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A Methodology for Quantifying the Number of Lightning-Initiated Simultaneous Outages of Parallel Transmission Lines

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SUMMARY

Lightning-initiated simultaneous outages of transmission lines sharing the same corridor are studied in this paper. This phenomenon has been known to occur once lightning strikes one circuit and, via an arc established through the ground, bridges the gap between the two circuits and causes a backflashover on the neighboring circuit. A probabilistic approach is proposed to calculate the number of expected simultaneous outages based on ground flash density, local soil resistivity, tower grounding resistance, and the physical separation between adjacent structures of neighboring circuits. This method can be used when determining the minimum required separation between adjacent circuits in the same corridor in order to meet a certain reliability criterion.

KEYWORDS

Lightning performance, simultaneous outage, probabilistic approach.

I. INTRODUCTION

Power utilities have been pushed towards sharing the same corridor for multiple transmission lines. There are many factors that influence this practice. One important factor is to minimize the environmental impacts, such as tree cuttings, endangering wildlife habitats, and occupying lands with significant historical values. In some cases, sharing a corridor can lead to savings in the capital cost of transmission line projects by using the existing access roads, acquiring smaller additional right-of-way (ROW), addressing the oppositions from various stakeholders, etc.

Despite its immediate benefits, sharing the same ROW may adversely impact the system reliability. Weather-related events, such as earthquakes, tsunamis, floods, tornadoes, landslides, and forest fires can cause a simultaneous outage of several circuits. The outages caused by weather-related events can be permanent or temporary. In some cases, simultaneous outages of high-voltage transmission lines can activate remedial action schemes such as generation/load shedding. The Institute of Electrical and Electronics Engineers (IEEE) categories such events as common-mode outages. A common-mode outage is defined by the IEEE Standard 859 as "A related multiple outage event consisting of two or more primary outage occurrences initiated by a single incident or underlying cause where the outage occurrences are not consequences of each other" [1]. The importance of the common-mode outages has been recently appreciated and the Probability Applications for Common Mode Events (PACME) Task Force has been formed under the IEEE Power & Energy Society Reliability Risk and Probability Applications Subcommittee to address this matter [2].

Transmission lines are usually shielded to protect the phase conductors against a direct lightning strike. 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 flash-over will occur across the insulator strings, which will be sustained by the power frequency current, causing a ground fault. The discharge of lightning current in the ground causes a 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 by adding ground rods or counterpoise wires. A minimum grounding resistance is usually defined to minimize the risk of back-flashovers. Due to the particular circumstances in the province of British Columbia, it has been decided not to shield the transmission lines, except for a short section outside the substations. This is explained in more details in Section II. Besides BC Hydro, there are other utilities in the world that own unshielded transmission lines and this paper would be of interest to a broader audience.

There have been several studies on improving the reliability of circuits sharing the same structures. Unbalanced (differential) insulation has been proposed in the '60s for minimizing the simultaneous outages for double-circuit transmission lines. In the differential scheme, phases of one circuit have longer insulator strings compared to the other circuit, rendering one circuit as the "sacrificial circuit". This idea is explained in more details in [3] along with some laboratory tests and field experiences. Several field experiences on the lightning performance of double-circuit transmission lines were reported in [4]. The difference in the insulation level can be achieved by adding more insulators to the strings of one circuit, adding arcing horns, or a combination of both.

Despite the lightning performance studies done for the circuits sharing the same structure, the authors are not aware of studies on the lightning performance of the circuits sharing the same corridor (on separate structures). In some cases, the overhead line designer considers the event where a structure of one circuit may fall on the neighboring circuit due to a structure/foundation failure. To account for this event, the circuits need to be placed apart at a distance greater than the height of the structures. Although this practice reduces the risk of simultaneous outages due to a lightning strike, it may not be sufficient, especially when guy wires are present. BC Hydro has experienced simultaneous outages of parallel lines due to lightning and has put mitigations in place to address the issue. This will be discussed later in Section II.

