Lightning Performance of Compact Transmission Lines

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Abstract – **Determination of the lightning performance of compact transmission lines is described. The tower top transient voltage, following a lightning stroke is determined using the EMTP(ATP) program. Computer models of towers, ground wires and conductors, and the earthing system are presented. Computer simulations include a sensitivity analysis relative to the waveform of the lightning current, stroke location, earth resistivity, type of tower and terrain profile.**

Keywords: Lightning Transients, Compact Transmission Lines, EMTP Modeling.

I. INTRODUCTION

CHESF-Companhia Hidro Elétrica do São Francisco, responsible for the electric power generation and transmission in the Northeast of Brazil, intends to expand its transmission system in that region by installation of a number of long, 230 kV and 500 kV, transmission lines (TL)[1]. In this regard, feasibility studies were conducted to determine costs and economical constraints involved in the project. One of the consequences of these studies was that, use of compact transmission lines would provide several benefits, including, longer time periods between upgrades, reduction of the shunt and series reactive compensations, as well as increase of the transmission capability of existing lines.

A new type of compact transmission line, named High Surge Impedance Transmission Line (HSIL)[2], with a higher level of compactness, has been recently put into operation in a few countries. The HSIL is a new concept of transmission line design because it uses a combination of features such as, distance reduction among conductors belonging to different phases and increase of both, the number and relative distances among sub-conductors of a single phase. In addition, the HSIL uses asymmetrical bundles instead of the symmetrical and circular distribution of subconductors, employed in conventional compact lines. This new geometric configuration equalizes and optimizes the electric field distribution around all subconductors. The HSIL optimization process allows obtaining a substantial reduction of the series inductance as well as a significant increase of the shunt capacitance, in turn producing a very high intrinsic transmission line capability.

Recent development of the HSIL technology has limited its use to a few countries and therefore, further development and implementation of HSIL towers brings new challenges to experts on transmission line studies and design[3]. The purpose of this work is to analyze the lightning performance of compact lines, including HSIL lines.

II. LIGHTNING STROKES ON POWER LINES

Studies related to the effects of lightning strokes on power lines are of fundamental importance during the stage of tower design, as inadequate choice of the electrical parameters of the tower may lead to high tripping rates. These studies determine clearances and shielding angles of the tower and minimum distances required to bring flashover probability down to acceptable levels. Because of the complexity and random nature of the mechanism of lightning discharges, studies in this field require a Monte Carlo approach to carry out simulations. This method adequately represents the randomness of the variables involved and has been widely used in the literature to solve diverse problems, e.g., solution of simultaneous equations, diffusion of neutrons through materials, determination of probabilistic thermal limits of power lines, to name a few examples. This method, therefore, is adequate for simulating lightning current intensity, wavefront characteristics, incidence angle of the discharge, insulation strength on the tower and location of the stroke.

Two situations may occur, depending on the discharge location relative to the wires composing the transmission line. The first one, named a direct stroke, takes place when a phase conductor is struck directly, in turn producing a voltage increase in that phase. This may lead to a discharge between the phase conductor and the tower, if the insulator strength is exceeded. In this case, the operating voltage maintains the discharge arc, causing a short circuit and consequently a line tripout. This is commonly referred to as a shielding failure. By studying direct strokes, it is possible to obtain an effective shielding by proper distribution of ground wires.

The second situation, named an indirect stroke, is illustrated in Fig.1, and occurs when the discharge hits the ground wire. Unlike the first situation, it is very difficult to eliminate tripouts entirely. However, tripout occurrence can be minimized by proper choice of tower clearances, optimization of the coupling parameters between conductors and ground wires, and by improving the tower grounding project.

For the case of indirect strokes, voltage and current traveling waves are generated at the discharge site, propagating along the wires thereafter, until they reach the adjacent towers. This in turn leads to the production of reflected waves, with characteristics determined by the relative values of the surge impedances involved in the process. These traveling waves induce transient voltages on the conductors, having shapes determined by the electric coupling among conductors and ground wires. If the voltage difference between conductor and tower exceeds the insulator strength, a discharge occurs. This phenomenon is called backflashover. It is important to point out that a backflashover is much more likely to occur on insulators than a flashover at midspan, because of the smaller distance between phase conductor and ground at the tower relative to that at midspan.

