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Local Atmospheric Electric Circuit Model Using Electrostatic Pickups on a 375kV Transmission Line

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HIGHLIGHTS

- Local Atmospheric Electrical Circuit – LAEC with line transmission
- The waveform in atmospheric coupling (transmission line - LT) is out of phase by 10.34.
- A voltage drop difference of 0.27% is observed in relation to the atmospheric coupling.
- Signal with peaks at 100kV induced approximately 0.66% of the LT voltage (375kV).

Abstract: The global atmospheric electric circuit is based on a model of electrical connection between the earth and the ionosphere (waveguide), capable of representing the flow of electric current in this waveguide. In the proposed model, a storm acts as a generator, allowing the ionosphere to maintain its highest electrical potential (approximately 300kV) in relation to Earth. When a storm forms, the bottom of the cloud becomes negatively charged. This study is focused on modeling this specific part of the global atmospheric electric circuit, which is renamed local atmospheric electric circuit. In the methodology, we use an RLC circuit to calculate the effects of electrified clouds in a 375kV transmission line considering an electrical coupling between them (an RLC circuit is an electrical circuit consisting of a resistor (R), an inductor (L), and to capacitor (C). The mathematical formulation was developed using transmission line theory considering a connection with the top of the storm cloud. Then, a model simulation using GNU Octave was performed, and the results demonstrated how this coupling affects voltage drop and phase shift in a 375kV transmission line. Thus, a local atmospheric electric circuit model, considering the particularities of the environment immersed

in a real transmission line model, configures an important model in the perspective of project management of electric energy transmission networks.

Keywords: electric atmospheric circuit; lightning; transmission lines; thunderstorm; differential equations.

INTRODUCTION

The proposal and development of global DC circuit models were motivated by research in atmospheric electricity, by three great scientists: Benjamin Franklin, William Thomson (Lord Kelvin) and C.T.R. Wilson. Since then, researchers have proposed some models to study the physics of global electrical circuits, trying to understand the electrodynamics and electrostatics behind the unbalanced distribution of charges in the earth's atmosphere and in the ground [1,2,3,4]. There is a huge electrical potential difference between Earth's soil and the ionosphere that fluctuates with different values throughout the day [12,17].

It is attributed to Franklin, the first statement of a global flow of humid, electrified air. Lord Kelvin, 100 years later developed potential theory, a mathematical tool needed for theoretically underpinning the global circuit. This variation has a distinct pattern called the Carnegie Curve [5,6,13]. Measurements by Wilson of the field changes associated with lightning in thunderclouds led him to conclude that the polarity of thunderclouds was systematically positive in upper levels and negative at lower levels. The observation of the transatlantic propagation of radio waves in 1903 by G. Marconi verified the presence of the conductive ionosphere [16].

This collective information led Wilson in 1920 to formulate his famous hypothesis for the global electrical circuit: thunderstorms are batteries and drive current upward to the conductive ionosphere where it spreads out to return to Earth in fair weather regions [10,12].

There is a current flowing from Earth to the Ionosphere [7,18] due to an electrical potential difference. Air has little electrical conductivity even though it is an insulator. Considering the entire globe, the resistance (R) between the ground and the ionosphere is around 300Ω and has U = 300kV [1]. We can calculate the electric current (I) using Ohm's law (U = RI), which gives us a current with a magnitude of 1kA. These parameters can change according to the level of pollution, humidity and temperature [1,6,12,19]. As it is a globally sized system and the parameters vary in spacetime, their accurate assessment is extremely difficult.

If this model were represented only by a current of 1kA going to the ionosphere, this system (ionosphere-earth ground) would become electrically null in approximately 10 minutes [1,4,6]. Therefore, the Carnegie Curve, in theory, would be just a constant centered on zero, as there would be no potential difference to be measured. This does not happen, because the atmosphere has other mechanisms responsible for charge separation, maintaining the electric field in the system [4,8,10,20].

The charge separation mechanism is not fully understood. One of the theories states that the sun heats the water on the Earth's surface to the point where it turns into steam, the convection process causes the water vapor to rise even more in the atmosphere because it has a higher temperature than of the environment [3,6,7,21]. As they ascend, the water droplets start to freeze from the outside to the inside. Consequently, the water particles polarize. The frozen portion of the drop becomes negatively charged and falls to the lower section of the cloud due to gravity, and the thawed portion becomes positively charged and continues to rise until it reaches the top of the cloud [1,2,6]. This structure in which the top is positively charged and the base negatively acts as a battery for the Global Electric Circuit [1,2,19].

Lightning occurs when the cloud is polarized. The air, as an insulator, tries to keep electrical current from flowing [14]. As negative charges accumulate at the base of the cloud, the electrical potential increases relative to the ground, as there is a greater concentration of negative charges [1,4,6].

As the cloud is polarizing vertically and gathering more charges of the same polarity, it can produce an electric field of such intensity that it can cause the air to ionize, releasing electrons. These produced free electrons will collide, producing even more ions, leading to an avalanche of electrons. When this phenomenon spreads and reaches the ground, it is called "step leader". This is the origin of an ionized path where charges can move more freely. The ionized channel causes the air to lose its insulating properties, enabling a sequence of electrical discharges following the same path created by the stepped leader, generally with greater intensity than the first, as the channel is already full of ions [13,18,21].