When lightning current is discharged in the ground through the structure footing, a phenomenon occurs in the soil, called soil ionization. There have been many studies, both experimental and theoretical, to describe the soil ionization phenomenon. Consider a driven rod in the soil. The basic idea is that the equivalent grounding impedance of this rod (under soil ionization) depends on the magnitude of the injected current. In other words, large impulse currents can create a low-resistance "ionized" zone around the electrode, increasing the effective dimensions of the grounding system. In fact, when instantaneous values of voltage and current impulses were used to calculate the equivalent resistance, it was observed that the resistance decreases as the current magnitude increases [5], [6]. The physical phenomenon has been best described by the ionization of the air voids in the soil [7], [8]. Mousa provided evidence from [9]-[13] to support the theory of soil ionization by break down of the air-filled voids in the soil. One important parameter to describe the soil ionization is the ionization gradient of soil, E_0.

Experimental results have shown different values for E_0. Mousa analysed the studies done in the ‘70s and ‘80s and determined that a value of 3 kV/cm would be reasonable for a generic soil. This value may be conservative, as it falls below the value of 4 kV/cm used in [14], and is lower than the smallest value reported in [15] (measured values between 5 to 14 kV/cm for various soil samples). A collection of various values reported for E_0 from different sources was given in [16] and [17]. A value of 2 kV/cm was determined to be reasonable based on the fact that E_0 for wet soil may be up to 35% lower than that of the dry soil [18]. Various models for incorporating the soil ionization in the impedance of grounding systems have been compared in [19] and it was determined that the CIGRE model described in [14] produces the smallest error.

In this paper, a probability-based approached is proposed for calculating the expected number of simultaneous outages for two parallel transmission lines sharing the same corridor. The rest of the paper is organized as follows. In Section II, the lightning protection practices in BC Hydro are described. The proposed method for determining the required circuit-to-circuit separation is explained in Section III. Simulation results are provided in Section IV.

II. LIGHTNING PROTECTION OF TRANSMISSION LINES IN BC HYDRO

The keraunic activities are relatively low in the province of British Columbia. In addition, most of the long transmission lines in BC were built in forested terrain. Trees provide natural shielding against lightning for transmission lines, as described in [20] and [21]. Moreover, the soil resistivity in BC is relatively high due to 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 to go with unshielded transmission line design: relatively low ground flash density, natural shielding by trees, and rocky terrains and high soil resistivity.

A. Historical Simultaneous Outages

Based on prior studies in BC Hydro, simultaneous outages of parallel circuits involving the same phase are expected to occur when guyed structures are used and the nearest towers of the two circuits are located next to each other. In such cases, the guy wires reduce most of the circuit-to-circuit separation within the ground. As a result, the tower of either circuit would be within the “GPR zone” of the other. A lightning strike to one structure could cause a flashover on the other.

Extensive field investigations and review of historical data led BC Hydro to believe the simultaneous outages experienced were a direct result of insufficient in-ground separation. Table I provides a summary of the investigations in a number of outages. The approximate locations of the faults were determined using fault locater feature of protective relays. As can been from this table, an average of 4.3 simultaneous outages per year were experienced between 1980 and 1998.

In order to minimize the occurrence of these outages, several strategies were then adopted, including:

- Existing lines: insulating guy wires, single-pole reclosing, line surge arresters;
- New lines: single-pole re-closing, self-supporting structures, staggered structures, insulated guy wires, improving the structure grounding, and line surge arresters.

These strategies have substantially reduced the number of simultaneous outages due to insufficient in-ground separations, based on the performance in the past two decades. It is, however, required to determine the minimum separation needed between two adjacent structures in order to meet a certain reliability criterion.