The voltage wave at the tower is called tower top transient voltage and is dependent on the lightning current and associated waveform, location of the stroke, and transmission line parameters. When applied to the insulator string it is given by [4],

$$V_s(t) = (1-k)V_t + V_n(t) \qquad (1)$$

where, $V_s(t)$ is the potential difference between ends of the insulator, k is the coupling coefficient between conductor and ground wire, V_t is the tower top transient maximum voltage and $V_n(t)$ is the instantaneous conductor voltage.

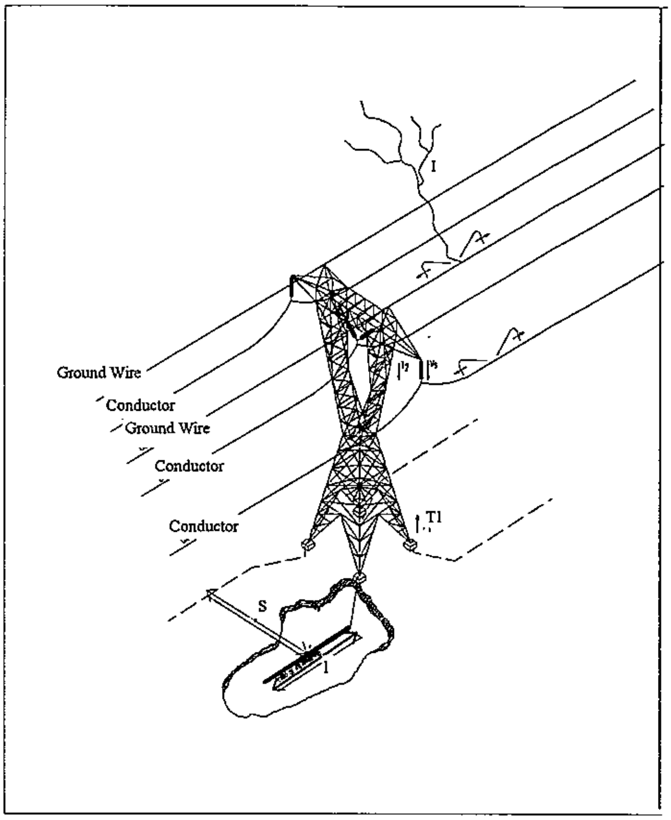


Fig.1. Representation of a lightning stroke on a TL.

The approach used in this work to determine performance of compact lines is based on the electrogeometric model developed by Whitehead [4], that takes into account the lightning type and formation of a conducting channel at the tip of the stroke. A diagrammatic representation of the striking distances relative to the TL wires is shown in Fig.2. According to this model, the discharge occurs when the electric charge concentration of the cloud exceeds the air strength, in turn propagating through a thermally ionized gas column wich is shaped like a cone. The cone radius corresponds to the strike distance S_d, illustrated in Fig.2, and is a function of the lightning current.

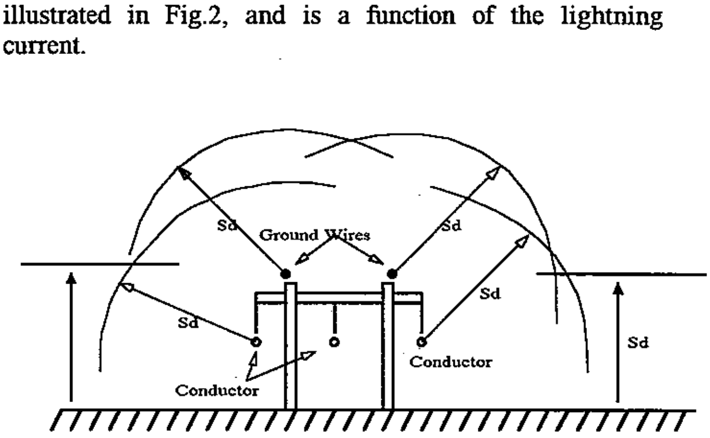


Fig.2.Diagramatic representation of the striking distances relative to the TL, according to the electrogeometric model.

