International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-15 Issue-3, February 2026

Simulation of Lightning Strikes on Towers Connected to the Grounding Grid and Located Near a Pipeline

Abdelhak Mehadjbia, Fouad Slaoui Hasnaoui

***Abstract:** Workers involved with underground pipelines might be subjected to dangerous transient voltages caused by adjacent lightning strikes on electrical towers linked to grounding systems. To better understand and predict these indirect effects, this paper investigates the transient electromagnetic behavior of a tower–grounding grid–pipeline system subjected to a direct lightning strike. The entire setup is simulated using transmission-line theory to enable a thorough understanding and accurate modelling of wave propagation, electromagnetic coupling, and ionisation across the various system components. A large-scale setup comprising five transmission towers linked by a grounding grid, and located near an underground pipeline with a total length of 2.8 km, is considered in this paper. The lightning current of 12. 5 kA is delivered at the first tower's top, and the pipeline transient currents and voltages induced are calculated. The lightning-wave propagation from the strike location through the tower arms, grounding grid, and soil to the pipeline is investigated under the assumption of uniform soil conditions. Different soil resistivities (100, 300, and 600 m) are used to assess their effects on system behaviour. Three electrical pipeline models, all based on transmission-line equivalences, are constructed and compared. The first model explores only resistive effects, whereas the second and third gradually incorporate inductive, capacitive, and conductive elements, thereby enabling a more precise depiction of electromagnetic coupling and dielectric losses. According to the simulations, the lightning current amplitude fades progressively through the resistive, inductive, and capacitive components of the tower, grounding grid, and pipeline. As expected, the induced current is maximum at the struck tower, and it decreases along the system. About the first pipeline model, the induced voltages were always at a level safe enough for personnel, regardless of the soil resistivity considered. However, the second and third models showed a significant increase in pipeline voltage, with the third model exhibiting very high voltages despite lower current magnitudes. Hence, the results clearly underscore the importance of pipeline modelling, soil resistivity, and electromagnetic coupling in evaluating lightning-induced hazards. The modelling approach introduced here not only advances understanding of the transient behaviour of grounding systems and pipelines subjected to lightning but also enables the development of safer grounding layouts, pipeline materials, and protective measures that better shield people from lightning hazards.*

Manuscript received on 29 January 2026 | First Revised Manuscript received on 07 February 2026 | Second Revised Manuscript received on 12 February 2026 | Manuscript Accepted on 15 February 2026 | Manuscript published on 28 February 2026.

*Correspondence Author(s)

Abdelhak Mehadjbia*, School of Engineering, University of Quebec in Abitibi-Temiscamingue, Quebec, Canada. Email ID: abdelhak.mehadjbia@uqat.ca, ORCID ID: 0009-0001-6139-1821.

Fouad Slaoui Hasnaoui, School of Engineering, University of Quebec in Abitibi-Temiscamingue, Quebec, Canada. Email ID: fouad.slaoui-hasnaoui@uqat.ca, ORCID ID: 0009-0000-2755-372X.

***Keywords:** Lightning, Towers, Grounding Grid, Transmission line, Resistivity, Pipeline.*

Nomenclature:

TL: Transmission-Line

EMTP: Electromagnetic Transient Programs

I. INTRODUCTION

Most accidents occurring on overhead transmission lines and electrical towers are attributed to lightning strikes. The lightning discharge current typically ranges from a few kiloamperes (kA) up to several hundred kiloamperes; statistical analyses indicate that peak currents can vary between approximately 3 kA and 200 kA, with a small percentage of events exceeding 140 kA, while nearly half of recorded lightning strokes exceed 30 kA [1]. Detailed investigations of lightning current propagation along transmission structures have shown that less than 1% of the injected lightning current energy propagates along inclined components during the discharge process. In contrast, propagation along horizontal elements is generally negligible [2]. Field observations and post-event analyses further indicate that lightning-induced faults account for a significant share of transmission line outages, typically 40%-70% of total line-related accidents, depending on regional lightning density and line configuration [3]. Moreover, the electromagnetic fields generated by lightning discharges can be effectively related to the channel-based current by using transmission-line-based (TL) and modified TL models, allowing the electric and magnetic field waveforms to be approximated by the spatial-temporal evolution of the lightning current [4].

Accurate evaluation of the transient response of multiconductor transmission lines under lightning excitation requires frequency-dependent modelling and the precise correction of numerical errors arising from time discretisation and wave propagation delays. Advanced EMTP-type simulations have been widely adopted to address these issues and to improve the reliability of lightning performance assessment in modern power systems [5]. The results presented demonstrate that the proposed approach is accurate for overhead transmission lines and significantly reduces overall computation time and model memorisation [6, 7]. It has been shown in [8] that as the number of segments of the nominal height increases, the peak value of the voltage at the top of the tower gradually decreases, and so does the time. The analyses in [9] and [10] are based on the empirical approach and the global circuit theory, respectively, with too many approximations. Therefore, the electromagnetic effects on the oil/gas pipeline near the transmission line are increasingly important. A lightning strike on the lines or towers could have electromagnetic effects on adjacent buried metal pipelines.

In this paper, we propose five towers connected to a grounding grid and in the vicinity of a pipeline. Three pipeline configuration models were simulated to observe transient responses under the indirect effects of a lightning strike. Also, to visualise the safety tensions for the people who intervene in it. Simulations were conducted at multiple points to visualise the dynamic behaviour of currents and voltages along the pipeline.