This model will not simulate the behavior of a system stimulated by the direct effects of electrical discharges, since there are already numerous studies on the subject, such as Silveira's thesis [8].

The indirect effects of a lightning strike will be simulated using data generated by Octave. The main this study, is the relationship between a cloud charged above an active electrical system placed under the cloud. In this case, the system is a 500km long 375kV transmission line.

This article is divided, into two parts. First, to level the reader, there are some theoretical considerations used to create the model and a brief explanation of the distinction between a continuum and an alternative component in the temporal base tension. First, the mathematical modeling of the system was developed, considering only the continuous component of the cloud voltage. To verify the thunderstorm influence, a 500km wide transmission line was simulated, under the cloud. The second part follows the same procedure, but also considering the alternative component, allowing a more detailed view.

MATERIAL AND METHODS

Theoretical Considerations

Some conditions are required to demonstrate the storm as an RLC electrical circuit model. The modeling is two-dimensional because the results will be used to calculate the transmission line parameters using Octave. Since the transmission line only extends in two dimensions, this model is an accurate approximation.

The base of the storm cloud is charged with negative ions, which creates an electrical potential difference of 35MV in relation to the Earth's surface and a current of magnitude 1000A [9,19]. The cloud gains a conductive characteristic for having free electrons [10,11,21]. For a more detailed analysis of the effects of a storm against the transmission line, the cloud voltage will be separated into two (continuous and alternating). One of them is a constant voltage with the value of 35MV, so its value is the same at all points in the simulation. The other part of analyzing the voltage signal oscillates along the time axis. The 35MV value is an average voltage within a given storm. Cloud-to-ground lightning occurs when a rapid charge transfer occurs between the cloud and the Earth's surface (about 1 Coulomb on average) [1,2,4,11]. As there is a variation in charge, the electrical potential also varies accordingly. These voltage fluctuations will be analyzed as the oscillatory component.

The small voltage variation between two distinct cloud points is not considering in this simulation. The cloud can be considered an equipotential surface that leads to a single value through the axis of space. Therefore, the horizontal component of the cloud is represented as an inductor [15].

Storms can be considered as generators, responsible for the separation of loads, through mechanical forces (gravitation) [9,10,12]. This creates a large potential difference, about 35MV (average). Cloud voltage is represented as a continuous voltage source.

Since there is a mass of charges with one polarity at the base of the cloud and more charges with reverse polarity at the ground separated by an insulator (air), the vertical component of the local atmospheric circuit can be represented as a capacitor. However, air is not a perfect insulator, even without dielectric breakdown, there is still a current of magnitude 1kA circulating through the atmosphere in fair weather conditions [7,14,15]. Therefore, in parallel with capacitance, there is also a resistivity component to represent the electron leakage that occurs even in fair weather [17,18].

Charges moving in the cloud or lightning caused by air collapse provide a voltage variation for a short period. This variation is considered random for simulation purposes. Following the same principles, a time-dependent voltage source is used to simulate the oscillatory voltage component of the cloud.

The equation involving voltage coupling in a transmission line is [19,20]:

$$V_2(z,t) = V_{DC} + V_{ac}(z,t), \tag{1}$$

Where, the z corresponds to the distance, in kilometers, from the line of transmission, and the t is the time in seconds. Both voltage sources are dissociated for a clearer view of the effect provided by each of them. In this case, V_{DC} is a constant value voltage of 35MV, $V_{ac}(z,t)$ corresponds to the oscillating portion of voltage, and $V_2(z,t)$ is the total cloud voltage [19,20].

Local Atmospheric Electric Circuit - LAEC

A Local Atmospheric Electric Circuit (LAEC) is a specific model formed by a small portion of the Global Atmospheric Electric Circuit (GAEC) [9,12,18]. The second is a circuital model designed for a more general view. As the name implies, a GAEC looks at electrical parameters including the entire globe and is not applicable in calculations to determine the effects of a storm in a particular region. For a more accurate analysis, the effects of atmospheric electricity are admitted to a transmission line under an active thunderstorm [14,15]. Since a GAEC is not accurate enough to do this, a new method is needed, so we presented a model of LAEC, proposing to use local electrical parameters to more accurately determine how a storm affects an electrical circuit active under the thunderstorm. In this case, a transmission line under the thunderstorm. A transmission line can reach hundreds of kilometers in length and is subject to several disturbances that cause significant damage to companies and the energy distributor. One such disturbance is thunderstorm activity around the globe that can act over for tens of kilometers and last from 45 minutes to 1 hour on average [9,18,19].