III. METHOD OF ANALYSIS

In this Section, modeling of the several components of the transmission line system, under lightning, is described. The model is then applied for determination of the performance of compact transmission lines, including the recently developed HSIL system.

A. *Transmission Line Modeling*

The elements of the transmission line are modeled according to Fig.3, that shows two circuit diagrams accounting for discharges occurring at the tower and at midspan, respectively [4-5].

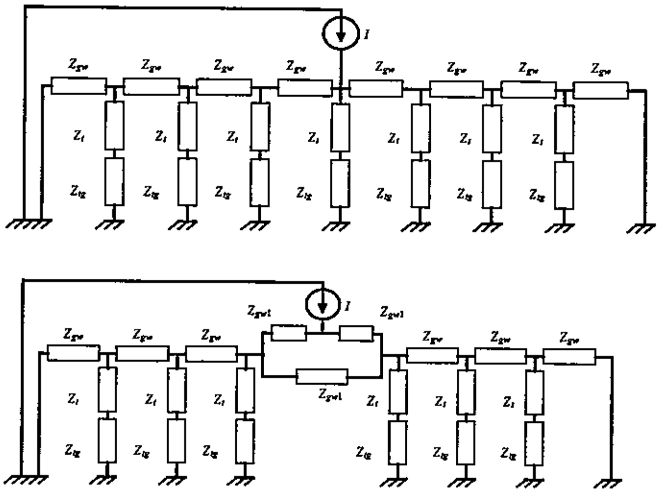


Fig.3. Equivalent circuits for a lightning discharge striking the tower (upper diagram) or midspan(lower diagram).

Parameters used to represent the circuits in Fig.3 are the lightning current I, the equivalent ground wire surge impedance Z_{gw}, and the ground wire, tower, and tower grounding, surge impedances Z_{gw1}, Z_t and Z_{tg}, respectively. It is worth noting that Z_{gw}=Z_{gw1}, if the tower has a single ground wire.

B. *Tower Ground Modeling*

To represent the tower grounding surge impedance Z_{tg}, a model suggested by Bewley[6] is employed. In this model the parameter Z_{tg}, is made equivalent to a series resistor in parallel with an RL circuit, as shown in Fig.4. In the equivalent circuit, when a unit step voltage is applied to the wire underneath earth, here represented by the counterpoise wire illustrated in Fig.5, its impedance varies over time, according to the equation,

$$Z_{tg}(t) = R_d + (Z_s - R_d)^{-\frac{tv}{2l}} \qquad (2)$$

where, R_d and Z_s are the values of Z_{tg} for $t \to \infty$ and for $t = 0$, respectively. In Eq.(2), v represents the current wave speed on the counterpoise wire of length l.

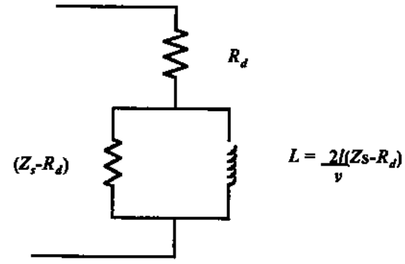


Fig.4. Tower grounding equivalent circuit.

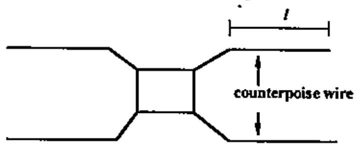


Fig.5. Typical earthing configuration of the TL.

Parameter R_d is obtained from the following expression[6],

$$R_d = \frac{\rho}{2\pi l}\left(\ln\frac{2l}{a} + \ln\frac{2l}{s} + 2.912 - 1.071\frac{s}{l} + 0.645\frac{s^2}{l^2} - 0.145\frac{s^4}{l^4}\right) \qquad (3)$$

where a is the wire diameter, s is twice the counterpoise depth and ρ is the soil resistivity.

