2. The average number of trees/span/side (N_{tr}) can be calculated using the LiDAR data. As can be seen, the impact of this parameter diminishes for more than 10 trees/span/side. Let us assume N_{tr} is known. Then the functions shown in Fig. 3 will only have one variable, tree height (h_{tr}). These functions were calculated for a given distance from the centerline (D_0). In order to obtain values for other distances, the graphs shown in Fig. 4 can be used to scale. This is done with the assumption that F_{HC} and F_{HS} follow the same pattern for different D. Therefore, the number of flashes terminated on the conductors and structures for various tree heights (h_{tr}) and distances (D) can be calculated as $F_{HC}(H)F_{DC}(D)/F_{DC}(D_0)$ and $F_{HS}(H)F_{DS}(D)/F_{DS}(D_0)$, respectively. The total number of flashes terminating on the conductors (N^C_{total}) and structures (N^S_{total}) are then calculated as:

$$N^S_{\text{total}} = \sum_{i=1}^{N_H}\sum_{j=1}^{N_D} F_{HS}(H_i)\frac{F_{DS}(D_j)}{F_{DS}(D_0)}P^{HD}(H_i, D_j) \qquad (1)$$

$$N^C_{\text{total}} = \sum_{i=1}^{N_H}\sum_{j=1}^{N_D} F_{HC}(H_i)\frac{F_{DC}(D_j)}{F_{DC}(D_0)}P^{HD}(H_i, D_j) \qquad (2)$$

The most conservative approach would be to assume all the flashes collected by structures and conductors will lead to a flashover, i.e. a ground fault. For extra high voltage lines, this assumption can be revised by calculating the minimum lightning current that can cause a flashover across the insulator strings. This topic is covered in the next section.

The ground flash density in the area of interest is 0.1 flashes/km^2/year. The number of expected flashovers was calculated for various tree densities, as shown in Table I. This line is about 52km long, with a total number of 208 spans (average 250m-long spans). The average tree density/span is about 6 for the proposed corridor. Therefore, the total number of flashes collected by structures and spans is 0.124 and 0.05, respectively, when considering the trees shielding effect, and 0.217 and 0.441, respectively, when no trees are considered.

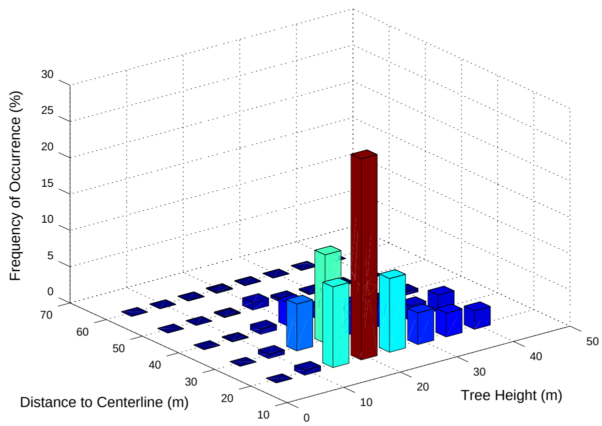
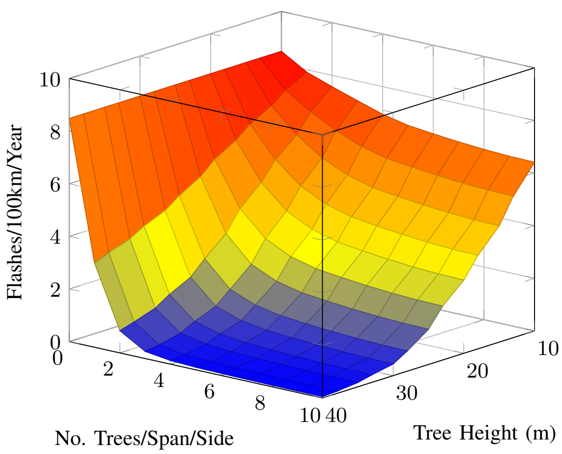
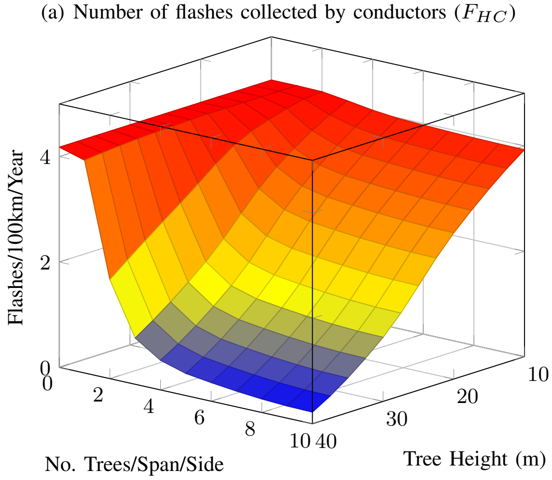