Transmission lines are used, to transport electrical energy between a source and a charge. As a motivation, regarding the inclusion of a transmission line model are, the advances in the expansion of the grid that distributes electricity to various regions of the country, and the consequent vulnerability of the electricity sector, when trying to monitor, prevent and maintain the transmission lines, in perfect conditions when a large part of the failures in this sector is admitted, due to the numerous cases of disconnection, failures and damage to the networks, caused by atmospheric discharges [16]. Therefore, this article simulates how electrodynamic conditions of a thunderstorm couples to a transmission line by capacitive, inductive and resistive means, using of a proposed model of the LAEC to calculate these effects coupling.

As will see later, this coupling resulted (simulation results) in a loss caused by leakage current going to the atmosphere (resistive aspect) and a phase shift due to capacitive and inductive effects. A phase-shifted voltage signal results in a lower power factor, which contributes to inefficient power transmission. Therefore, the consequences of these couplings are important to understand the power quality assessment of a transmission line.

DC Mathematical Modeling

Using transmission line theory to model the system allows us to run simulations in the GNU Octave environment to calculate voltage and current waveform changes due to the presence of thunderstorms. The coupling circuit diagram is shown in Figure 1. The surface of the Earth corresponds to the ground, and V_1 represents the voltage signal from the transmission line, located about 60m from the ground and V_2 is the basic voltage of the thunderstorm, set at about 1500m above the ground. Tables 1 and 2 reveal the RLC parameters used in the simulation.

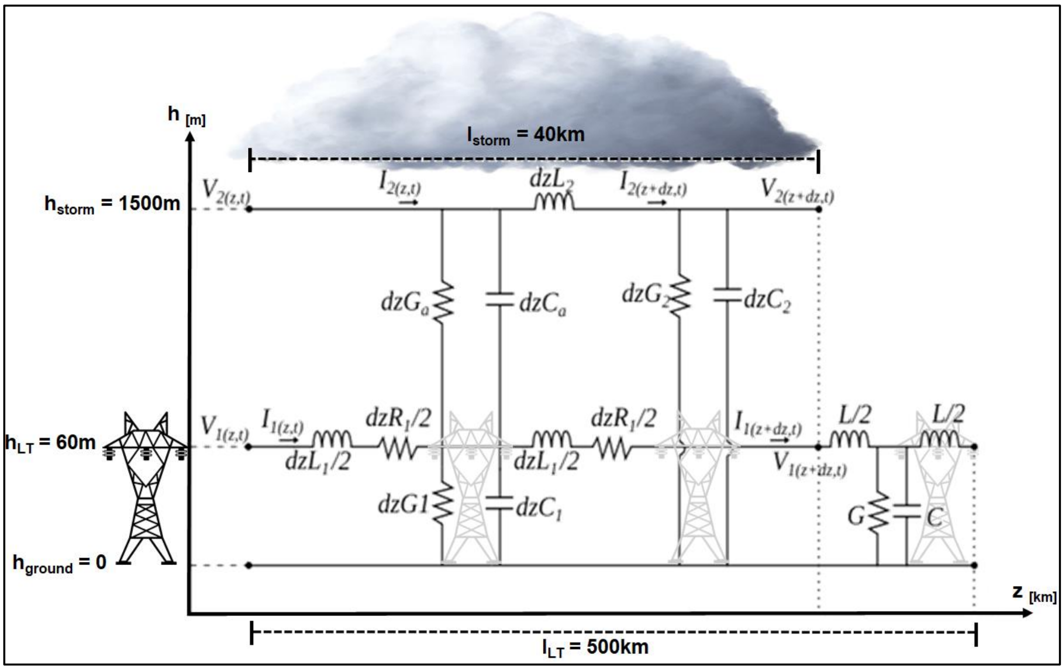


Figure 1. Model of local atmospheric electric circuit coupling with a transmission line. In this representation, there are capacitances, inductances, resistances and inductances between the ground and the storm cloud. The considered length of the transmission line is 500km and the storm cloud is about 1500m from the ground. Source: The authors (2021).

The voltage (V_1) and current (I_1) propagate along the transmission line and depend on the time. Therefore, V_1 and I_1 are function of space z and time t and have a sinusoidal behavior with a frequency of 60 Hz given by the energy distributor. On the other hand, V_2 and I_2 represent the thunderstorm parameters. The magnitudes of these parameters were taken from Rycroft, M.J. et al. (1998, 2000). Since only the continuous component of the voltage is considered in this part, then $V_2 = V_{DC}$. The thunderstorm usually lasts about 45 minutes and let us assume that its extension for 40km. There are several voltage fluctuations over this period, but for a first analysis, the voltage was considered constant in space and time, which means that these derivative functions with respect to time are equal to zero.

Paramectric System

We will assume a LAEC is the size of an average thunderstorm, in this case, it has a radial size of 40km and a ground height of 1500m. The frequency of the electrical network being 60Hz (Brazilian system), the wavelength in this circuit is greater than the 40km stipulated for the distance range this study. Consequently, the electromagnetic behavior of this system is "quasi-static". Therefore it is possible to add the atmospheric coupling components (dealt with in the "Theoretical Considerations" section) to the transmission line (using the transmission line theory) and proceed for the final mathematical development.