B. Statistical Properties of Lightning Current

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. Of particular interest to lightning performance analysis of transmission lines is the peak current magnitude for the first and subsequent strokes. A probability distribution of lightning peak current magnitude (first negative strokes) was proposed by Anderson [22]:

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

in which I_m is the median stroke current magnitude, assumed 31 kA; α is assumed 2.6 [22], [23]. A log-normal distribution has been proposed in several references, e.g., [24], [22], and [25]. This distribution is described by the following equation:

$$P\{I > I_p\} = \frac{1}{2}\mathrm{erfc}\left(\frac{\ln(I_p) - \ln(I_m)}{\sqrt{2}\sigma_{\ln(I)}}\right) \qquad (2)$$

where $\sigma_{\ln(I)}$ is the standard deviation of the natural logarithm of current magnitudes and "erfc" is the complementary error function.

The following parameters have been suggested for the log-normal distribution: I_m = 25kA, $\sigma_{\ln(I)} = 0.39$ [24]. Different values for these parameters have been reported in the literature [25] and [26]. It should be noted that the distributions described in (1) and (2) have been obtained using old and relatively small data set collected using various methods in different locations worldwide.
Canada's Lightning Detection Network (CLDN), operated by Environment and Climate Change Canada (ECCC), was established in 1998 and has more than 80 sensors spread across the country. The CLDN allows for collecting relatively accurate lightning data using the electromagnetic waves generated by the lightning flashes. Using the data collected from 2007 to 2017 in BC, over 1.4 million samples have been obtained from ECCC. Statistical analysis was then performed on the dataset to find the complementary cumulative distribution function (CCDF) of lightning current magnitudes. The CCDF is the common method of representing the statistical characteristic of lightning current magnitude, as shown in (1) and (2). The CCDF obtained using the CLDN dataset is compared against (1) and (2) in Fig. 1. As can be seen, there are differences between the three CCDF curves in Fig. 1. Fine tuning the parameters of (1) and (2) based on the CLDN data can minimize these differences. In order to find the best parameters, a least-square curve fitting problem was formulated. Solving this problem yields the parameters shown in Table II. The parameters listed in this table are used in this paper.

III. SIMULTANEOUS OUTAGE RATE CALCULATION

The electro-geometric model (EGM) of lightning termination on objects 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:

$$S = \Phi I^{\beta} \qquad (3)$$

Suggested parameters for Φ and β in (3) can be found in various references, e.g., [27], [28]. For the studies in this paper, the following values were assumed [26]: $\Phi = 10$ 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 [27]. Different correction factors have been suggested for striking distance to the ground and tall structures [28].

Table I: Parameters for (1) and (2) Obtained using Curve-Fitting Technique based on the CLDN Data Set for BC.

I_m in (1)	α in (1)	I_m in (2)	$\sigma_{\ln(I)}$ in (2)
20.613	2.304	20.583	0.750

Table II: Historical Simultaneous Outage Data in BC Hydro (1980-1998) due to Insufficient in-Ground Separation.

Adjacent Circuits	Number of Outages
500 kV & 230 kV	28 @ 1 location
500 kV & 138 kV	6 @ 2 locations
500 kV & 500 kV	21 @ 7 locations
500 kV & 60 kV	22 @ 2 locations

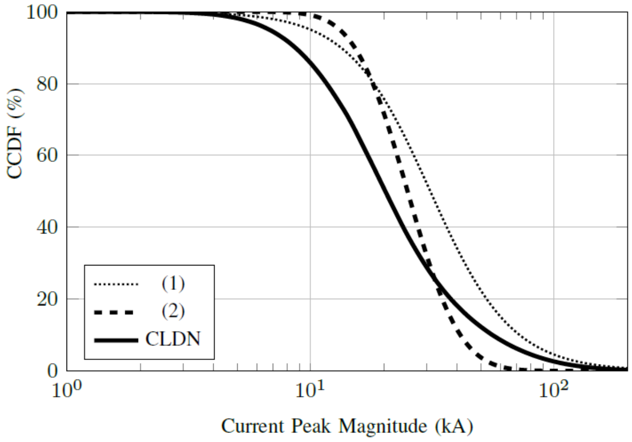


Figure 1: Comparison of the CCDF of lightning current obtained from (1), (2), and the 10-year ECCC data set.