II. RELATED WORK

Lightning is widely recognised as a significant cause of faults and transient disturbances in power transmission systems. When a lightning strike hits a transmission tower, the resulting current, often reaching several tens of kiloamperes, propagates through the tower structure and grounding system, generating severe overvoltage and electromagnetic disturbances [11]. These disturbances do not remain confined to the struck structure but can spread through the soil and affect nearby metallic installations, such as buried oil and gas pipelines [12]. To analyse these fast-transient phenomena, many researchers rely on transmission line theory, which provides a practical framework for modelling the propagation of lightning currents and voltages along conductors and grounding structures [13]. This approach enables the representation of towers, grounding grids, and pipelines as distributed-parameter systems, making it particularly suitable for transient studies involving lightning strikes. Compared with simplified lumped-circuit models, transmission-line-based methods are better suited to capturing wave-propagation effects and time delays, which are critical in lightning studies [14].

Several studies have focused on improving the accuracy of lightning transient simulations by accounting for frequency-dependent line parameters and soil characteristics. Electromagnetic transient programs (EMTP-type tools) have been extensively used to model lightning interactions with overhead lines and grounding systems, demonstrating high accuracy while maintaining reasonable computational efficiency [17]. More recent studies have shown that including soil ionisation and nonlinear grounding behaviour can significantly affect predicted peak voltages and current distributions, particularly for high-magnitude lightning currents [5]. The role of the grounding grid is vital in determining how lightning currents disperse into the soil. When a tower is connected to a grounding grid, the injected lightning current produces a ground potential rise that can extend over large distances, depending on soil resistivity and grid configuration. This ground potential rise is a key mechanism through which lightning disturbances are transferred to nearby buried pipelines. Studies have shown that neglecting mutual electromagnetic coupling between grounding conductors can lead to underestimation of induced voltages, especially in complex grounding layouts.

The electromagnetic effects of lightning on pipelines near transmission lines or towers have therefore received increasing attention in recent years. Research has demonstrated that lightning strikes can induce significant transient voltages and currents on pipelines through both conductive and inductive coupling mechanisms. These induced effects may stress pipeline coatings, accelerate corrosion processes, and pose safety risks to personnel working on pipeline platforms [15],[16],[17]. Several authors have investigated the influence of pipeline coating resistance on induced voltages. Results consistently indicate that higher coating resistance generally results in higher transient voltages along the pipeline, thereby increasing the risk of insulation breakdown and unsafe touch voltages [21]. Consequently, accurate modelling of the pipeline, accounting for coating properties, burial depth, and soil parameters, is essential for realistic safety assessments. Despite these advances, many existing models rely on simplifying assumptions, such as empirical formulations or global circuit representations, which may not fully capture the complex interactions between towers, grounding grids, and pipelines. Recent studies emphasise the need for integrated modelling approaches that combine transmission line theory with detailed grounding and coupling models to represent large-scale systems comprising multiple towers and extended pipelines [18], [19].

In this context, modelling the tower–grounding grid–pipeline system as an interconnected transmission-line network offers a powerful and flexible approach. Such models enable detailed analysis of lightning-current propagation from the point of impact through the tower arms, the grounding grid, and the surrounding soil, and ultimately to the pipeline. This approach also enables comparison of different pipeline configurations and assessment of transient voltages against safety limits for personnel, a key objective of the present study.

III. ANALYTICAL CONSIDERATION

The bi-exponential form for the lightning current is the most used in the literature. For our case, we consider the analytical expression of equation (1) below.

$$I(t) = I_m\left(e^{\{\alpha t\}} - e^{\{-\beta t\}}\right) \quad \ldots \quad (1)$$

The current parameters are:

I_m: represents the peak value of the current (A).

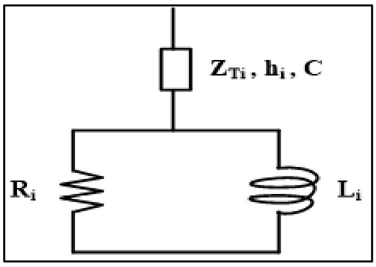
α: is the inverse of the descent time.

β: is the inverse of the rise time.

A. Tower Model

The study tower comprises four sections, each corresponding to the geometric shape of its vertical column. We materialise the electrical circuit of a portion as follows:

International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-15 Issue-3, February 2026



[Fig.1: Vertical Arm [20]]

The electrical circuit of each section of the tower column consists of an impedance Z_{T1} a resistance R_i, and an inductance L_i which are given in the equations below:

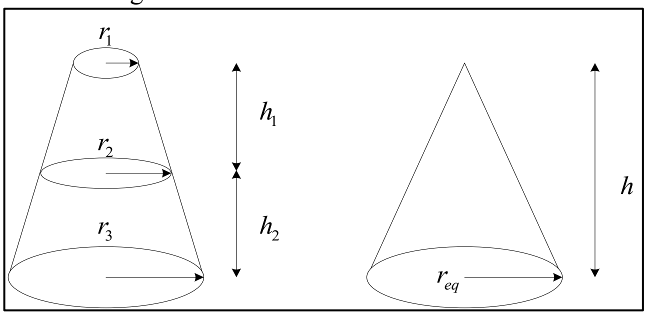
$$R_i = \frac{-2Z_{T1}.ln\sqrt{\gamma}}{h_1 + h_2 + h_3} \quad (i = 1,2,3) \quad ... \quad (2)$$

$$R_4 = -2.Z_{T2}.ln\sqrt{\gamma} \quad ... \quad (3)$$

$$L_i = \alpha.R_i.\frac{2h}{c} \quad (i = 1,2,3,4) \quad ... \quad (4)$$

R_4: Impedance of the lower part of the 4th section of the tower, taking into account the conical shape, which is different from the shape of the upper section R_i (i=1,2,3).
Z_{T1}: is the surge impedance of the three upper sections of the tower.
Z_{T2}: is the surge impedance of the lower part of the tower.
r_{ek} : Equivalent radius (m).
c : is the speed of light (=300 m/µs).
h_i: is the height of each tower section.
γ : is the attenuation coefficient.
α : is the damping coefficient.