Capacitive parameters (Capacitance cloud-ground - C_2 and Atmosphere Capacitance - Ca) in Faraday, were calculated using the equations 2 and 3.

$$C_2 = (\varepsilon_o \varepsilon_r 2\pi l_{storm})/2 \,, \quad (2)$$

$$C_a = (\varepsilon_o \varepsilon_r 2\pi l_{storm})/\,(cosh^{-1}(h/r_{LT}))\,, \quad (3)$$

With respective parameters of ε_o = 8.85x10^{-12} C^2/Nm^2, (relative permittivity of air) ε_r = 1.00054, radial distance l_{storm} = 40x10^3 m, and height of storm cloud h = 1500m [18,19] for equation 2, and r_{LT} [m] is the radius of the transmission line electric cable (using 20mm diameter). The model parameters must be their values by distance because a differential approach was, used to develop the model. The transmission line in question uses parameters calculated with 500km in length, while the storm extends over 40km in diameter. Thus, the results of equations are in Tables 1 and 2, will be divided by their respective distances to determine the average value per distance unit, according it treats the parametric equations of transmission lines.

Table 1. Electrostatic parameters of the atmosphere in the middle of a thunderstorm. Adapted: [9,12,18,19,20].

Electric Parameters of Atmosphere	Magnitude
Electric potential (V_2)	~35MV
Conductivity cloud-ground	14.18x10^{-6} S
Base height of thunderstorm	1500m
Duration of the thunderstorm	40min
Thunderstorm base diameter (l_{storm})	40km
Capacitance cloud-ground (C_2)	2.9x10^{-5} F
Capacitance (C_a)	1.8x10^{-7} F
Inductance (L_2)	3.5x10^{-3} H
Conductivity (G_a)	3.4x10^{-10} S

Table 2. Transmission line parameters considering an electric active storm. Adapted: [9,12,18,19,20].

Electric Parameters of Atmosphere	Magnitude
Electric potential (V_1)	375kV
Resistance (R_1)	40.7Ω
Cable height (h_{LT})	60m
Angular frequency (ω)	377rad/s
Length (l_{LT})	500km
Operational frequency (f)	60Hz
Capacitance (C_1)	3.572μF
Inductance (L_1)	0.8H
Conductivity (G_1)	278μS

RESULTS AND DISCUSSION

Assuming a propagation in the *z* direction in the coupling, the transmission line model, as shown in Figure 1, has a length (l_{LT} dz) conductance (G_1dz), inductance (L_1dz) and capacitance (C_1dz). The rates of change of voltage and current with respect to z are expressed by the transmission line equations, according to [5,12,18,19] model, obtained by the successive application of Kirchoff's voltage law and Kirchoff's current law, on the model of transmission line with and without loss and of length dz, as shown in Figure 1. Let's consider that the voltage in the transmission line has a solution using Kirchoff's law of voltages, thus, we conventionalized a closed path in the circuit model (Figure 1) in a clockwise direction (Equation 1).

$$\mathrm{V} = \frac{1}{2}RIdz + \frac{1}{2}\mathrm{L}\frac{\partial \mathrm{I}}{\partial t}dz + \frac{1}{2}\mathrm{R}(\mathrm{I} + d\mathrm{I})\Delta z + \frac{1}{2}\mathrm{L}\frac{\partial(\mathrm{I}+d\mathrm{I})}{\partial t}\Delta z + \mathrm{V} + d\mathrm{V}. \quad (1)$$

The second equation of the transmission line is obtained, by applying Kirchoff's current law to the central node in the circuit in figure 1, noting that from the symmetry, the voltage at the node will be $V = (dV/2)$, thus:

$$I = I_G + I_c + (I + dI) = Gdz\left(V + \frac{dV}{2}\right) + Cdz\,\frac{\partial}{\partial t}\left(V + \frac{dV}{2}\right) + (I + dI), \tag{2}$$

Where I_G is the current through the conductance Gdz and I_C is the current through the capacitor Cdz. Isolating the term, dV/dz, we take the $\lim_{dz\to 0}(dV/dz)$ so, we have a derivative for V_1 and V_2. As dz tends to 0, so dI will also tend. Making this algebraism on equations 1 and 2, we will have the expressions:

$$\frac{\partial^2 V_1}{\partial z^2} = -\left[R_1\theta + L_1\frac{\partial\theta}{\partial t}\right], \tag{3}$$

$$\frac{\partial^2 V_2}{\partial z^2} = -\left[R_2\theta + L_2\frac{\partial\theta}{\partial t}\right], \tag{4}$$

Where, $\theta = -\left(\frac{\partial V_1}{\partial t}(C_1 + C_a) + \frac{\partial V_2}{\partial t}C_a - V_1(G + G_a) + V_2G_a\right)$. Making the same mathematical procedure for equation 2, we follow the following expressions:

$$\frac{\partial^2 I_1}{\partial z^2} = -\left[\frac{\partial\emptyset}{\partial t}(C_1 + C_a) - C_a\frac{\partial\varphi}{\partial t} + \emptyset\,(G_1 + G_a) - \varphi G_a\right], \tag{5}$$

$$\frac{\partial^2 I_2}{\partial z^2} = -\left[\frac{\partial\varphi}{\partial t}(C_2 + C_a) - C_a\frac{\partial\emptyset}{\partial t} + \varphi\,(G_2 + G_a) - \emptyset G_a\right], \tag{6}$$