In a three-dimensional 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 determines the effective flash-collecting area (A) for the object. The ground flash density NG is defined as the average number of flashes/km^2/year for a particular area. The number of flashes collected by an object for a given current magnitude is N^G.

Using the probability distribution of the lightning current magnitude defined earlier in (1), the total expected number of flashes terminating on a given object can be calculated. Most of the shielding failure analysis in this paper is done using SES Shield-3D program. This program basically adopts the EGM, based on the proposed methods by Mousa [29] and Eriksson [30].

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 span, i.e. towards the structures. The surge impedance of a conductor, considering the corona effects, can be calculated as [26]:

$$Z_s = 60\sqrt{\ln\left(\frac{4h}{d}\right)\ln\left(\frac{4h}{D_c}\right)} \tag{4}$$

where Z_S is the conductor surge impedance under corona (Ω); h is the average conductor height above ground (m); d 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 [22]:

$$D_c \ln\left(\frac{4h}{D_c}\right) = \frac{2V_c}{E_c} \tag{5}$$

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

$$D'_c = D_c + D_{\text{eq}} \tag{6}$$

in which D_{eq} is the equivalent bundle diameter (m). When lightning strikes a conductor, the current splits in two directions, each half facing a surge impedance of Z_S. 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 when one phase voltage is at its peak with the opposite polarity, the instantaneous voltage across the insulator (V_I) can be obtained as

$$V_I = Z_s\frac{I}{2} + \sqrt{\frac{2}{3}}V_{LL} \tag{7}$$

where I is the peak lightning current (kA); V_{LL} is the line-line RMS voltage (kV). This needs to be compared against the impulse withstand voltage of the insulator strings. One suggested method to calculate this for an insulator with length W is [26]:

$$V_{3\sigma} = 585(1 - 3\sigma)W = 532W \tag{8}$$

Assuming a normal distribution and $\sigma = 3\%$, this corresponds to a withstand probability of 99.9%. The minimum lightning current (I_{crt}) that would result in a flashover across the insulator string is calculated as:

$$I_{\text{crt}} = 2\frac{V_{3\sigma} - \sqrt{\frac{2}{3}}V_{LL}}{Z_s} \tag{9}$$

If the lightning current magnitude is greater than I_{crt}, a flashover may occur, which usually leads to a ground fault. Therefore, lightning events with peak current values smaller than I_{crt} can be disregarded in the analysis for flashes terminating on conductors.

If the lightning strikes a transmission line structure directly, the current flows to the ground through the structure footing. When the structure surge impedance is large enough, a back-flashover can occur. The structure surge impedance is in series with the equivalent grounding impedance of the structure foundation. The surge impedance of the structures with different shapes has been discussed in Chapter 6 of [22 An electromagnetic transient program (EMTP) simulation would be required to calculate the voltage stress across the insulators. In order to calculate the GPR resulting from the discharge of a lightning current, the structure grounding resistance under lightning impact is required, in which case soil ionization needs to be taken into account.

A. Soil Ionization

1) Shape of the Ionized Zone: The soil ionization phenomenon has been studied by various researchers, as discussed in Section I. One important consequence of soil ionization is the temporary reduction of the resistance-to-ground of the structure. This is due to the virtual increase of the grounding electrode size by the ionized soil. An elementary approximation of the ionized zone is a hemisphere [7], [8]. From a theoretical point of view, however, the shape of the ionized zone can deviate from a hemisphere, depending on the grounding electrode geometry. The dynamic model suggested by Liew [13] leads to cylindrical shapes for ground rods at lower current magnitudes. At higher soil resistivity and current magnitudes, the shape is closer to a hemisphere.

Since metallic components of adjacent circuits are usually located within a horizontal distance, it becomes important to determine the radius of the ionized zone in order to determine the minimum required separation distances to minimize the risk of an arc being established between the struck circuit and the healthy circuit. Note that the ionized zone is assumed to extend the electrode size.