Figure 2 below is a vertical column shape of a section of the tower to determine the analytical expression of the impedance Z as a function of the radius and height of the section being determined.



[Fig.2: Geometry for Impedance Calculation for a Section of the Tower]

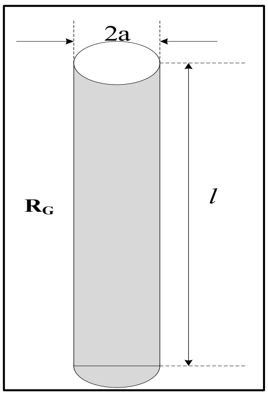
$$Z_{Ti} = 60\left(ln\left(\frac{h}{r_{eq}}\right) - 1\right) \quad (i = 1,2) \quad ... \quad (5)$$

$$r_{eq} = \frac{r_1 h_2 + r_2 h + r_3 h_1}{2h} \quad (h = h_1 + h_2) \quad ... \quad (6)$$

Z : is the surge impedance of each top section of the tower.
h: is the height of the tower.
r_{eq}: Is the equivalent radius obtained from the geometry shown in Figure 2. The attenuation coefficient is between 0.7 and 0.8, while the unit was the value usually chosen for the damping coefficient [20].

B. Vertical Electrode Between the Tower and the Grounding Grid

An earth electrode of length L is connected to the tower, and the calculation of its resistance R_G depends on its geometry.



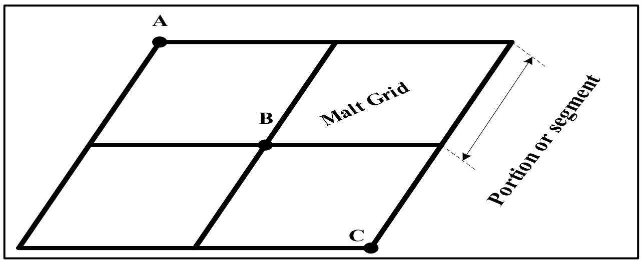
[Fig.3: Vertical Electrode Between the Tower and the Grounding Grid [21]]

$$R_G = \frac{\rho}{2.\pi.l}\left(ln\left(\frac{4.l}{a}\right) - 1\right) \quad ... \quad (7)$$

a : Radius of the electrode in (m).
l : Length of the electrode in (m).
ρ : Soil resistivity $\Omega.m$.
R_G : Resistance of the electrode in Ω.

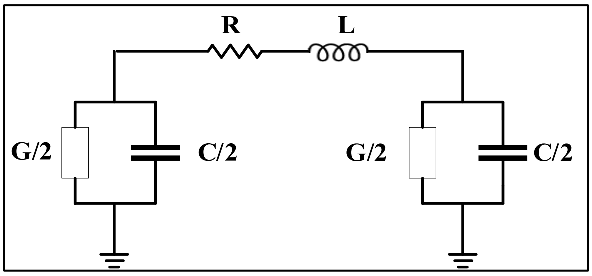
C. Grounding Grid

Each portion of the grounding grid is also considered as a transmission line composed of a resistance R, an inductance L, an admittance G and a capacity C.



[Fig.4: Illustration of a Grounding Grid]

The electrical circuit below is a representation of a portion of the grounding grid.



[Fig.5: Electrical Circuit of a Portion of the Grounding Grid]

The equations of the electrical circuit in Figure 5 are given below.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

$$R = \frac{\rho l}{S} \quad \dots \quad (8)$$

$$L = \frac{\mu_0 l}{2\pi} \times \left(ln \frac{2l}{\sqrt{2rh}} - 1 \right) \quad \dots \quad (9)$$

$$G = \frac{\frac{l}{2} \times \frac{\pi l}{\rho}}{ln \frac{2l}{\sqrt{2rh}} - 1} \quad \dots \quad (10)$$

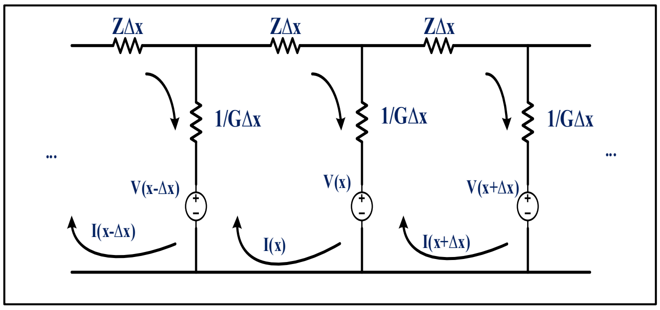
$$C = \frac{l}{2} \times \frac{\pi \varepsilon_r \varepsilon_0}{ln \frac{2l}{\sqrt{2rh}} - 1} \quad \dots \quad (11)$$

D. Pipeline Model

The return current injected into the ground causes potential rises and results in leakage currents in nearby metal structures. Conductors buried in the ground over large areas, such as cables, pipelines, railroads and, to a lesser degree, tanks and metal structures, are the most susceptible to disturbances caused by ground currents. Among the long-term effects on conductors carrying a return current is corrosion, which can progress to an advanced stage, especially in areas where the current returns to earth regularly.

In the following, we will assume that the electrical properties of cables and pipelines are uniform and that these conductors are buried in homogeneous soil. In particular, we will consider that the conductors can be covered with a protective coating and that the dimensions are such that infinite length can be assumed. We can also neglect the currents and electrical potential increases at the ends of conductors of finite length. These assumptions apply to large-scale pipelines buried in conductive soil. We will assume a priori that a transmission line can adequately represent the response of a pipeline buried in homogeneous soil.

Figure 6 shows the equivalent electrical circuit of a pipeline buried in homogeneous soil subjected to a potential distribution V (x). The current flowing in the pipeline I(x), the interior electric potential $\phi_i(x)$, the exterior electric potential $\phi_0(x)$ and the current density dI/dx attenuates in the soil for large values of x. Z is the linear resistance, and G is the sum of the inverse of the coating conductance and the shunt conductance at the contact surface between the pipeline and the soil [16].