Where, $\emptyset = -\left(R_1I_1 + L_1\frac{\partial I_1}{\partial t}\right)$ e $\varphi = -\left(R_2I_2 + L_2\frac{\partial I_2}{\partial t}\right)$. As V and I have a sinusoidal behavior, we can represent them as equations in frequency domain, so we do $\frac{\partial V}{\partial t} = j\omega V$ and, also $\frac{\partial I}{\partial t} = j\omega I$.
This will make numerical modeling easier, so we take the value of θ and we calculate $\partial\theta/\partial t$, then, we take the value of $\emptyset$ and making $\partial\emptyset/\partial t$, so, we can write V_1 as a function of V_2 phasorial, according to Equation 7.

$$\frac{\partial^2 V_1}{\partial z^2} = V_1\gamma_1^2 + V_2K\,, \tag{7}$$

Where, $\gamma_1^2 = R_1j\omega(C_1 + C_a) + R_1(G_1 + G_a) - L_1\omega^2\,(C_1 + C_a) + L_1j\omega(G_1 + G_a)$, with $K = -R_1G_a$.
One of the solutions of Equation 7 is to consider the real part ($\mathbb{R}e$) (excluding the imaginary part ($\mathbb{I}m$)) of the propagate wave in the positive direction (V^+) of the system, so that the result for V_1, is given by:

$$V_1 = V_1^+e^{-\mathbb{R}e(\gamma_1)z}\cos(\omega t - \mathbb{I}m(\gamma_1)z) + V_2K\left(\frac{z^2}{2}\right) \tag{8}$$

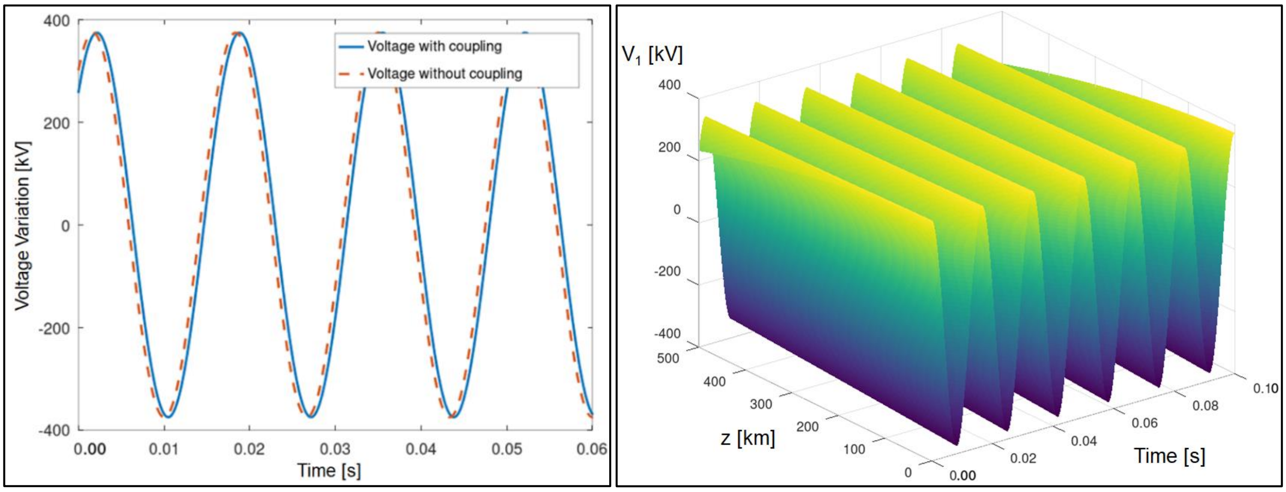
Making the same mathematical procedure for representing I_1 with the function of I_2, we have:

$$I_1 = I_1^+e^{-\mathbb{R}e(\gamma_1)z}\cos(\omega t - \mathbb{I}m(\gamma_1)z) - I_2\sqrt{R_2G_a}\left(\frac{z^2}{2}\right) \tag{9}$$

As we are interested in verifying the qualitative behavior of the voltage, given the proposed coupling, we will only use equation 8. The results of this numerical modeling are treated in the next section.

