Effect of Continuous Cable between Adjacent Towers on Lightning Resilience of a 90kV Transmission Line with High Soil Resistivity

Remi Courtellemont, Alain Xemard, Pierrick Prigent

***Abstract*—This paper evaluates the efficiency of using a continuous insulated cable between adjacent towers to improve the lightning performance of a 90 kV transmission line in high soil resistivity conditions. Through EMTP simulations, we analyze the impact of this solution on surge voltage reduction and backflashover rates. The study considers the influence of various parameters including soil resistivity, tower footing impedances, and lightning current distribution following CIGRE recommendations. Results demonstrate that connecting adjacent towers with a continuous ground cable can significantly reduce backflashover occurrences, particularly when tower footing impedances are between 30-60 Ω, where the improvement reaches up to 30 %, whereas, in the standard configuration, the BFOR can reach up to 18 strikes per 100 km per year. The solution proves most effective at moderate ground resistance values. This research provides insights for improving transmission line lightning performance in challenging soil conditions.**

***Keywords*: backflashover rate, EMTP simulation, grounding cable, high soil resistivity, lightning protection, transmission line**

I. Introduction

The resilience of power transmission networks against lightning strokes is needed to maintain a reliable electricity supply. Particularly in areas with high ground resistance and soil resistivity, the risk of backflashover events increases significantly. A backflashover occurs when a lightning strike on a transmission tower or sky wire causes a surge voltage that travels through the tower footing to the ground, potentially leading to flashover of the tower's insulators. Such incidents is a source of voltage dips detrimental to power quality.

High soil resistivity intensifies these issues by diminishing the efficiency of tower grounding systems and increasing the likelihood of flashovers. According to CIGRE Technical Brochures 63 [1] and 839 [2], common mitigation strategies include adding line arresters, reducing the tower footing impulse impedance and enhancing the insulation level to achieve the desired Backflashover Rate (BFOR), which helps to lower overvoltage amplitude and improve insulation withstand levels.

In some regions where soil resistivity may reach 5000 Ω.m or more, it is difficult to reduce the tower footing impedance by conventional methods, thus unconventional methods can be adopted. One of them involves connecting adjacent towers with a cable, thus paralleling the tower footing impulse impedances.

This configuration reduces the overall ground impedance, enhancing the network's performance against lightning strokes. This paper aims to evaluate with numerical simulations the efficiency of this configuration using EMTP on a 90 kV transmission line.

II. Literature Review

A. Tower-Footing Impulse Impedance

The lightning impulse impedance of tower foundations is determined by several key factors, as detailed in CIGRE Technical Brochure 839 [2]. These factors encompass soil characteristics (particularly its resistivity), the configuration of grounding electrodes, and soil ionization phenomena during high lightning currents. Specifically, there is a direct relationship between soil resistivity and impulse impedance - when soil resistivity increases, the impulse impedance, provided that the geometry is kept the same, tends to rise due to reduced current dissipation capabilities and limited ionization effects.

To enhance tower grounding performance, a widely adopted technique involves the installation of counterpoise systems. These systems consist of buried conductors (made of galvanized steel or copperweld) installed approximately 0.6 meters below ground level, extending beyond the tower's base [3]. This solution proves particularly effective in areas with medium to high soil resistivity, as it helps optimize the local grounding characteristics of transmission structures [4].

When analyzing first return strokes, research demonstrates that using a simplified representation of tower grounding impedance (as a lumped parameter) yields results virtually identical to those obtained through detailed physical modeling [5], especially when soil resistivity is not too high. Peak overvoltages at the tower top are primarily influenced by the apparent foot impedance, as reflections from the base reach the top significantly earlier than those from neighboring towers. The influence of the apparent tower footing impedance on the tower top voltage is determined by its response time and current dependence. Response time becomes a significant factor only when counterpoise extends beyond 30 meters [6].

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The behavior of impulse impedance compared to steady-state resistance changes with soil conditions. In soils with high resistivity (≥ 700 Ω.m), impulse impedance is usually lower than steady-state resistance because of soil ionization during lightning strikes. On the other hand, in low-resistivity soils (≈ 100 Ω.m), inductive effects can become more important, especially for long electrodes, causing impulse impedance higher than low-frequency resistance. This behavior also depends on the shape of the electrode and the characteristics of the lightning current.