[Fig.6: Portion of the First Model of the Pipeline as a Transmission Line]

$$Z = R_p = \frac{\rho_s}{\pi t(2r - t)} \quad \dots \quad (12)$$

$$G = \left[\frac{1}{G_c} + \frac{\rho_e}{\pi} ln \left[\frac{1.123}{[r^2 + 4d^2]^{1/2}} \right] \right]^{-1} \quad \dots \quad (13)$$

$$\Gamma = [ZG]^{1/2} \quad \dots \quad (14)$$

$$K = [Z/G]^{1/2} \quad \dots \quad (15)$$

$$G_C = \frac{2\pi r}{R_C} \quad \dots \quad (16)$$

$$G_g = \left[\frac{\rho_e}{\pi} ln \left(\frac{1.123}{\Gamma[r^2 + 4d^2]} \right) \right]^{-1} \quad \dots \quad (17)$$

$$\frac{d^2 I(x)}{d(x)} - ZGI(x) = GE_x(x) \quad \dots \quad (18)$$

$$I(x) = \frac{1}{2K} \int_0^{+\infty} E_x(u) \left[e^{-\Gamma|x-u|} - e^{-\Gamma(x+u)} \right] du \quad \dots \quad (19)$$

$$\phi_i(x) = \frac{\Gamma}{2} \int_0^{+\infty} V(u) \left[e^{-\Gamma|x-u|} + e^{-\Gamma(x+u)} \right] du \quad \dots \quad (20)$$

The potential $\phi_0(x)$ is obtained by taking into account the voltage drops in the protective coating as follows:

$$\phi_0(x) = \phi_i(x) + \frac{1}{G_c} \frac{dI(x)}{dx} \quad \dots \quad (21)$$

G: Linear conductance of the pipeline (S/m).
Gc: Linear coating conductance in (S/m).
$G_{g:}$ Linear conductance at the pipeline surface in (S/m).
r: Radius of the conduit in (m).
d: Depth of burial in (m).
Z: linear impedance of the pipeline in (Ω/m).
t: Thickness of the pipeline wall in (cm).
ρ_s : the resistivity of the steel (5.10^{-7}) in (Ω. m);
ρ_e : the resistivity of the soil in (Ω. m).
$R_{c:}$ Resistance of the coating in (Ω.m^2).
Γ : Propagation constant (m^{-1}).
K: Characteristic impedance (Ω).
$\phi_i(x)$: Voltage inside the pipeline in Volt;
$\phi_0(x)$: External electric potential;
E_X : Electric field along the pipeline in (N/C).
$I(x)$: Conductor current along the x-axis in (A).
u: Coordinate parallel to the abscissa in (m).
$V(u)$: Voltage in the vicinity of the electrode in (V).

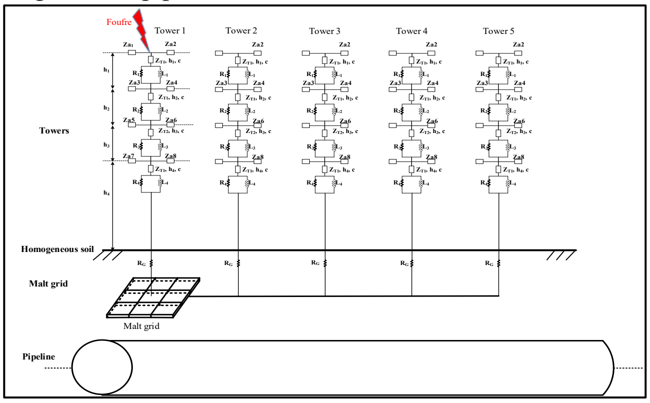
IV. SIMULATION OF THE SYSTEM TOWER-GROUNDING GRID-PIPELINE

A. Simulation of Lightning Impact on the First Model of the Pipeline

Figure 7 shows a facility consisting of a pipeline located near a grounding system. The five towers are connected to a grounding grid and form a counterweight between them. A direct lightning current (12.5kA) is injected on the

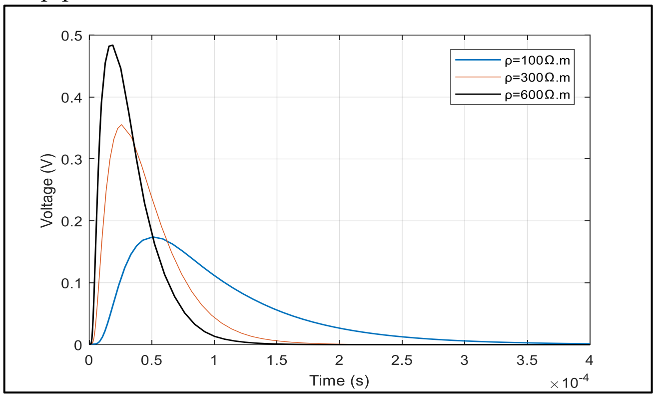
Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

first tower, and currents and voltages are obtained by simulations on the pipeline. The distances between the towers are equal to 100 m. The induced current at the top of the tower is larger, as this is the direct strike point of the lightning. The length of the pipeline is estimated at 2.8km.