Fig. 2. Histogram of the tree heights and distances to the centerline for one BC Hydro transmission line corridor located in the North West of the province (extracted from LiDAR data).



(a) Number of flashes collected by conductors (F_{HC})



(b) Number of flashes collected by structures (F_{HS})

Fig. 3. The impact of number of trees per span and tree heights on the number of flashes collected by conductors and structures at a fixed distance to centerline of 40m (calculated using SESShield-3D).

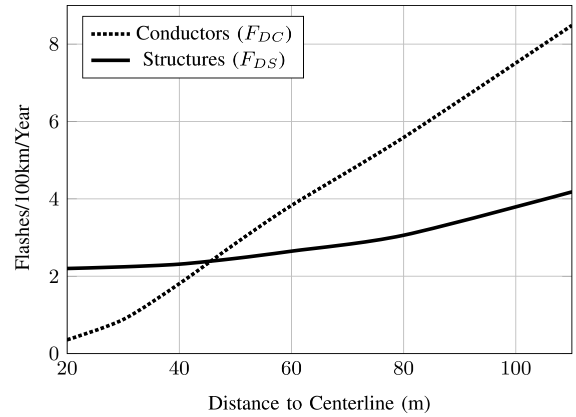


Fig. 4. The impacts of trees' distance to the transmission line centerline on the number of flashes collected by conductors and structures for a fixed height of 25m and density of 8 trees per span, 4 trees on each side (calculated using SESShield-3D).

III. Minimum Lightning Current to Cause a Flashover

Lightning strokes can be characterized by several features, such as rise time, tail time, polarity, and peak value. These parameters are statistical in nature. Based on historical data collected over long periods, numerical probability distributions have been derived for these parameters. The probability distribution of lightning peak current magnitude (first negative strokes) was proposed by Anderson [6]:

$$P\{I > I_p\} = \frac{1}{1 + \left(\frac{I_p}{I_m}\right)^{\alpha}} \tag{3}$$

in which I_m is the median stroke current magnitude, assumed 31 kA; α is assumed 2.6 [6], [7].

The electro-geometric model (EGM) uses the concept of striking distance. The striking distance, also known as the attractive radius or final jump length, is defined as the distance, measured from the reference object, within which the lightning channel will be terminating on the object. In other words, the striking distance virtually increases the size of the object in the view of the lightning flash. The striking distance can be calculated based on the following equation:

$$S = \Phi \ I^{\beta} \tag{4}$$

TABLE I
Number of Flashes Collected by Structures and Conductors of the 287 kV Transmission Line

No. Trees/Span/Side	No. Flashes by Each Structure	No. Flashes by Conductors/Span
0	1.04e-3	2.12e-3
2	8.57e-4	3.85e-4
4	6.37e-4	2.69e-4
6	5.99e-4	2.39e-4

Suggested parameters for Φ and β in (4) can be found in various references, e.g., [8], [9]. For the studies in this paper, the following values are assumed [10]: $\Phi = 10$ and $\beta = 0.65$. The striking distance is a statistical quantity and has been shown to be dependent on both the current magnitude and structure height [8]. Different correction factors have been suggested for striking distance to the ground and tall structures [9]. No correction factors are used for the purposes of this study. In a 3D geometry, the striking distance concept creates an envelope surrounding the object at a distance of S for a given current magnitude I. The projection of this envelope on the flat ground, A, determines the effective flash-collecting area for the object. In calculating A, the shielding effects from surrounding objects and the ground is taken into account. The ground flash density N_g is defined as the average number of flashes/km^2/year. The number of flashes collected by the object (N) for a given current magnitude I (or striking distance), is then calculated as $N = N_g\, A$. Using (3), the total expected number of flashes terminating on a given object can be calculated. To this end, intervals for current magnitudes need to be used to discretize the continuous spectrum. Assume a fixed interval width of ΔI. The probability of the current magnitude falling into the interval $[I_0, I_0 + \Delta I]$ can be calculated as (3):