Consequently, for EMTP simulation purposes, it is appropriate to model the tower grounding system as a simple equivalent resistance representing the impulse grounding impedance [7]. The modeling takes into consideration the elevated ground resistance conditions typical of high-resistivity soil environments by implementing tower footing resistance values that range from 5 to 500 Ω in the simulations.

B. Continuous Electrodes between Adjacent Towers

The paper from Visacro and Silveira [8] gives an overview of the different measures to improve the lightning performance of transmission lines. One effective measure to improve the lightning performance of transmission lines, particularly in regions with extremely high soil resistivity, involves the installation of continuous electrodes connecting adjacent towers. This solution consists of burying long grounding electrodes along the transmission line route, creating a conductive path that interconnects the grounding systems of neighboring towers. The continuous electrodes act as low-impedance path for lightning currents, reducing the tower-footing impedance and mitigating the overvoltages across insulators.

This approach is particularly advantageous in cases where traditional counterpoise wires cannot achieve sufficiently low tower-footing resistance due to environmental constraints or high soil resistivity. By interconnecting towers, the system benefits from the cumulative effect of multiple grounding systems, effectively lowering the overall impedance seen by the lightning current. Additionally, this solution remains effective even in soils with very high resistivity (e.g., 10 000 Ω.m or more), as the continuous electrodes are perceived by lightning currents as parallel low-surge-impedance paths.

While this method is costly due to the extensive length of electrodes required, it is sometimes more economical than alternative measures like widespread use of surge arresters in high-voltage lines and it can provide a solution to improve the lightning performance of overhead lines when it is no possible to install line arresters because of the tower design.

III. Grounding Cable between Adjacent Towers

An insulated buried cable was chosen for this study instead of a bare conductor for two main reasons. First, bare conductors are susceptible to corrosion (impact on long-term performance and reliability), which is not the case for insulated cables. Also, accurately modeling of bare conductors in high-resistivity soil needs advanced simulation tools with finite element analysis. Using an insulated cable allows for a focused evaluation of how interconnecting tower grounding systems improve lightning performance, while ensuring consistent and reliable results within the scope of this study.

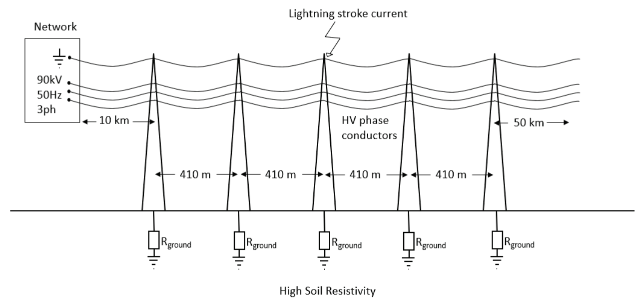

Fig. 1. Standard model (without cable)

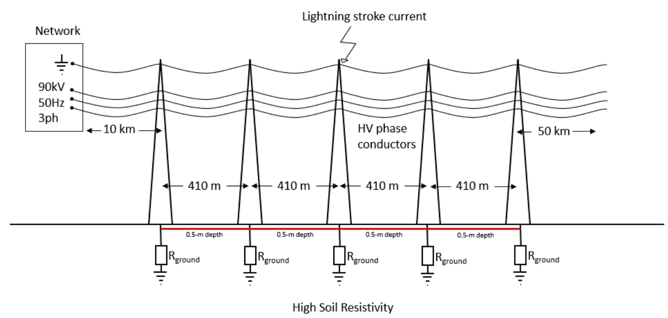

Fig. 2. New model (with continuous cable between adjacent towers - in red)

Backflash simulations were conducted on a realistic EDF 90kV/50Hz overhead transmission line under two configurations:

- **Standard configuration** (figure 1)
- **Configuration with an additional continuous cable between adjacent towers** (figure 2)

The objective of the simulations is to compare the results from both configurations to assess the efficiency of the continuous cable solution.