Calculated values of the equivalent circuit parameters are listed in Table 1, for typical values of soil resistivity and 4AWG copperweld wire.

Tab 1. Parameters of the tower grounding equivalent circuit.

ρ(Ωxm)	$(Z_s\text{-}R_d)$[Ω]	L [μH]
500	3.5	1.05
1500	57.1	59.5

C. *Lightning Current Wave*

Two linear functions are used to represent the current waveshape, as illustrated in Fig.6. Parameter T_d is the time required for the current amplitude to fall back to half of its maximum value, and T_f is the rise time.

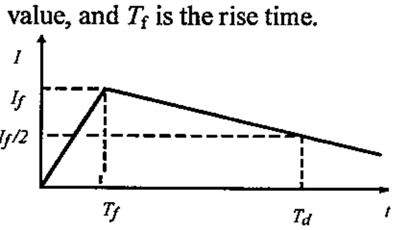


Fig.6. Model function describing the lightning current wave.

Experimental observations indicate that the parameters characterizing the lightning current are typically $T_d \approx 50\mu$sec and $T_f < 5$ μsec [4].

D.Tower Surge Impedance

Three types of compact towers were selected, namely, the self-supporting 500 kV (with one and two ground wires) and the cross rope chainette (500kV) and HSIL (230kV). Figures 7, 8 and 9 represent these tower configurations [5,7].

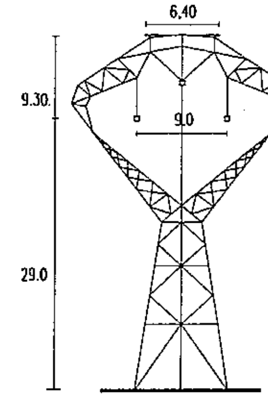


Fig.7. Self supporting 500kV(one and two ground wires).

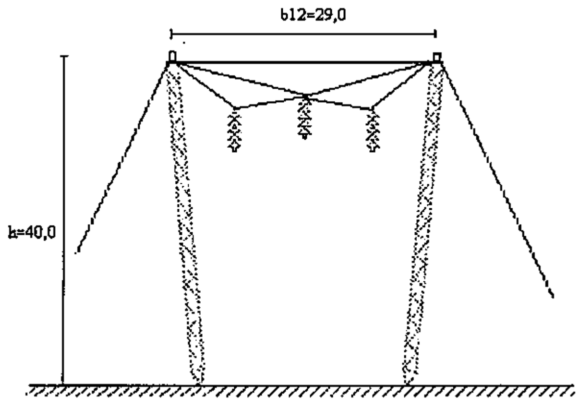


Fig.8. Cross rope chainette 500kV.

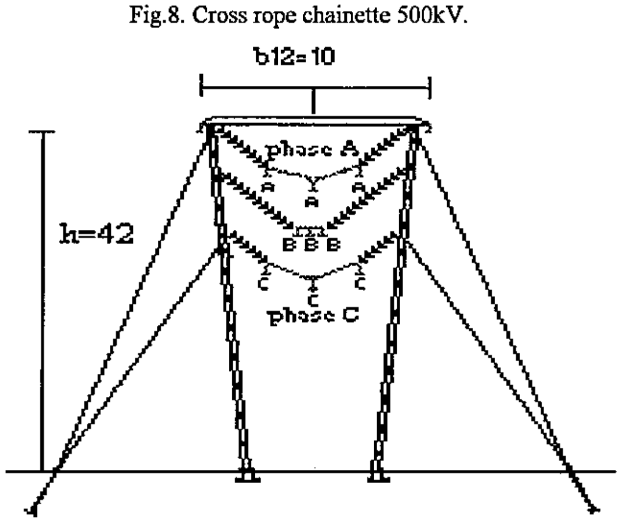
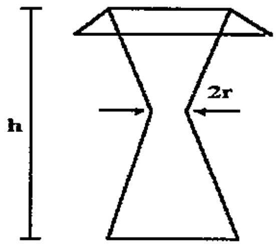


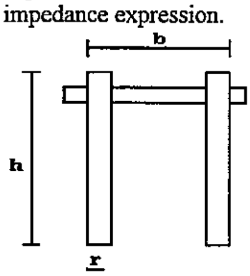
Fig.9. Cross rope chainette HSIL 230 kV.