$$p(I_0) = P\{I_0 < I < I_0 + \Delta I\} = P\{I_0\} - P\{I_0 + \Delta I\} \quad (5)$$

A summation over the entire current spectrum yields the total number of flashes collected by the object (N_{total}):

$$N_{\text{total}} = \sum_{j=1}^{N_I} p_j\, N_j \quad (6)$$

For more complicated geometries such as transmission line conductors, Mousa developed a methodology for calculating the flash-collecting area [11].

In case of unshielded transmission lines, a lightning flash can terminate on either the phase conductors or directly on the structures. In case of termination on conductors, a voltage surge is generated which travels towards the two ends of the spans. The surge impedance of a conductor, considering the corona effects, can be calculated as [10]:

$$Z_c = 60\sqrt{\ln\left(\frac{4h_c}{d_c}\right)\ln\left(\frac{4h_c}{D_c}\right)} \quad (7)$$

where Z_c is the conductor surge impedance under corona (Ω); h_c is the average conductor height above ground (m); d_c is the conductor diameter (m); and D_c is the equivalent corona diameter of the conductor at a surface gradient of 15 kV/cm. The following formula has been suggested for calculating D_c for a single conductor [6]:

$$D_c \ln\left(\frac{4h_c}{D_c}\right) = \frac{2V_c}{E_c} \quad (8)$$

where V_c is the voltage applied to the conductor (kV); and E_c is the limiting corona gradient below which the envelope can no longer grow, assumed 15 kV/cm. In the case of bundle conductors, the equivalent diameter (D'_c) can be calculated as $D'_c = D_c + D_{\text{eq}}$, where D_{eq} is the equivalent bundle diameter (m). When lightning strikes a conductor, the current splits in two, each half facing a surge impedance of Z_c. The voltage surge that appears at both ends of the struck span imposes a total potential difference across the insulators. Assuming that the lightning occurs at the worst time in the power frequency cycle, i.e. when the phase voltage is at its peak with the opposite polarity, the instantaneous voltage across the insulator (V_I) can be obtained as $V_I = Z_c\frac{I}{2} + \sqrt{\frac{2}{3}}V_{LL}$, where I is the peak lightning current (kA); V_{LL} is the line-line RMS voltage (kV). Assuming that the lightning strikes the conductors at the maximum opposite polarity of the phase voltage is conservative. The average phase voltage in a cycle is zero and for the long-term statistical assessment, V_{LL} may be considered zero. For the purpose of this study, only the first stroke is considered. The critical flashover voltage (CFO) in air for lightning impulses can be calculated as [10]:

$$V_{CFO} = \left(400 + \frac{710}{t_r^{0.75}}\right)W \quad (9)$$

in which t_r is the time to flashover ($0.5\mu s < t_r < 16\mu s$) and W is the length of the air gap (m). A detailed analysis was carried out in [12] to calculate the minimum current causing a flashover for both the first and subsequent lightning strokes. Various models for the dielectric strength of the insulator air gap were studied. A simpler expression was proposed for the CFO gradient in [12] as 680 kV/m, which is in line with the recommended value of 700 kV/m in IEC Std. 60071-2 [13]. The standard deviation (σ) for lightning impulse withstand voltage is assumed 3% [6]. Longer rise times correspond to lower withstand levels. Mousa suggests using 6 μs for the time to flashover in (9), which is close to the median value suggested in [14]. With these assumptions, the lightning impulse withstand voltage of an insulator with a length W can be calculated as:

$$V_{3\sigma} = 585(1 - 3\sigma)W = 532W \quad (10)$$

Assuming a normal distribution, this corresponds to a withstand probability of 99.9%. It is now possible to calculate the minimum lightning current ($I^c_{\min}$) that would result in a flashover across the insulator string:

$$I^c_{\min} = 2\frac{V_{3\sigma} - \sqrt{\frac{2}{3}}V_{LL}}{Z_c} \quad (11)$$

If the magnitude of the lightning current terminated on a phase conductor is greater than $I^c_{\min}$, a flashover occurs, which usually leads to a ground fault. Therefore, lightning events with peak current values smaller than $I^c_{\min}$ can be disregarded in the analysis as the generated over-voltage surge is unlikely to cause a flashover. This $I^c_{\min}$ is used in (6) as the minimum value and the maximum value is usually set at 200 kA. For the case of a 287 kV line, the insulator string is about 2.2m long, which yields $V_{3\sigma}$= 1170 kV. For a twin-bundle conductor with sub-conductor diameter of 2.8 cm, the conductor surge impedance would be $Z_c = 317\Omega$, using (7). Substituting these values into (11), the minimum current that can cause a flashover is $I^c_{\min}$ = 5.8 kA.

If the lightning strikes a transmission line structure directly, the current flows to the ground through the grounding system of the structure. The structure surge impedance (Z_s) is in series with the grounding resistance (R_g) and the produced voltage can cause a back-flashover. The basic method to model the reflections in the structure is to use a Constant-Parameter (CP) line model for the structure and terminate it using the equivalent grounding resistance R_g. Calculation methods for tower surge impedance of various structure designs were studied in the literature through empirical and theoretical approaches, as described in [6] and [15]. A simple electromagnetic transient (EMT) analysis yields the minimum current $I^s_{\min}$ that causes a back-flashover when lightning strikes the structure directly. Note that the traveling time in towers is lower than the speed of light and values around 250 $m/\mu s$ have been proposed [16], [17]. For a H-frame structure, the tower surge impedance can be calculated as [18]

$$Z_1 = 60 \ln\left(2\sqrt{2}\frac{h_s}{r_s}\right) - 60 \tag{12}$$

$$Z_2 = \frac{60 d_s \ln\left(2\frac{h_s}{r_s}\right) + h_s Z_1}{h_s + d_s}, \quad Z_s = \frac{Z_1 Z_2}{Z_1 + Z_2} \tag{13}$$

in which h_s is the structure height, r_s is the radius of each pole, and d_s is the distance between the two poles. For the 287 kV structures, $h_s = 30$, $r_s = 0.35$, and $d_s = 8.8$. Substituting these values into (13) yields $Z_s = 137\Omega$. For other structure designs, formulas were derived and can be found in [18]. The grounding impedance varies depending on the soil condition and grounding design. For this particular line, the grounding resistance R_g varies between 1 to 100Ω. Simulating the CP line built with these parameters, the minimum current that causes a back-flashover was calculated as $I^s_{\min}$ =207, 91, and 11.5 kA for $R_g = 1$, 10, and 100Ω, respectively. The probability of lightning current exceeding these values, using (3), is 0.7, 5.7, and 93%, respectively. This shows the importance of taking it into account as in some cases most of the lightning strikes will cause a back-flashover ($R_g = 100\Omega$), whereas in other cases most of the lightning strikes will not cause any back-flashover ($R_g = 1\Omega$).

The calculated $I^c_{\min}$ and $I^s_{\min}$ are used as minimum levels when performing the summation in (6). These can be entered as inputs into SESShield-3D program.

IV. Conclusion

A methodology was proposed to evaluate the shielding effect of trees at the edge of transmission lines right-of-way. This method uses the statistical distribution of trees along the corridor obtained through LiDAR surveys. Depending on the tree heights, distances to centerline, and tree density per span, the flashover rates for an unshielded transmission line can be significantly reduced by the surrounded trees. The proposed method is simple to use and can be applied to various line configurations. When calculating the flashover rates, the proposed method deals with conductors and structures separately. Without considering the effect of trees, the lightning performance of the line is dominated by the number of lightning strokes to the conductors. Considering trees, the lightning performance is dictated by the number of lightning strokes to the structures. The proposed method can be extended to evaluate the shielding effect of trees on the lightning performance of shielded transmission lines. This is in the agenda as a future development.

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