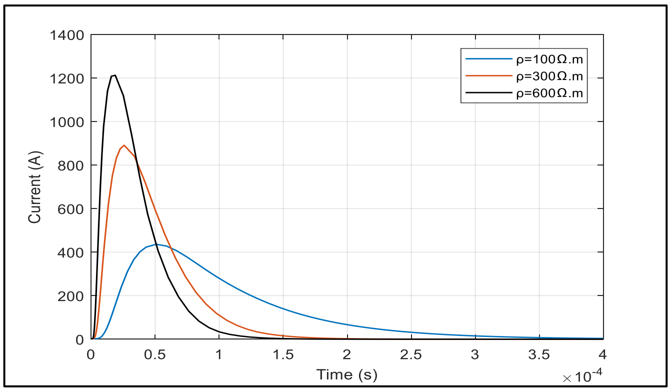
[Fig.7: Grounding-Pipeline Tower-Grid System Assembly]

The results of the whole-system simulation applied to the first pipeline model are presented in Figure 8, which shows the pipeline voltages for soil resistivities of 100, 300, and 600 Ω · m. These voltage values are safe for people working on the pipeline.



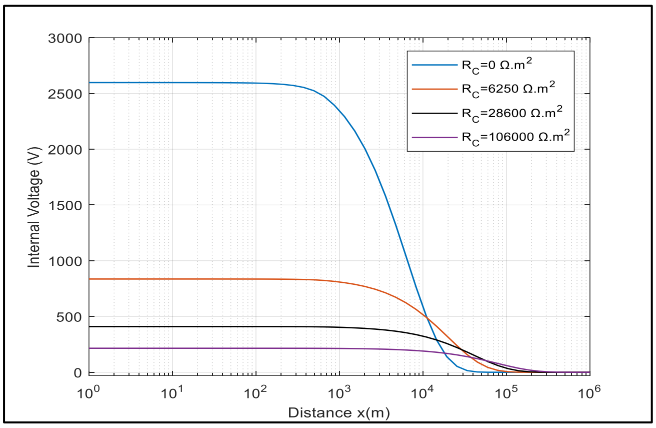
[Fig.8: Tensions are Coming to the Pipeline]

The curves in Figure 9 illustrate the results of the current flow patterns arriving at the pipeline for soil resistivities equal to 100, 300 and 600 Ω.m. These results show peak currents of 1.2 kA, 0.9 kA, and 0.42 kA at 20 µs, 25 µs, and 50 µs on the pipeline, and a gradual attenuation in the soil for resistivities of 100, 300, and 600 Ω.m.



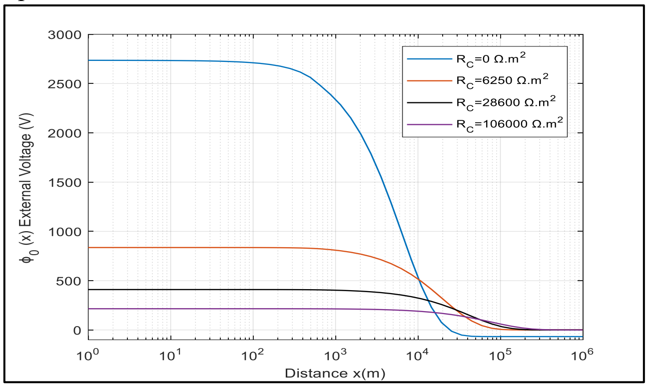
[Fig.9: Currents to the Pipeline]

The curves in Figures 10 to 13 show the voltage, current and density profiles on a pipeline subjected to a direct lightning strike on a tower and an indirect lightning strike on the pipeline located 700m away from the grounding grid or electrical tower.



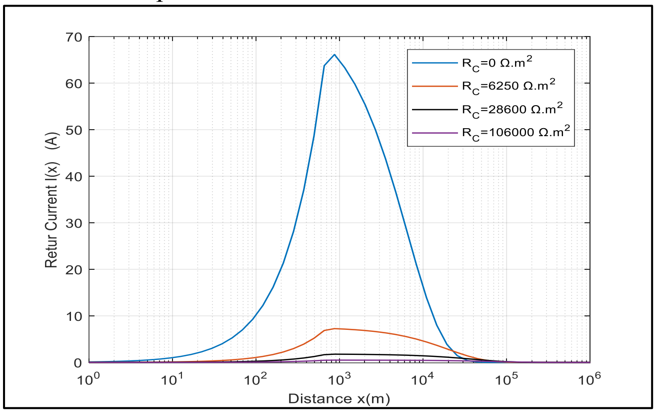
[Fig.10: Internal Voltage Pipeline]

The external voltage or potential distribution at the pipeline surface is calculated by summing the internal voltage and the voltage drop across the coating. For R_c equal to 0Ω.m^2; 6250Ω.m^2; 28600Ω.m^2 and 105000Ω.m^2, we have $\phi_0(x)$ equal to 2.7kV, 8.2kV, 0.4kV and 0.25kV.



[Fig.11: External Voltage Pipeline]

The simulated curves in Figure 12 illustrate the return current in the pipeline, accounting for the coating resistance values—the case where R_c=0 corresponds to a pipeline without overlap.

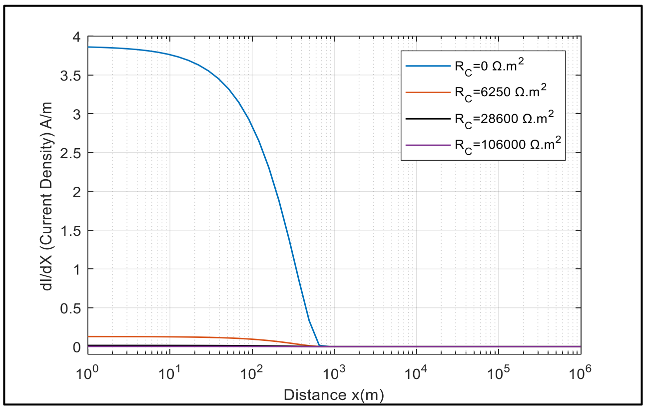


[Fig.12: Return Currents in the Pipeline]

dI/dx represents the current density, otherwise known as the leakage current entering the pipeline. Its calculation accounts for the shunt conductance, voltage drop, internal voltage, and external voltage of the pipeline. For coating resistance values of 0 Ω.m2 and 6250 Ω.m^2; 28600Ω.m^2 and

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

105000Ω.m²we have the following density values: 3.85 A/m, 0.2 A/m, 0.02 and 0.01A/m.