To represent the tower surge impedance, it is necessary to consider the propagation time of the current wave along the tower structure for each of the configurations shown in Figs.7 through 9. A simple model of this parameter is given in Ref.[4], yielding the tower diagram models illustrated in Figs. 10 and 11, along with the expressions for the surge impedance.



$$Z_t = 60\left(\ln\left(2h\frac{\sqrt{2}}{r}\right) - 1\right)$$

Fig.10. Model of self supporting tower and corresponding surge impedance expression.



$$Z_t = \frac{Z_1 + Z_2}{2}$$

$$Z_1 = 60\ln\left(\frac{h}{r}\right) + 90\left(\frac{r}{h}\right) - 60$$

$$Z_2 = 60\ln\left(\frac{h}{b}\right) + 90\left(\frac{b}{h}\right) - 60$$

Fig.11. Model of cross rope chainette 500kV and HSIL 230kV towers and corresponding impedance expression.

Table 2 lists the calculated values of tower surge impedances considered in this work.

E .Equivalent Ground Wire Surge Impedance

The equivalent ground wire surge impedance is given by[4],

$$Z_{gw} = 60\ln\left(\frac{2h_{gw}}{r_{eq}}\right), \quad (4)$$

where h_{gw} is the average ground wire height, that is a function of the terrain profile, and r_{eq} is the equivalent radius of the ground wire combination. Both of these parameters are obtained according to the procedure outlined in Ref.[4].

Calculated values of the ground wire surge impedances, for the tower types and dimensions shown in Figs. 9 through 11, are listed in Table 2.

Tab 2. Calculated values of the parameters Z_t and Z_{gw} for the tower types analyzed in this work.

Tower type	$Z_t(\Omega)$	Z_{gw} (Ω)
Self supporting (1 ground wire)	173	557
Self supporting (2 ground wires)	176	345
Cross rope chainette (500 kV)	108	307
Cross rope chainette (HSIL 230kV)	100	304

F.*Lightning Impulse Insulation Strength*

Figure 12 depicts the lightning impulse withstand curves for the distinct tower air gaps [4]. This information, along with the parameters calculated earlier, are used to determine lightning performance and voltage transients as described in the next Sections.

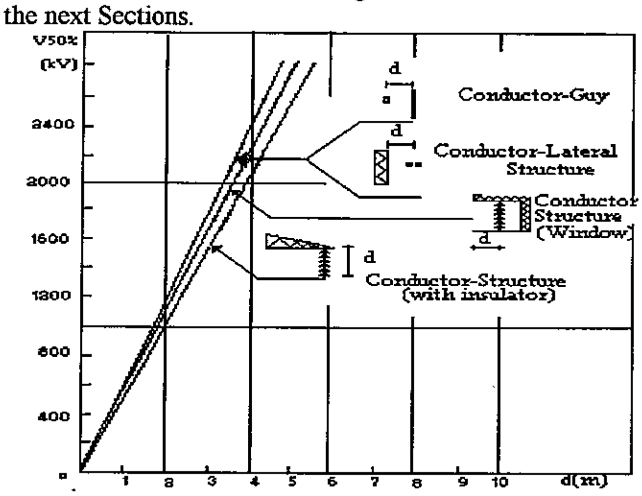


Fig.12. Lightning impulse insulation strength.

IV. TOWER TOP TRANSIENT VOLTAGE

Prior to determining lightning performance for the distinct tower types investigated in this work, the tower top transient voltage was studied using the EMTP(ATP) program, for a fixed value of the peak discharge current. Fixing the peak current in these simulations allowed to investigate how the voltage transient could be affected by changing the remaining four parameters, namely, lightning rise time, soil resistivity, tower type and stroke location. Calculations were carried out by setting the peak lightning current at 10 kA, as approximately 80% of observed discharges are known to produce peak currents exceeding this value[4]. In order to obtain the results 48 simulations were carried out using the EMTP(ATP) program.