In the case of multiple current injection points, e.g., a self-supporting transmission tower with four grillage foundations, the ionized zone assumes more complicated shapes. It can be assumed that the current is equally split between the legs. The GPR is a function of the equivalent grounding resistance and the lightning current magnitude. The equivalent grounding resistance is addressed in the following section.

2) Resistance of the Ionized Zone: There are several methods proposed in the literature for estimating the grounding resistance of electrodes under lightning impulse condition. Examples are the dynamic model of Liew [13], Korsuntcev Theory of Similitude [31] and [11], current-dependent CIGRE method [14], and the hemisphere method [8]. Without loss of generality, the hemisphere method is adopted here. The grounding resistance of a conductive hemisphere with radius r buried in a soil with resistivity ρ is calculated as

$$R_1 = \frac{\rho}{2\pi r} \tag{10}$$

The radius of the ionized zone is calculated as

$$r = \sqrt{\frac{I\rho}{2\pi E_0}} \tag{11}$$

When multiple injection points exist, e.g., towers with four legs, the mutual effect between the electrodes must be taken into account. Tagg proposed formulas for such instances where multiple hemispheres are part of the grounding system [32]. For the case of two hemispheres located at a distance *y*, the total grounding resistance is calculated as [32]:

$$R_2 = \left(1 + \frac{r}{y}\right)\frac{R_1}{2} \tag{12}$$

For four hemispheres located at a distance of *y* from each other, the total grounding resistance is calculated as [32]:

$$R_4 = \left(1 + 2.7\frac{r}{y}\right)\frac{R_1}{4} \tag{13}$$

When ionization occurs in case of multiple injection points, the hemispheres representing the ionized zones may overlap for large current magnitudes and/or high soil resistivity values. In those cases, calculation of the equivalent grounding resistance of the multiple ionized zones can be a challenge. Approximations are required in such cases, e.g., to neglect the mutual effect between the ionized zones of multiple grounding points and assume a single injection point in the center of the grounding system, resulting in a single hemisphere. In this paper, when $r > 0.4y$, the grounding resistance is calculated assuming a single hemisphere where all the lightning current is injected into. Note that this simplification is only to calculate the equivalent grounding resistance and does not affect the shape of the ionized zones formed around each injection point. The shapes are important in determining the edge of the ionized zones and finding the arcing distance to a nearby object.

3) Arcing Distance: Assuming the equivalent grounding resistance of R_g, the ground potential rise can be calculated as GPR = $R_g I$. The farthest distance to which an arc can develop from the edge of the ionized zone (X^{arc}) can be calculated using the breakdown gradient of soil, denoted by E_b and assumed 0.5 kV/cm [7]:

$$X^{\mathrm{arc}} - r = \frac{\mathrm{GPR}}{E_b} \tag{14}$$

in which *r* is the extension of the ionized zone in meters. If the metallic components of the foundation extend beyond *r*, i.e. the maximum dimension of the foundation D^F is greater than the radius of the ionized zone, then *r* assumes the value of D^F . Note that X^{arc} is measured from the center of the ionized zone. Figure 2 illustrates the idea of the reduced inground separation between two structures when soil ionization occurs.

B. Algorithm

The proposed methodology is described in Algorithm 1. The inputs to the program are listed. There are two loops here: the outer loop is on the structure number ($k = 1 : N^S$) and the inner loop is on the current magnitude interval ($j = 1 : M$). The length of the current intervals is usually taken as $\Delta I = 1$ kA. The critical current I_{crt} is calculated using (9) for flashes terminating on conductors, and the maximum current I_{max} is usually taken as 200 kA. The probability of the current magnitude exceeding this value is negligible. $\overline{N}^T$ and $\overline{N}^C$ are the number of flashes collected by structures and conductors, respectively, calculated for a range of current magnitudes, similar to what is shown in Fig. 3. These parameters are dependent on the circuit geometry and need to be calculated for each specific case. The existing separation between adjacent structures X^{sep} needs to be measured between the closest in-ground metallic components, e.g., guy anchors. In case of helical piles, the underground portion of the helices need to be taken into account (usually driven into the ground at an angle). The lightning withstand voltage of the insulator strings V_{CFO} is used to see if a back-flashover can occur on the adjacent circuit, for a given GPR. Since the standard deviation of the withstand voltage is small, around 3%, it was decided to use the median value V_{CFO}.