The physical mechanism behind the expected reduction in lighting stress at the impacted tower can be explained through transmission line theory and wave propagations principles. When lightning strikes a tower, the initial surge current encounters three parallel paths at the tower base: the tower footing impedance (Z_f) and two characteristic surge impedances (Z_c) corresponding to the buried cables connecting to adjacent towers. During initial transient period ($t < \tau$, where τ is the one-way propagation time along the buried cable), the effective impedance at the tower base is determined by the parallel combination of these three impedances:

$$Z_{effective}(initial) = (Z_f{}^{-1} + 2 * Z_c{}^{-1})^{-1} \qquad (1)$$

With typical values in high-resistivity soil conditions (Z_f=500 Ω, Z_c≈300 Ω at 1 MHz), this parallel arrangement reduces the effective impedance to approximately 115 Ω, representing 77 % reduction compared to the tower footing impedance alone. This significant reduction occurs immediately upon lightning strike and generate an initial decrease in tower base.

After time τ (approximately 2 µs for standard span – 410 m – at 1Mhz), reflection waves from adjacent towers return to the struck tower. At these adjacent towers, the reflection coefficient (Γ) can be calculated as:

$$\Gamma = \frac{(Z_{eq} - Z_c)}{(Z_{eq} + Z_c)} \quad (2)$$

Z_{eq} corresponds to the equivalent impedance of three impedances: Z_f, Z_c and Z_t (characteristic impedance of the tower, 150 Ω in our case), which gives approximately 83 Ω. In this condition, Γ ≈ -0.56, indicating a reflection with opposite polarity. After travelling back to the struck tower, this wave reduces the remaining stress due to its opposite polarity. Then, the same reflection happens again.

IV. Modelling of the 90 kV Transmission Line Struck by Lightning

A. Assumptions

- **High soil resistivity**: an average homogeneous value of 5000 Ω.m is assumed for all calculations.
- **Line and tower configuration**: all towers are identical, based on a standard design and uniform spacing.
- **Lightning strokes**: Direct lightning strokes are assumed to strike the shield wire at towers, occurring 3 µs after the start of the simulation and lasting for a duration of 30 µs, with a time step of 1 ns.

B. Transmission Line Design

- **Tower type**: Lattice-type towers are utilized as presented in Figure 3.
- **Conductor height**: The first conductor is positioned 19.5 meters above ground level at the tower and 11 meters above ground level at mid-span.
- **Span between towers**: 410 meters.
- **Conductor characteristics**:
  - External diameter: 19.6 mm.
  - Max DC resistance at 20°C: 0.146 Ω/km.
- **Shield wire characteristics:**
  - External diameter: 13 mm.
  - Max DC resistance at 20°C: 0.56 Ω/km.
- **Arcing horns**: the effective gap distance across the insulator strings is set at 71 cm.

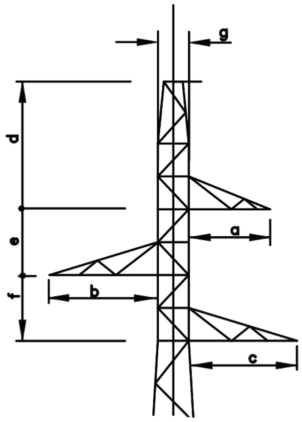

Fig. 3. Typical tower top-structure for 90 kV – 50 Hz line (a = 2.5 m, b/c = 3.2 m, d = 1.9 m, e/f = 1.7 m and g = 0.8 m)

The transmission line illustrated in Figure 1 is modeled using EMTP. Additionally, a second model, depicted in Figure 2, incorporates a continuous cable buried at a depth of 0.5 meters between adjacent towers. The cable characteristics are provided below:

- **Conductor material**: copper.
- **Conductor section**: 150 mm^2.
- **DC resistance at 20°C**: 1.1 x 10^{-5} Ω.m.
- **Insulation material**: PVC, with the following properties:
  - Thickness: 2 mm.
  - Relative permittivity: 2.3.
  - Loss factor: 0.0004.