Figures 13 through 16 illustrate the behavior of the tower top transient voltage, obtained by varying a single parameter. The three plots shown in Fig.13 were obtained by setting T_d=50μsec, and attributing the values of 1μsec, 3μsec and 5μsec, to the parameter T_f. One can notice that the voltage transients follow basically the lightning current waveform during risetime with undulations occurring during the lightning current decay time. It is worth noting the changes of approximately 40% to 60% in maximum voltage for the distinct curves.

Figure 14 shows that the soil resistivity greatly influences both the shape and the maximum value of the parameter V_s. Increasing the soil resistivity from 500 to 1500 Ω×m produces approximately 50% increase of the maximum voltage. This shows that the grounding modeling plays an important role in lightning performance studies. Figures 15 and 16 illustrate the effects of changing the type of tower and location of the stroke. For the curves shown in Fig.15, the largest change observed in the maximum value of V_s is approximately 25%, while location of the stroke influences the time lag for onset of the voltage transient, without significant variation in the maximum value.

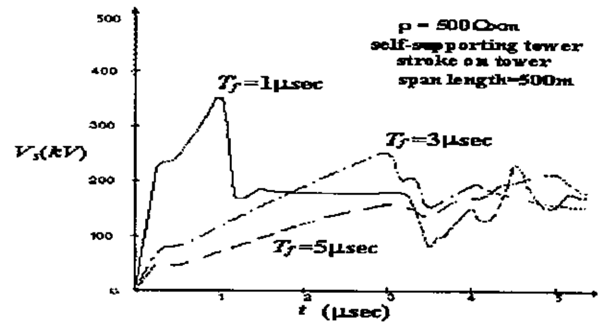


Fig.13. Tower top transient voltage dependence on the lightning wavefront.

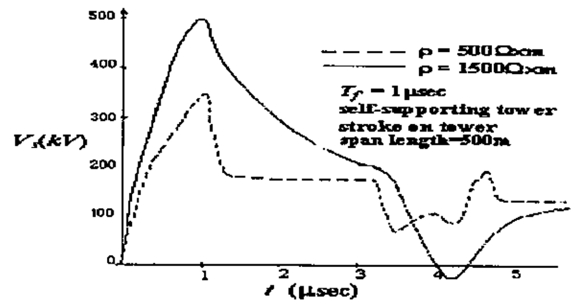


Fig.14. Tower top transient voltage dependence on the soil resistivity.

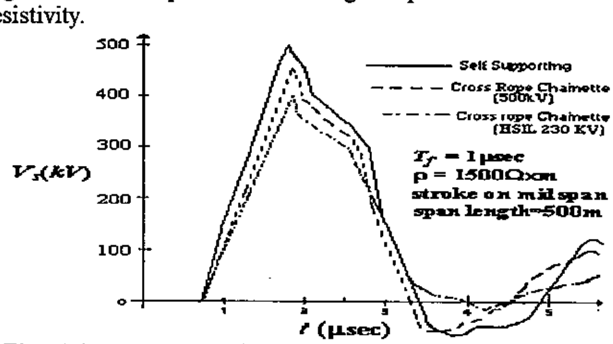


Fig.15. Tower top transient voltage dependence on tower type.

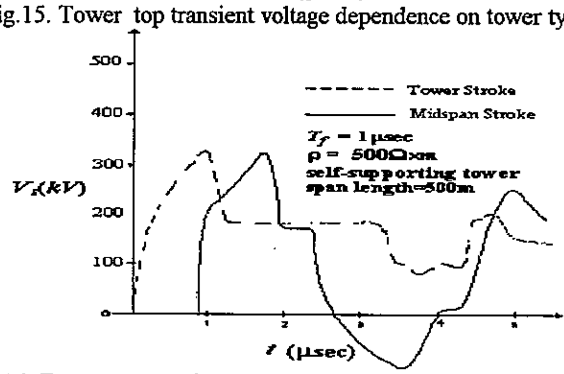


Fig.16. Tower top transient voltage dependence on stroke location.