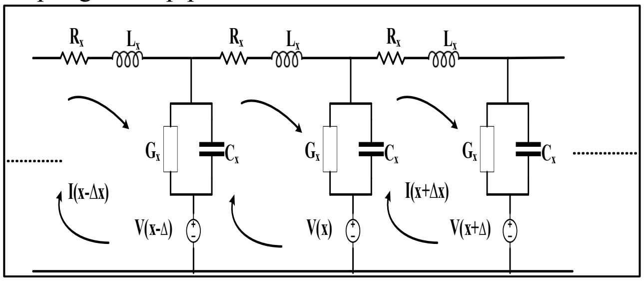
[Fig.13: Leakage Current Densities Entering the Pipeline]

For the linear current density flowing through the pipeline surface, positive values of dI/dx indicate that current is flowing into the pipe.

The coating resistance, being the inverse of the conductance per unit area, significantly affects the magnitudes of the current and voltage flowing across and within the pipeline.

B. Simulation of the Lightning Impact on the Second Model of the Pipeline

In this second model, the electrical circuit of the pipeline as a transmission line is composed of a resistor Rx, which represents the Joule effect losses, an inductor Lx, which means the magnetic effects related to the current flow in the pipeline, and a capacitor Cx, which means the vacuum in the pipeline conduit and a conductance Gx, which represents the dielectric losses in the conduit. The addition of a capacitor and an inductor to the second model allows consideration of all components of a transmission line and the electromagnetic coupling of the pipeline.



[Fig.14: Second Electrical Model of the Pipeline]

$$R_x = \frac{\rho}{\pi} A \quad \ldots \quad (22)$$

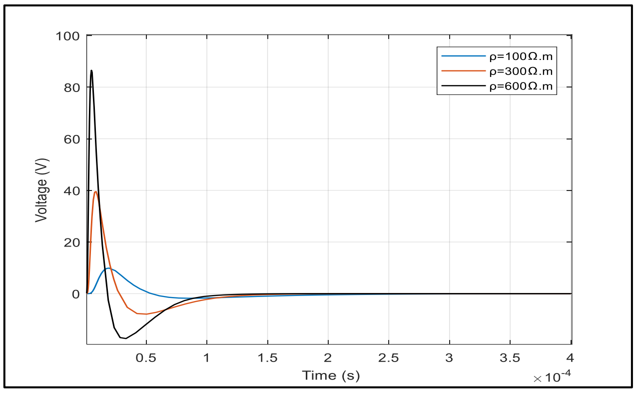
$$L_x = \frac{\mu_0}{2\pi} A \quad \ldots \quad (23)$$

$$C_x = \frac{\pi \varepsilon}{A} \quad \ldots \quad (24)$$

$$G_x = \frac{1}{R} \quad \ldots \quad (25)$$

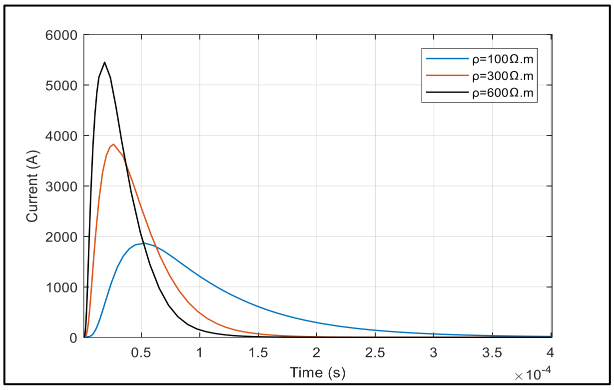
$$A = \left[ln \left(\frac{1.123}{\Gamma[r^2 + 4d^2]} \right) \right]^{-1} \quad \ldots \quad (26)$$

In Figure 12, we present the simulation results for the voltages arriving at the pipeline for soil resistivities of 100, 300, and 600 Ω.m. These voltages are safe for personnel working on the pipeline and for soil resistivities of 100 Ω.m, 300 Ω.m, and 300 Ω.m.



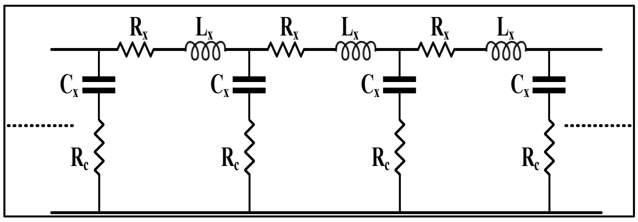
[Fig.15: Tensions are Coming to the Pipeline]

Figure 16 shows the currents (1.8kA to 5.5kA) arriving at the pipeline for soil resistivities equal to 100, 300 and 600 Ω.m.



[Fig.16: Currents to the Pipeline]

As the voltages are always safe, the currents are approximately equal to 4.5 times the currents of the first model. The third model of the pipeline circuit as a transmission line consists of a coating resistor Rc, a resistor Rx, an inductor Lx, and a capacitor C_x. This model develops a pipeline model by considering its physical form and characteristic parameters.