C. Transmission Line Modelization

A wideband line/cable EMTP model is employed, considering electromagnetic couplings between aerial and buried conductors along the transmission line. This model is widely recognized as the most accurate for time-domain simulations of lines and cables, particularly when precise results are required across a broad frequency range. Operating in the phase domain, it accounts for the full frequency dependence of transmission line and cable parameters. The model is calibrated for a frequency range spanning from 0.01 Hz to 1 MHz, with 8 decades of analysis and 10 sampling points per decade. This methodology ensures a high level of accuracy in representing electrical behaviors across the entire frequency spectrum.

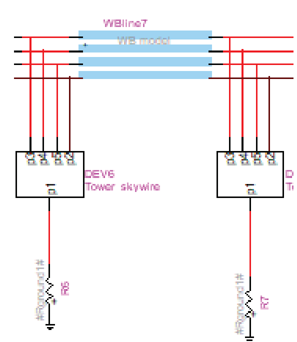

Fig. 4. EMTP Transmission Line modeling (2 towers + 1 line)

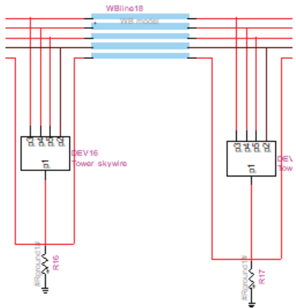

Fig. 5. EMTP Transmission Line modeling with continuous cable between adjacent towers (2 towers + 1 line + 1 continuous ground cable)

The tower is modeled as a constant parameter (CP) line with a length of 19.5 meters and a characteristic impedance of 150 Ω.

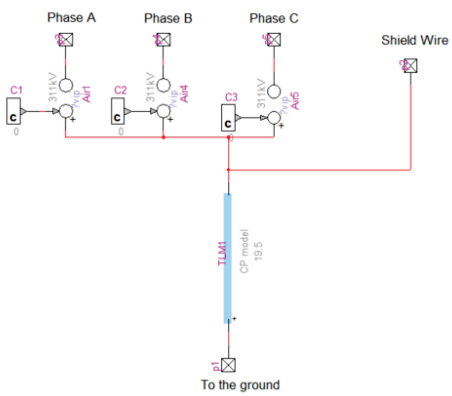

Fig. 6. EMTP model of a tower

D. Air Gap Switch Model

The air gap insulation is modeled by the equal area criteria:

$$\int_{t_0}^{t} \left[\left|v_{gap}(t)\right| - V_0\right]^K dt \geq D \qquad (3)$$

An energy accumulation-based model is used for simulating the behavior of insulators arcing horns. This model is recommended by standard IEC/TR 60071-4 [11] for air gaps smaller than 1.2 meters. More information on this model can be found in [9]-[10]. The calculated results are K = 0.92; V_0 = 311 kV; D = $1.3e^{-1}$.

Standards EN60071-2 [12] and EN50341-1 [13] provide important guidelines to evaluate the discharge behavior of air gaps.

E. Lightning Stroke Current Model

The CIGRE model is used in EMTP. The shape of the first-return stroke wave is as following:

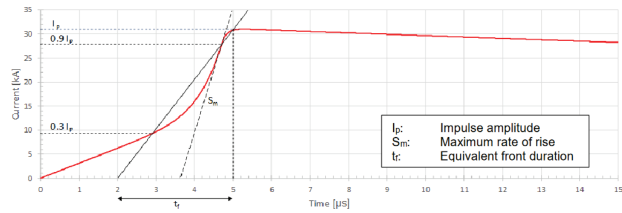

Fig. 7. Analytically derived lightning current impulse, showing the front parameters [1]

The CIGRE lightning current amplitude follows a log-normal distribution, with a median of 31.1 kA and a gaussian standard deviation of 0.484, according to CIGRE Technical Brochure 63 [1], which corresponds to the approximate distribution of the first descending negative polarity lightning current. The value of the slope S_m and the rise time t_f are determined from the median values given by the formulas in Table 4 of the document [1].