$\widehat{N}^T$ and $\widehat{N}^C$ are initialized at zero at every iteration and if a flashover is expected to occur for a given current interval, the number of expected strikes for that particular current interval is added to $\widehat{N}^T$ and $\widehat{N}^C$. The application of the algorithm to a case example is shown in the next section.

IV. SIMULATION RESULTS

A case study is provided in this section to demonstrate the application of the proposed method for determining the circuit-to-circuit separation requirements. Assume two 230 kV transmission lines within the same corridor, with 21 m centerline-centerline separation. The structures are mostly H-frame design with a phase-to-phase spacing of 5.5 m, 12 insulators per string, and ACSR Grackle phase conductors with diameter of 3.4 cm. In some locations, 4-leg lattice towers with grillage foundations are used. The average conductor height above ground is 12 m (18 m at the structures with a maximum sag of 8 m, average span length of 200 m) and the area has an average elevation of 900 m above the sea level. The average Keraunic level (NG) in this area is assumed 1 flashes/km^2/year. These lines are not shielded.

The surge impedance of the conductors is calculated using (4) as 373 Ω. The insulators length is 12*0.146 = 1.75 m, which yields $V_{3\sigma}$ = 932 kV using (8). The minimum lightning current that can cause a flashover (I_{crt}) is calculated using (9) as 4 kA. The minimum current that causes a back-flashover when striking the H-frame structures was calculated using an electromagnetic transient program. The minimum strike current on the structures that causes a back-flashover was calculated as 3 kA. These numbers are relatively small and may not play a great role in this case study. However, I_{crt} plays a role in cases of higher voltage levels, e.g., 735 kV lines.

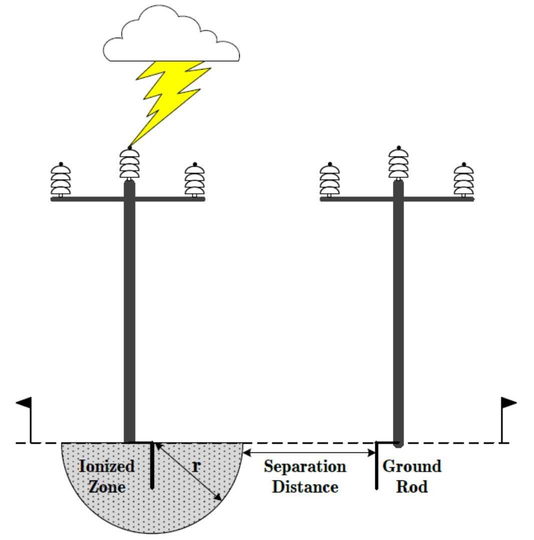
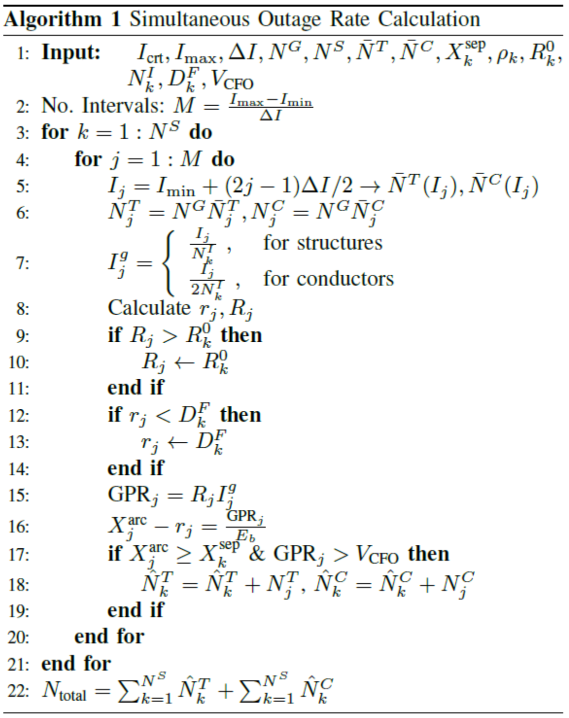