Numerical Modeling of DC Voltage in a 375kV Transmission Line - Simulations

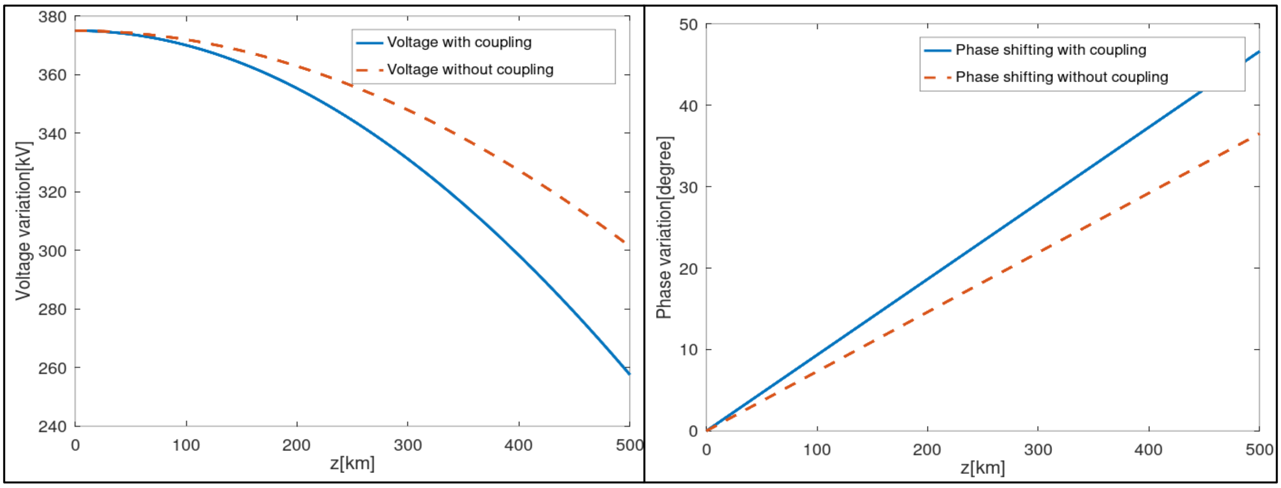
The voltage variation along the transmission line under "Fair Weather" conditions will be observed, with and without losses, and then compared to the voltage variation curve within a region affected by a storm. In this case, it is possible to verify the effects of the atmospheric coupling proposed in this article in a transmission line. However, to facilitate the numerical calculation of the behavior of the V_1, was generated 2D graphics to simplify the analysis.



(a) **(b)**

Figure 2. (a) Transmission line voltage in respect to time and space. (b) Comparison curves between transmission line voltages with and without atmospheric coupling effect, z = 500km (no losses). The authors (2021).

Equation 8 consider z = 500km (Figure 2(a)) and refers to the voltage variation over time at the end of the transmission line admitting the existence of a without losses, atmospheric coupling. Therefore, the LT does not show signs of coupling in the presence of a thunderstorm, as can also be seen in Figure 2(b). The result of Equation 8 was numerically plotted in Figure 3, and shows the same voltage variation curves, but now, with time t = 0, while the distance z varies from the origin to the end of the transmission line. The voltages (Figure 3), with and without atmospheric coupling, were 256kV and 301kV, respectively. The voltage difference between the curves is ~15% and is caused by the phase shift between the two waveforms, which corresponds to ~26^o.



(a) **(b)**

Figure 3. (a) Correlation between transmission line voltage with and without atmospheric coupling in respect to z (no losses). (b) Phase shifting in respect to distance (no losses) ~14%. The authors (2021).

It is possible to visualize the phase shift of the voltage wave of the transmission line in relation to the distance in Figure 3(b). This graph shows the variation of the phase shift of a transmission line considering and not the atmospheric coupling. The Figures 4(a) and 4(b) were generated from Equation 8, but include the components related to losses; Therefore, when considering the losses, the resistance in the transmission line cable depends on the length of the transmission line and, tends to have a small voltage drop over the distance. Figure 4(a) is an outline of the voltage variation over time, and is a representation of the general behavior of the coupling with losses in a TL in the presence of a thunderstorm. The difference between the maximum voltages of each curve represents the magnitude of the voltage drop in the transmission line (~0.27%).