V. EMTP Simulations

A. Surge Voltage Attenuation

A preliminary simulation is conducted with the following fixed parameters:

- **Network phase angles**: Phase A = 0°, phase B = -120°, phase C = +120°
- **Lightning stroke**: amplitude of 20 kA, with a steepness (S_m) of 20.05 kA/µs and a front time (t_f) of 3.1 µs, representing the median values calculated using [1].
- **Tower Ground Resistance**: 100 Ω

The simulation considers two scenarios—without and with a continuous cable between adjacent towers. Calculations are performed using EMTP, and the voltage is measured at each air gap switch (one per phase) of the tower impacted by the lightning stroke.

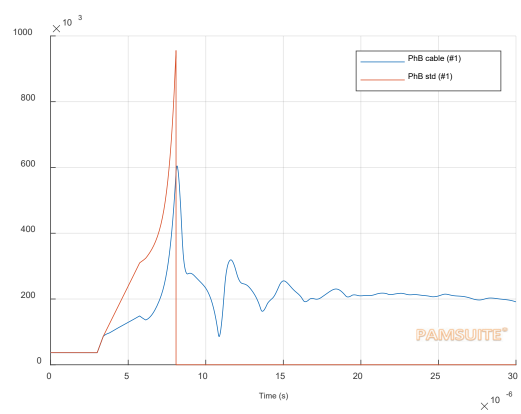

Fig. 8. Surge Voltage (V) on air gap switch of phase B of the tower (red curve is without cable, blue curve is with cable)

In the standard configuration, without a continuous cable between adjacent towers, the surge voltage reaches approximately 900 kV. In contrast, when a continuous cable is integrated between adjacent towers, the surge voltage is significantly reduced to approximately 600 kV. Furthermore, a backflashover is observed on phase B in the standard configuration, whereas no backflashover occurs in the configuration with the continuous cable.

In figure 8, we can observe the physical mechanism described in paragraph III: the surge voltage increases much less with continuous ground cable than without it, due to the lower equivalent impedance at the base of the struck tower. Then, after few microseconds, we observe the oscillations of the stress due to the multiple reflections between the struck tower and the adjacent towers.

B. Influence of the Distance between Adjacent Towers

To assess the impact of the distance between towers, the previously described simulation is repeated, with the inter-tower distance modified from 410 meters to 10 kilometers.

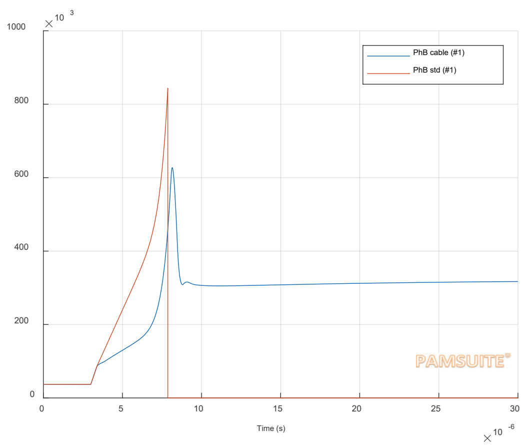

Fig. 9. Surge voltage (V) on air gap switch of phase B of the tower (red curve is without cable, blue curve is with cable), with modified distance between adjacent towers (10 km instead of 410 meters)

The results indicate that the peak voltage is slightly reduced in the standard configuration, with an approximate decrease of 12%. However, the backflashover on phase B remains observable. In contrast, in the configuration incorporating a cable between adjacent towers, the maximum voltage remains nearly unchanged compared to the initial simulation.

The comparison between these two scenarios suggests that the distance between towers has a negligible impact when considering the configuration with a cable connecting adjacent towers.

As observed with continuous electrodes, the continuous cable functions as a low-impedance path for lightning currents. This reduces the tower-footing impedance and effectively diminishes the overvoltages across the insulators.

In figure 9, The voltage remains stable after the lightning strike, with no oscillation as seen in figure 8. This is because the wave does not travel back from adjacent tower due to the long distance between them (10 km instead of 410 m). These observations confirm the theory explained in paragraph III.