Figure 2: Illustration of an ionized zone formed around a ground rod and its reduction effect on the in-ground separation between two adjacent circuits.



Algorithm 1 Simultaneous Outage Rate Calculation

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Input: $I_{\text{crt}}, I_{\max}, \Delta I, N^G, N^S, \bar{N}^T, \bar{N}^C, X_k^{\text{sep}}, \rho_k, R_k^0, N_k^I, D_k^F, V_{\text{CFO}}$
No. Intervals: $M = \frac{I_{\max} - I_{\min}}{\Delta I}$
for $k = 1 : N^S$ do
    for $j = 1 : M$ do
        $I_j = I_{\min} + (2j-1)\Delta I/2 \rightarrow \bar{N}^T(I_j), \bar{N}^C(I_j)$
        $N_j^T = N^G \bar{N}_j^T, N_j^C = N^G \bar{N}_j^C$
        $I_j^g = \begin{cases} \frac{I_j}{N_k^I}, & \text{for structures} \\ \frac{I_j}{2N_k^I}, & \text{for conductors} \end{cases}$
        Calculate $r_j, R_j$
        if $R_j > R_k^0$ then
            $R_j \leftarrow R_k^0$
        end if
        if $r_j < D_k^F$ then
            $r_j \leftarrow D_k^F$
        end if
        $\text{GPR}_j = R_j I_j^g$
        $X_j^{\text{arc}} - r_j = \frac{\text{GPR}_j}{E_b}$
        if $X_j^{\text{arc}} \geq X_k^{\text{sep}}$ & $\text{GPR}_j > V_{\text{CFO}}$ then
            $\hat{N}_k^T = \hat{N}_k^T + N_j^T, \hat{N}_k^C = \hat{N}_k^C + N_j^C$
        end if
    end for
end for
$N_{\text{total}} = \sum_{k=1}^{N^S} \hat{N}_k^T + \sum_{k=1}^{N^S} \hat{N}_k^C$
```

The number of flashes collected by the conductors and structures of one circuit was calculated using SESShield-3D software using the minimum current values calculated above. The average value for each circuit is as follows:

- Flashes collected by conductors: 8.514e-3 /span/year.
- Flashes collected by structures: 4.613e-3 /structure/year.

Note that the simulation takes into account the shielding effects of the adjacent circuit. For the single circuit (no shielding effect from an adjacent circuit), the total number of flashes collected by the conductors and structures are 1.376e-2 and 8.306e-3 flashes/span/year, respectively. For each small range of current magnitude (ΔI), there is a corresponding expected number of flashes collected by the structures ($\bar{N}^T$) and conductors ($\bar{N}^C$). These values were calculated for this particular test case and are shown in Fig. 3. The maximum number of flashes occur at 23 kA and 28 kA for conductors and structures, respectively. Integrating over the entire range yields the total number of flashes reported above.