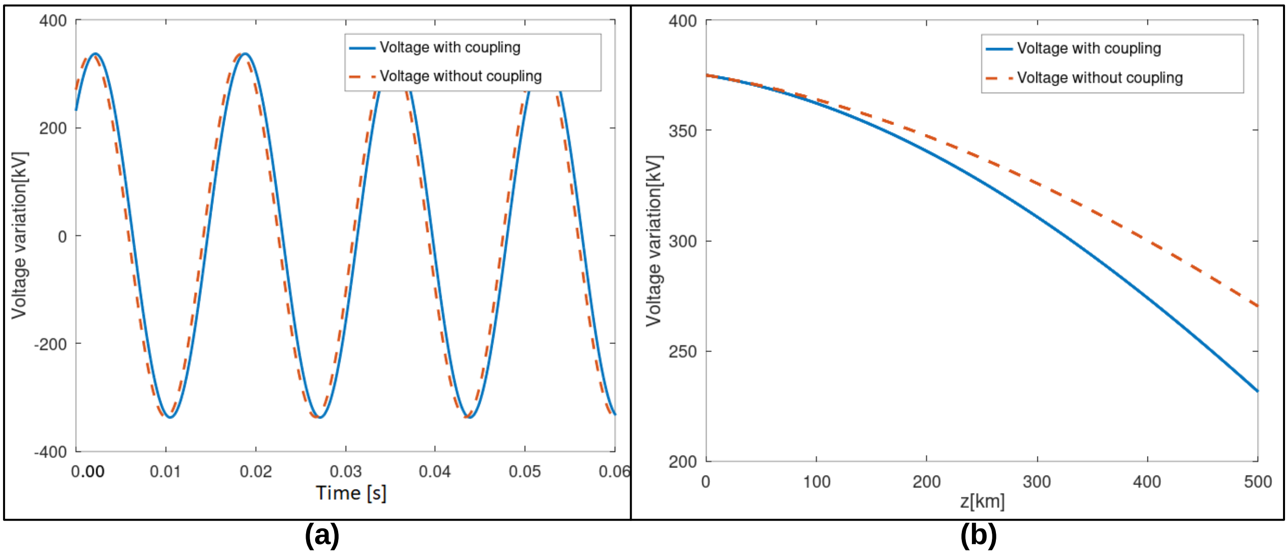


Figure 4. (a) Transmission line voltage with and without atmospheric coupling, considering losses (z = 500km). (b) Voltage magnitude with respect to distance, considering losses. Considering the atmospheric coupling, the voltage drop accumulated along the transmission line is more relevant than in the case of no coupling. The authors (2021).

Considering the losses (Figure 5), the model of the local atmospheric electric circuit, presented a phase variation with coupling and without coupling, respectively equal to 52º and 44º. These amounts are even higher than the no-loss case. Although there is the phase shift and losses, there is also an "offset" in the voltage waveform which has a value equivalent to $V_2K(z^2/2)$ obtained from Equation 8, This gives us a shift voltage of approximately -3V, between distances of 0 and 500 km, that corresponds exactly to the length of line transmission, in this model.

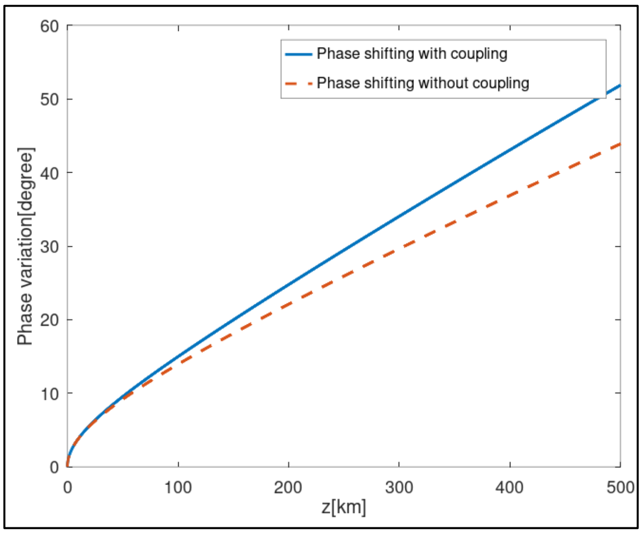


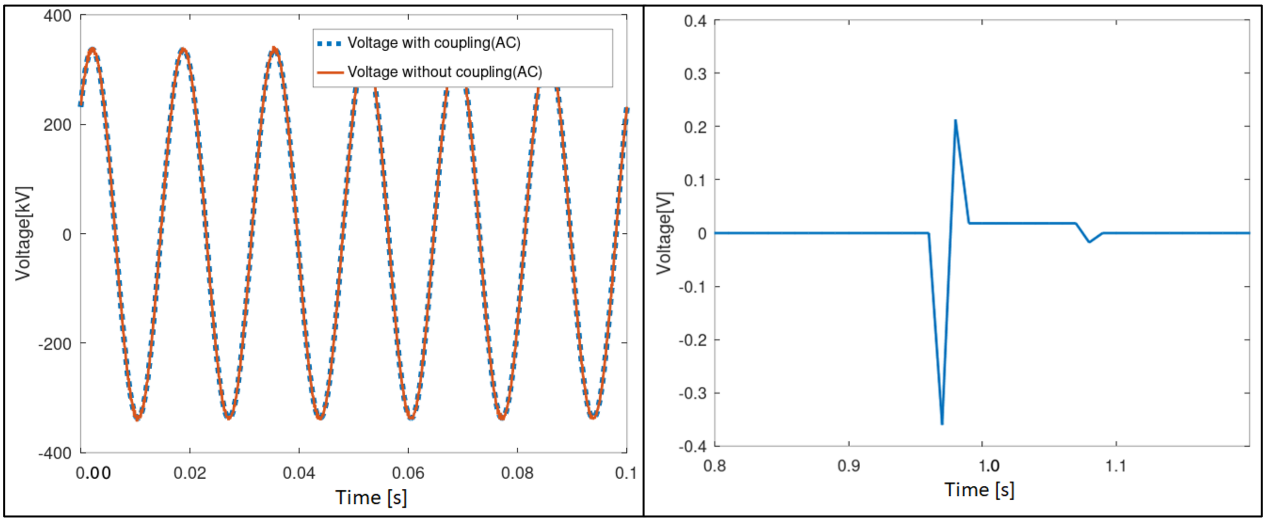
Figure 5. Phase shift in relation to distance, considering losses in a 375kV transmission line. The authors (2021).