VI. Parametric Simulations

A. Parameters and Modeling

The PAMSUITE module of EMTP is used to perform parametric studies with multiple simulations.

TABLE I – PARAMETRIC VARIABLES

Parameters	Values / Distribution
Phases (balanced)	*Random Uniform* Phase A from 0° to 359.9° Phase B: Phase A – 120° Phase C: Phase + 120°
Lightning Strokes (negative first return stroke)	*Random Log-Normal* Final Crest Current I_F (kA) : • Gaussian Median :3.43 • Gaussian Standard Deviation : 0.484 Slope S_m (kA/µs) : $12*I_F^{0.171}$ Rising time T_f (µs) : $1.77*I_F^{0.188}$
Towers Impulse Resistance	*Fixed and identical value for each tower* Between 5 Ω and 500 Ω
Number of simulations	5000 for each value of impulse resistance

A backflashover event is identified in the simulation when a current is detected flowing through at least one of the air gap switches of the tower directly struck by the lightning. The aim is to calculate the backflashover rate for each value of the impulse grounding impedance, while considering a log-normal distribution of lightning stroke amplitudes.

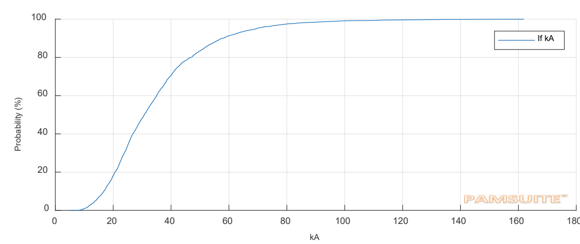

Fig. 10. Lightning strokes cumulative distribution for the simulations

B. Surge Voltage Reduction

When the tower footing impulse impedance is set to 37 Ω, 15.3% of the simulated cases (corresponding to 767 observations) do not result in a flashover in either configuration, whether without or with a continuous cable between adjacent towers. In these scenarios, the lightning current amplitude (I_F) is 20 kA or lower.

The following figure illustrates the distribution of the maximum peak voltage across the air gaps:

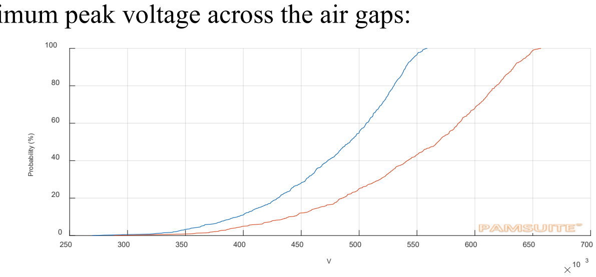

Fig. 11. Peak voltage (Vmax) distribution across air gap switches of the tower, considering an impulse resistance set to 37 Ω (red curve is without cable, blue curve is with cable)

Observations for the standard configuration:

- Peak voltage ranges between 300 and 650 kV
- The peak voltage has 50% probability of occurring at approximately 570 kV

Observations for the configuration with cable:

- Peak voltage ranges between 300 and 550 kV
- The peak voltage has 50% probability of occurring at approximately 490 kV

These results confirm the efficiency of a continuous cable between adjacent towers in reducing surge voltages on the transmission line during lightning events.

C. *Backflashover Percentage*

Description of backflashover percentage results (figure 12):

- **Standard configuration**: the backflashover percentage increases quickly, reaching 95% when the impulse resistance value reaches 60 Ω.
- **Configuration with continuous ground cable**: The backflashover percentage rises more gradually and stabilizes at approximately 90% when the tower's impulse resistance reaches 500 Ω.
- **Comparison between configurations**: at 5 Ω, there is no observable difference between the two configurations. However, the differences increase significantly as the impulse resistance rises to values between 30 and 60 Ω, where the maximum difference of 30% is observed. Beyond 60 Ω, the differences diminish progressively.