V.CALCULATION OF LIGHTNING PERFORMANCE

Lightning performance determination, expressed in the form of tripouts/(100km×year), was done by use of the Monte Carlo method. To carry out computer simulations, use was made of the field data on the yearly incidence of lightning discharges in the Northeast region of Brazil, as well as TL geometric characteristics together with the corresponding data relative to the type of terrain profile along routes. Values of the remaining parameters were selected according to their associated probabilities of occurrence. The lightning current peak amplitude was associated to the accumulated probability function given by[4],

$$P(I_f \geq I) = \frac{1}{1 + (I/25)^2} \qquad (5)$$

where I_f is the peak current and I is the independent variable, both expressed in *kA*. The parameter T_d was set at 50 μsec, and the rise time T_f was randomly chosen from the set of values (1 μsec, 3μsec and 5 μsec). Field data in the region under study indicated a typical variation in soil resistivity between 500 and 1500 Ω×m and a gaussian probability density function was adapted to allow statistical selection of this parameter. Probabilities associated to the stroke location along the line as well as the lightning discharge incidence angle were obtained from typical experimental data reported in Ref.[4]. For each studied case at least 10000 simulations runs were conducted.

The studies have taken into account corona effects by using the model reported in Ref. [4]. According to that model the cable radius has to be corrected by use of the expression $R_c = k_1 v^2 + k_2 v + r$, where, R_c is the corrected cable radius, k_1 and k_2 are coefficients that are dependent on the cable height, v is the voltage and r is the cable radius .

Simulation results expressed in terms of tripout rates are listed in Table 3, for the tower configurations studied in this work, for distinct types of terrain profiles, including the case of a typical terrain profile in the Northeast region of Brazil. The value adopted to the keraunic level was 15.

Note that the tripout rate listed in Table 3 show a decrease as the terrain profile is varied from flat to mountainous. This occurs because the distance between conductor and ground wire decrease as the profile deviates from the flat condition, causing an increase in the value of *k*. As can be demonstred from (1), this effect will produce a decrease in the voltage V_s applied on insulator string

An examination of the values listed in Table 3, indicate that all rates fall around 3 tripouts/(100km×year), a maximum limit generally adopted as standard by many companies of electric power generation and transmission. It is also worth noting that lightning performance, for the types of tower investigated in this work, can be greatly influenced by the terrain profile. Finally, a comparison of the tripout rates listed in the second and third columns of Table 3, indicate that use of a single ground wire instead of two, in the self supporting tower, is technically feasible.

Tab 3. Tripout rates of compact lines [tripouts/(100km×year)].

Profile of Terrain	Self Supporting (1 g wire)	Self Supporting (2 g wire)	Cross Rope 500 kV	Cross Rope HSIL
Flat	0,8	0,5	0,6	3,1
Semi Hilly	0,7	0,3	0,4	2,7
Hilly	0,7	0.2	0,3	2,4
Mountainous	0.2	0.0	0.0	1.8
Typical[a]	0,7	0,4	0,5	2.9

[a] 55% Flat, 20% Semi Hilly, 20% Hilly and 5% Mountain

VI. CONCLUSIONS

The results obtained in this work can be summarized according to the following conclusions:

1-The tower top transient voltage is influenced by variations of the lightning current wavefront, soil resistivity and tower type, as indicated in Figs.13 through 16.

2-Lightning transient studies indicate that it is necessary to establish a suitable modeling of the grounding system as well as to include the soil resistivity variation in the lightning performance studies.

3-It is very important to take into account the type of terrain profile in studies concerning lightning performance of transmission lines.

4-Compact towers are technically feasible due to their good lightning performance, being recommended for consideration in expansion planning studies.

5-Use of self supporting towers using a single ground wire is also technically feasible, and their use could reduce TL installation costs.

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