The results of the analysis are shown in Table III for strikes to one circuit. The total number of expected simultaneous outages (Nout) for the ten structures is 0.0618 outages/year, or one outage every 16 years. Nout has a great correlation with the soil resistivity and the separation distance. For instance, at Str. No 8 where the separation distance is relatively large and at Str. No. 7 where soil resistivity is relatively low, the expected number of outages is zero.

The expected number of simultaneous outages as a function of soil resistivity and in-ground separation distance is shown in Fig. 4. These results were generated for only one structure and its two adjacent spans, assuming two injection points (two ground rods). Note the flat section on the graphs up to a certain separation distance (~23 m). This means that increasing the separation in smaller distances (below ~23 m) does not change the probability of simultaneous outages. Two conditions must be met for a certain current magnitude to cause an arc to the adjacent circuit: a) generate a high enough GPR to result in X^{arc} greater than the separation distance ($I > I_1$); b) the GPR must be greater than the insulator withstand voltage to cause a back-flashover on the adjacent circuit ($I > I_2$). For separation distances below ~23 m, $I_2 > I_1$ and, therefore, $I > I_2$ governs.

It is important to note that the maximum value N_{out} can assume would be always smaller then the total number of flashes collected by conductors and structures. At closer distances and higher soil resistivity values, almost all the outages of one circuit lead to an outage of the second circuit.

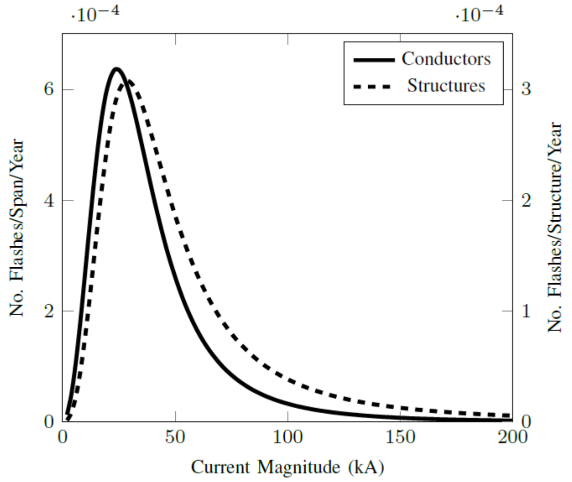

Figure 3: Number of flashes collected by conductors and structures versus lightning current magnitude for an H-frame 230 kV transmission line (span length: 200m, structure height: 22m, phase spacing: 5.5m, $N^G = 1$).

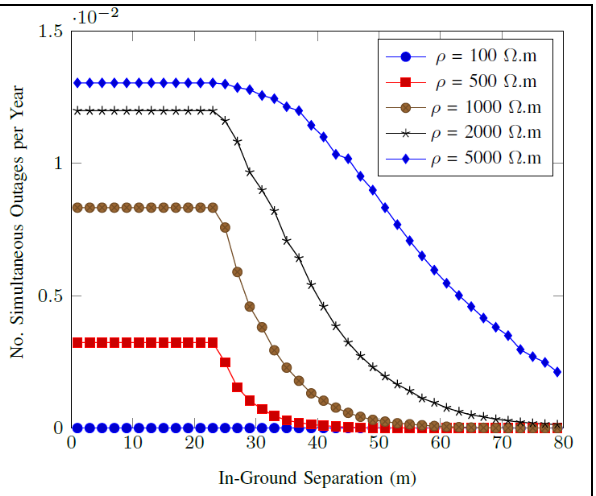

Figure 4: Expected number of simultaneous outages for various soil resistivity and separation distances for one structure location (230 kV H-frame structures, two ground rods per structure, $N^G = 1$).

Table III: Simulation results for two parallel 230 kV circuits (outages due to strikes to one circuit).

Str. No	$\rho(\Omega.m)$	X^{sep} (m)	R^0 (Ω)	N^I	D^F (m)	N_{out}
1	1000	15	200	2	0.4	8.33e-3
2	800	20	162	2	0.4	6.98e-3
3	1600	23	314	2	0.4	1.10e-2
4	3500	31	190	4	3.0	1.03e-2
5	500	12	92	2	0.4	3.23e-3
6	700	18	65	4	3.0	2.28e-3
7	50	22	30	2	0.4	0
8	600	53	55	4	2.9	0
9	1700	13	229	2	0.5	1.14e-2
10	2300	29	181	4	2.9	8.20e-3

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