Numerical Modeling of AC Voltage in a 375kV Transmission Line - Simulations

For AC modeling, another approach will be used. In this case, we will make $V_2 = V_{ac}(t)+V_{DC}$. The effects caused by fluctuating storm cloud base voltage on a transmission line will now be considered. As $V_{ac}(t)$ is the representation of the voltage fluctuations that exist in the storm cloud, it is not a known value and it varies constantly with time, that is, in this case, randomly. therefore, no we can calculate its derivative as a general solution. The derivative of $V_{ac}(t)$ can only be calculated if, computationally, we create a database with certain values as a function of time.

Equation 3 can be used for both DC modeling and AC modeling. However, in the mathematical modeling in DC, the $\partial V_2/\partial t$ was calculated with V_2 being equal to V_{DC} so, this derivative in the DC case is equal to zero. In the case of AC modeling, V_2 and its derivative will remain unknown. We will use the Octave environment to do the calculations for V_1, where V_2 will be treated as a discrete-time signal, as it would be the data collected by any device that is measuring the electrical potential variation of the storm. So, calculating the double integral as a function of the distance over equation 3.

Since we don't have a database that measures cloud variation based on voltage, we use random data generated from Octave. The generated data was limited to a maximum peak of 100kV, which is about 0.28% of the storm's average base voltage. Figure 6(a) show the result of the double integral of equation 3 as a function of distance and presents the waveform of the transmission line voltage “with” and “without” the AC coupling effect. Using a peak oscillation of 100kV as a parameter, the AC coupling curve overlaps the curve where the oscillatory component was not accounted for, but adds noise of approximately 2.5kV. Therefore, considering an oscillation similar to the proposed 100kV, the influence of the AC component can be ignored, by an error margin of 0.66%.



(a) **(b)**

Figure 6. (a) Transmission line voltage correlation with and without atmospheric coupling considering the AC component (z=500km). (b) Indirect induced transmission line voltage due to an atmospheric cloud to ground discharge. The authors (2021).

Atmospheric Discharge Simulation Near of Transmission Line of 375kV

To simulate the indirect effects of an atmospheric discharge near a transmission line, random data generated by Octave was used. When dielectric breakdown allows a path for a cloud to ground atmospheric discharge, charge transfer between the cloud base and the Earth's surface can reach up to 5 Coulombs [13]. Therefore, the voltage level of the cloud around the discharge point experiences a sudden voltage drop for a short period of the time (~ms). This simulation imposes that a lightning strike (cloud to the ground) results in a voltage drop of 10MV that occurs instantly and affects a region 1km wide area.

Figure 6(b) shows the indirectly induced voltage of a transmission line due to an electrical discharge. The time variable axis value starts at 0.8 for better visualization.

With the parameters chosen to simulate the indirect effects of an electrical discharge against a transmission line, as shown in figure 7(b), the induced voltage is approximately zero. Therefore, in this model, isolated lightning using the proposed parameters does not contribute to the transmission line voltage.

DISCUSSION

Through the results found by the DC simulation, we can see that the value of the V_{DC} component, even having a magnitude of 35MV, could only induce an offset = -3V which is about 0.0008% of the original magnitude of the transmission line voltage. In this case, the electrical potential presented in the thunderstorm acts as a condition, in which the LAEC can to exist. The electrical potential found at the base of the cloud exists only because there are a large number of negative charges in it, so the cloud acquires a conductive property, allowing the region of the transmission line that is below the storm to form an electrical coupling.

It was possible to verify that, at the end of the transmission line (z = 500km), the waveform considering the atmospheric coupling is out of phase by 10.34º in relation to the wave in conditions of fair weather. The voltage at the end of the transmission line also presents a voltage fall difference of 0.27% considering the atmospheric coupling.

The simulations taking into account the Vac component of the storm were obtained through data generated by the Octave software, using a maximum oscillation limit equal to 100kV. Using these parameters for a simulation, the voltage induced in the generation transmission line adds noise in the 2.5kV range. Therefore, considering a maximum peak variation of 100kV implies induction of approximately 0.66% of the original value (375kV) of the transmission line. As the value of Vac increases, its inclusion becomes more necessary to perform a simulation, otherwise, the result will become imprecise (margin of error of 0.66%).

The magnitude of the voltage induced in the transmission line is strongly dependent on the distance at which atmospheric coupling occurs (as shown in equation 8). As in the simulation, it was proposed that a voltage fall caused by an atmospheric discharge that propagates for 1km of distance, an induced voltage in the transmission line is practically null (0.8V). For this model, an isolated lightning strike was simulated, however, in the case of multiple lightning strikes occurring along with the thunderstorm, its effect tends to grow exponentially.

Although random data was used when introducing real Vac values into the AC simulation, it is still possible to conclude that the LAEC model proposed in this study can represent a coupling with the transmission line, because we observe that, exist losses and phase lag that, increase depending on the length of the transmission line. Having knowledge of the values obtained by these simulations and, working together with a system of detection of an approaching electrical storm, the operators of an electrical system can prevent itself, as for a change of a storm-induced change in voltage and phase levels, along the transmission line.

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