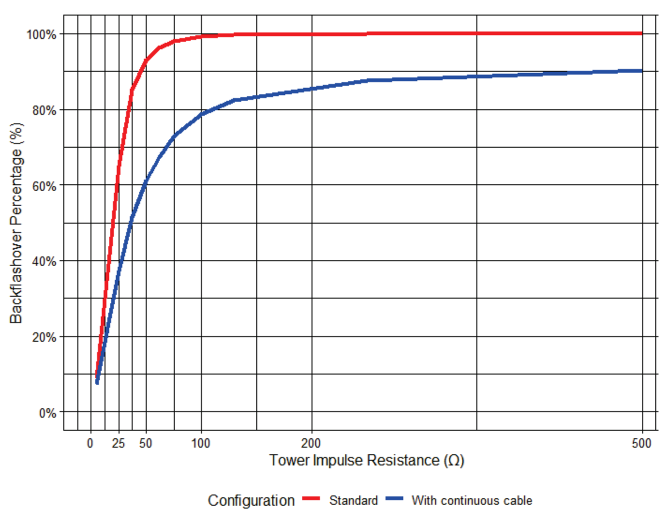

Fig. 12. Backflashover percentage depending on tower-footing impulse resistance

VII. Backflashover Rate

To calculate the backflashover rate, the CIGRE brochure 63 [2] provides a methodology which consists in calculating the average attractive radius on each side of a transmission line:

$$R_a\ (m) = 14\ H_T^{0.6} \tag{4}$$

Where H_T = average tower height in meter.

In our case, considering H_T = 24.8 m, the calculated R_a = 96.117 m.

For estimation of the expected average incidence of strikes to a line:

$$N_L = N_g \frac{(2\ R_a + b)}{10} \tag{5}$$

Where
N_L is expressed in Strikes / 100 km / year
N_g = the regional ground flash density
b = the width of the line in m

Considering an average N_g = 1 and a width of b = 7.2 m, then we get approximately N_L = 20 Strikes / 100 km / year.

The BFOR is presented in the following table.

TABLE 2 – BFO RATE OF 90KV TRANSMISSION LINE

Tower Impulse Resistance (Ω)	Configuration without cable	Configuration with cable
5	1.7	1.4
25	13	7.4
37	16.9	10.2
50	18.5	12.2
75	19.5	14.5
100	19.8	15.7
250	19.9	17.5
500	19.9	18

Initially, the problematic nature of BFOR for such a line is evident. The standard configuration exhibits a rapid increase in BFOR even with low values of tower footing grounding impedance.

Comparing the two configurations, the efficiency of using a continuous ground cable between adjacent towers is most pronounced when the tower footing ground impedance is in the range of 40 to 50 Ω. At this impedance level, the cable solution can prevent approximately 6.5 outages per 100 km per year from occurring. However, at higher impedance values, such as 500 Ω, the improvement diminishes, preventing only 2 outages per 100 km per year.

These results highlight the benefits of the continuous ground cable solution in moderate impedance conditions but requires further optimization or alternative strategies for very high impedance scenarios to maintain its efficiency.

VIII. Conclusion

The investigation of using a continuous ground insulated cable between adjacent towers as a lightning protection measure for 90kV transmission lines in particular conditions (homogeneous high resistivity soil) yields several findings:

- The solution demonstrates notable efficiency in reducing surge voltages, with simulation results showing lower peak voltages compared to traditional configurations.
- The improvement in backflashover performance is most pronounced for tower footing impedances between 30-60 Ω, where the difference in backflashover percentage reaches up to 30% between configurations with and without the connecting cable.
- The distance between towers shows minimal impact on the efficiency of the cable solution, suggesting that the ground continuous cable act as a low impedance path for lightning currents.
- In terms of practical benefits, the solution can prevent approximately 6.5 outages per 100 km per year when tower footing impedance is around 40-50 Ω, though this benefit reduces to about 2 outages per 100 km per year at higher impedance values (500 Ω).

These findings suggest that implementing a continuous cable between adjacent towers can be an effective solution for improving lightning performance of transmission lines in high soil resistivity areas, particularly when moderate tower footing impedances are encountered and when the installation of line arresters is not an appropriate solution. However, the efficiency diminishes at very high ground resistance values, indicating that alternative or complementary protection measures might be necessary in such extreme conditions.

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