[Fig.17: Third Electrical Model of the Pipeline]

$$R_x = \frac{\rho}{\pi} A \quad \ldots \quad (27)$$

$$L_x = \frac{\mu_0}{2\pi} A \quad \ldots \quad (28)$$

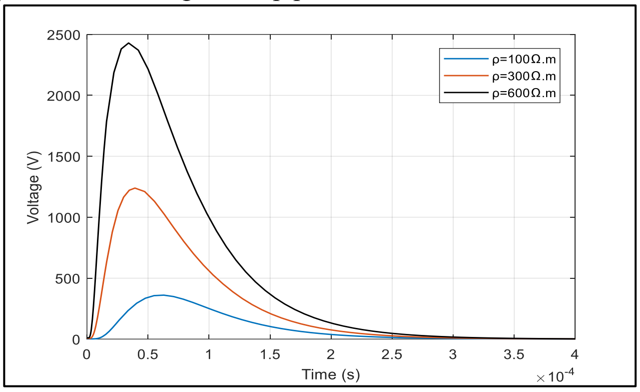
$$C_x = \frac{\pi \varepsilon}{A} \quad \ldots \quad (29)$$

Retrieval Number: 100.1/ijeat.C474615030226
DOI: 10.35940/ijeat.C4746.15030226
Journal Website: www.ijeat.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

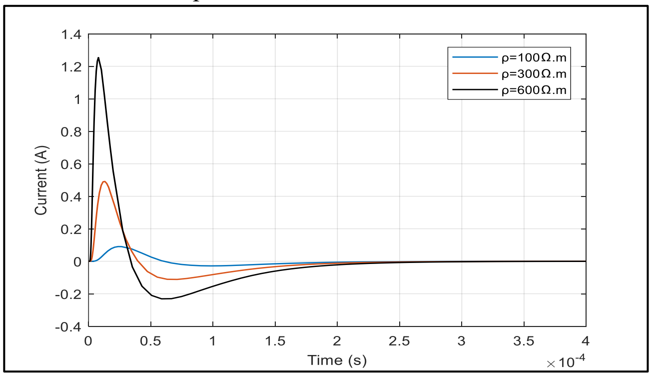
$$A = \left[ln \left(\frac{1.123}{\Gamma[r^2 + 4d^2]} \right) \right]^{-1} \quad ... \quad (30)$$

The results of the whole-system simulation applied to the second pipeline model are presented in Figure 18, which shows the pipeline voltages for soil resistivities of 100, 300, and 600 Ω · m. These voltages are considered dangerous for personnel working on the pipeline.



[Fig.18: Voltage Coming to the Pipeline]

Figure 19 shows the currents arriving at the pipeline for soil resistivities equal to 100, 300 and 600 Ω.m.



[Fig.19: Currents to the Pipeline]

The first and second have current magnitudes substantially equal to 1.2kA and 5.4KA for a soil resistivity equal to 600 Ω.m. The voltages are safe for personnel working on the first and second models. However, the third model of the pipeline dissipates more current at very low values, but with dangerous voltages for the intervening people.

V. CONCLUSION

This paper focused on the direct impact of lightning on towers connected to the grounding grid and on towers in the vicinity of a pipeline, and it considered multiple research fields. A detailed study assuming some conditions, namely the type of soil, which is homogeneous and where the pipeline duct will be buried. The coupling between the electromagnetic field radiated by the return arc and the network induces currents and voltages in the various wire conductors.

We considered five towers connected to a grounding grid and in the vicinity of the underground pipeline. The pipeline length is treated as a portion of the transmission line in all models. Variations in soil resistivity determined variations in the magnitudes of voltage and current. In addition, the amplitude of the lightning current decreases as it passes through the resistive, inductive, and capacitive components of the different sections of the tower, grounding grid, and pipeline.

The observed simulations will allow us to characterise the real behaviour of the ionisation phenomenon. The modelling and simulation presented in this work are practical engineering applications for evaluating the dynamic behaviour of currents and voltages in grounding systems. In addition, this originality enables the simulation of the transient response of the tower-grounding grid-pipeline system for a large-scale model. In sum, the third model of the pipeline dissipates more current at very low values but with unsafe voltages. The first and second models have safe voltages for personnel working on the pipeline. The work can be used to improve the grounding grate protection system. The choice of pipeline materials and coatings is a factor to consider when reducing the risk of dangerous voltages on the pipeline deck during lightning strikes.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted objectively and free from external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals

REFERENCES

1. Y. Ma, H. Shu, C. Xiao, G. Yang, C. Xie, M. Zhu, and P. Cao, "Lightning Current Distribution of the First and Subsequent Strokes Based on the Lightning Location System: Survey in Yunnan Power Grid," Atmosphere, vol. 16, no. 1, art. 15, 2025, DOI: https://doi.org//10.3390/atmos16010015
2. T. Cakil, H. F. Carlak, and S. Ozen, "The indirect effect of lightning electromagnetic pulses on electrostatic and electromagnetic fields, and induced voltages in overhead energy transmission lines," Applied Sciences, vol. 14, no. 7, art. 3090, 2024, DOI: https://doi.org//10.3390/app14073090
3. J. Colqui, R. A. Ribeiro de Moura, M. A. De Oliveira Schroeder, J. Pissolato Filho, and S. *Kurokawa, "The Impact of Transmission Line Modelling on Lightning Overvoltage," Energies, vol. 16, no. 3, art. 1343, 2023, DOI: https://doi.org//10.3390/en16031343
4. Y. Zhang, X. Xie, W. Fu, X. Chen, S. Hu, and L. Zhang, "Indirect lightning performance of 10-kV overhead distribution lines," Front. Energy Res., vol. 12, art. 1367183, 2024, DOI: https://doi.org//10.3389/fenrg.2024.1367183
5. M. Boukhoune, B. Nekhoul, and B. Khelifi, "Time-domain modelling of lightning transients in grounding systems considering frequency dependence and soil ionisation," Electric Power Systems Research, vol. 234, art. 110542, Sept. 2024,

DOI: https://doi.org//10.1016/j.epsr.2024.110542
6. Caballero, P.T., S. Kurokawa, and B. Kordi, Accelerated frequency-dependent method of characteristics for the simulation of multiconductor transmission lines in the time domain. Electric Power Systems Research, 2019. 168: p. 55-66, DOI: https://doi.org/10.1016/j.epsr.2018.11.006
7. T. Spielböck and A. Beláň, "Design of a one-sided, impedance-based transmission line fault locator using line topology and source impedances," Electric Power Systems Research, vol. 161, pp. 123–138, Aug. 2018, DOI: https://doi.org/10.1016/j.epsr.2018.03.013
8. Guo, X., et al., A non-uniform transmission line model of the±1100 kV UHV tower. Energies, 2019. 12(3): p. 445, DOI: https://doi.org/10.3390/en12030445
9. F. S. Almeida and F. H. Silveira, "Influence of tower modelling on the assessment of backflashover occurrence on transmission lines due to first negative lightning strokes," Electric Power Systems Research, vol. 197, art. 107307, 2021, DOI: https://doi.org//10.1016/j.epsr.2021.107307.
10. Zhang, Z., et al. Study on Transient Impact Characteristics of Grounding Grid in UHV Converter Station and Its Influencing Factors, in 2018 International Conference on Power System Technology (POWERCON). 2018. IEEE, DOI: http://doi.org//10.1109/POWERCON.2018.8601841
11. M. Boukhouna, B. Nekhoul, and B. Khelifi, "Time domain modelling of lightning transients in grounding systems considering frequency dependence and soil ionisation," Electric Power Systems Research, vol. 234, art. 110542, 2024, DOI: https://doi.org//10.1016/j.epsr.2024.110542.
12. X. Wang, T. Lu, J. Chen, and Y. Liu, "Study of transmission line AC interference with steel-buried pipelines under lightning strikes," Electric Power Systems Research, vol. 218, art. 109226, 2023, DOI: https://doi.org//10.1016/j.epsr.2023.109226.
13. A. S. Zalhaf, E. Zhao, Y. Han, P. Yang, A. H. Almaliki, and R. M. H. Aly, "Evaluation of the transient overvoltages of HVDC transmission lines caused by lightning strikes," Energies, vol. 15, no. 4, art. 1452, 2022, DOI: https://doi.org//10.3390/en15041452.
14. Daniele Mestriner, Rodolfo Antônio Ribeiro de Moura, Renato Procopio, and Marco Aurélio de Oliveira Schroeder, "Impact of grounding modelling on lightning-induced voltages evaluation in distribution lines," Applied Sciences, vol. 11, no. 7, art. 2931, 2021, DOI: https://doi.org//10.3390/app11072931.
15. W. Liu, Y. Hu, H. Tian, Z. Jiang, X. Su, J. Xiong, W. Su, and Y. Wang, "Research on lightning overvoltage protection of line-adjacent pipelines based on solid-state decoupling," Applied Sciences, vol. 13, no. 22, p. 12529, 2023, DOI: https://doi.org//10.3390/app132212529.
16. Shangmao Hu, Yuanchao Hu, Jing Wang, Yunzhu An, Gang Liu, Zhixiang Liu, and Yan Cheng, "Research on lightning overvoltage of oil-gas pipeline caused by lightning strikes on adjacent electrical transmission line," Frontiers in Energy Research, vol. 10, art. 830638, 2022, DOI: https://doi.org//10.3389/fenrg.2022.830638.
17. Jianli Yu, Shanmao Gu, Jianjun Liu, He Liu, "Indirect lightning performance of 10-kV overhead distribution lines," Frontiers in Energy Research, vol. 12, art. 1367183, 2024, DOI: https://doi.org//10.3389/fenrg.2024.1367183.
18. A. Piantini et al., "Lightning-induced voltages on low-voltage distribution lines: Measurements and 3D modelling," Electric Power Systems Research, vol. 235, Oct. 2024, Art. no. 110526, DOI: https://doi.org//10.1016/j.epsr.2024.110526.
19. L. Boussayoud and B. Nekhoul, "Transient electromagnetic lightning disturbances induced in the collector cables of a wind farm," Electric Power Systems Research, vol. 241, Apr. 2025, Art. no. 111345, DOI: https://doi.org//10.1016/j.epsr.2024.111345.
20. J. A. Martinez-Velasco, Ed., Power System Transients: Parameter Determination. Boca Raton, FL, USA: CRC Press, 2017, DOI: https://doi.org/10.1201/9781420065305
21. H. Kwon, Y. Kil, and S. Kim, "A method for grounding resistance calculation of vertical electrode," Electr. Power Syst. Res., vol. 224, Nov. 2023, Art. no. 109718, doi: 10.1016/j.epsr.2023.109718, DOI: https://doi.org/10.1016/j.epsr.2023.109718

AUTHOR'S PROFILE

Abdelhak Mehadjbia holds a bachelor's degree in computer science, a master's degree in Intelligent Systems Engineering, and a Master's degree in Electrical Engineering, with publications in the fields of artificial intelligence and computer vision. He is currently an Engineering Research Student pursuing a PhD at the University of Quebec at Abitibi-Témiscaming, working on various projects in intelligent systems and computer vision. He is actively involved in several research projects addressing real-world challenges, with interests in deep learning, image analysis, electrical engineering, and intelligent decision-making systems.

Fouad Slaoui Hasnaoui received his B.Sc. A. and M.Ing. in Electrical Engineering in 1986 and 1995, respectively, from Ecole Polytechnique de Montréal. He also earned his PhD from École de technologie supérieure in Montréal, Canada, in 2003. Dr Slaoui worked as a power industrial engineer for a few years in Morocco, where he was responsible for the electrical maintenance department at one of the country's largest fish industries. Then he worked in Montreal, Canada, on various research projects in power systems, grounding systems, and ground-fault distribution in substations, towers, and ground wires. He is currently a professor of power systems at the University of Quebec in Abitibi-Temiscamingue. His research interests include numerical analysis in power system stability and grounding, as well as artificial intelligence, the Internet of Things, and computer vision.