Lightning Performance of Transmission Lines with Tall Sections

A. J. G. Pinto, E. C. M. Costa, J. H. A. Monteiro, S. Kurokawa, J. Pissolato

***Abstract*—An analysis is proposed on the lightning performance of non-homogeneous transmission line sections composed of very-high tower structures. These line sections are 140 to 350 meter high and have been designed for transmission lines in the South America and Asia. The proposed analysis is carried out based on well-established modeling techniques for transmission lines and towers, following the standards established by the CIGRE and IEC to study lightning performance of power transmission systems. Two transmission line sections are considered: a conventional line with 40 meters high and a non-conventional line section composed of towers with more than 220 meters high (based on new transmission line sections in the Amazon region in the Northern Brazil). The lightning performance of both line sections are compared and an alternative lightning protection is proposed using metal oxide surge arresters connected directly at the towers.**

***Keywords*: transmission lines; longitudinal impedance; transversal admittance; parameter estimation; modal analysis.**

I. INTRODUCTION

THIS research proposes a discussion on the transient behavior of transmission lines with non-homogeneous sections composed of tower with 140 up to 350 meters high which have been installed in the South America and Asia to overcome natural and environmental barriers. In 2009, a transmission line with similar structures was proposed for the *Tucuruí-Manaus* connection across the Amazon forest in the Northern Brazil. The *Tucuruí-Manaus* line is 1850 km length and has several sections composed of towers with approximately 200 meters high (fig. 1) [1, 2]. Several line sections with tall structures have been constructed into the Amazon forest, across long rivers and floodplain areas, which represent a great challenge regarding the project itself and logistic issues. Nevertheless, several technical issues require an additional attention concerning insulation coordination, variation of the line electrical parameters, grounding and lightning surge protection.

Fig. 1. Transmission tower with 250 meters height into the Amazon forest.

The geometrical characteristics of the towers (height and distance among wires) are intrinsically related to the transversal and longitudinal parameters of the line, which could result in significant variations on the propagation characteristics of the line [3]. Another important characteristic is the lack of a corridor in order to avoid major environmental impacts. Despite several technical issues deserve a special attention; this research analyzes electromagnetic transient behavior and possible vulnerabilities in which the high line sections are subject due to possible failures in the lightning shield (grounding wires) and a possible major incidence of lightning strokes because of the height of the metallic structures.

This research evaluates two 440-kV line sections by modeling using the *Electromagnetic Transient Program* - EMTP [4]. The first system represents a conventional transmission line with towers of approximately 40 meters high. Second line section is composed of towers with 300 meters high, based on technical descriptions provided by an international power company. The two line sections were modeled using an EMTP and based on well-established models described by the CIGRE and the IEEE [5, 6]. Simulations were carried out following the high-voltage and lightning test standards provided by the IEC [7]. Two situations were studied for each line section: with ZnO surge arresters connected directly at the towers (line surge arresters) and without the inclusion of surge arresters.

Significant variations on the transient performance of the tall line section were observed and compared to the conventional line with 40-m-high towers. Even including a surge protection composed of 360-kV line surge arresters, the transient voltage peaks on the non-conventional line are much

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higher than expected [8]. These results lead to several questions on the reliability of these non-conventional transmission lines, if the tower models available in the technical literature are also suitable to model transmission towers with more than 140 meters high and if a conventional surge protection apparatus (with 360-kV line surge arresters) is also suitable for a 440-kV transmission line supported by tall towers. The objective of this paper is to promote a comprehensive technical discussion on the variations observed in the electrical performance of the tall transmission section, aiming a better understanding of these variations (compared to the conventional 440-kV transmission line) as well as development of alternative surge protection methods and suitable computational models for this emergent power transmission technology.

II. METHODOLOGY

The proposed analyses are based on the accurate modeling of the transmission line sections, towers, atmospheric impulse and line surge arresters. These elements are modeled based on well-established methods available in the technical bibliography [3, 5, 6, 7]. From this methodology, the surge voltage is simulated on the transmission tower where the atmospheric impulse occurs, with and without the presence of line surge arresters connected at the towers in parallel with the insulator chains. Figure 2*a* shows an asymmetrical transmission line equipped with line surge arresters, highlighted by red circumferences, and in fig. 2*b* a line surge is shown.

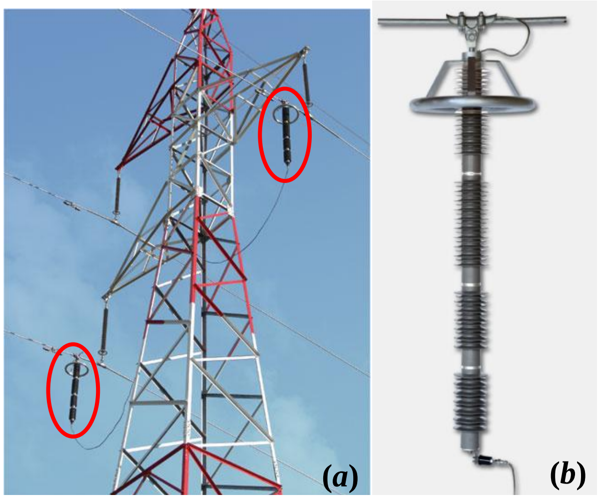

Fig. 2. Line surge arresters installed in a conventional asymmetrical tower (*a*) and a line ZnO surge arrester described in details (*b*).

In fig. 2*a*, the line surge arresters are connected in parallel with the line insulators. The superior terminal is connected to the phase whereas the inferior terminal is wired to the metallic structure of the tower. Figure 2*b* shows in details a line surge arrester with an anti-corona ring at the superior terminal.

A. *Transmission line modeling*

The conventional and non-conventional line sections are modeled using a frequency-dependent transmission line model available in the EMTP. It is well-known that an atmospheric impulse is composed of a wide range of frequencies; hence the line modeling should take into account the frequency dependence of the line parameters for the range of frequencies which an atmospheric impulse is composed. Thus, the range considered in the line modeling is up to 1 MHz. The frequency-dependent line parameters are calculated considering an ideal soil resistivity of 1000 Ω.m [8].

The geometrical characteristics of the transmission line sections are indicated in fig. 3 and given in the table 1.

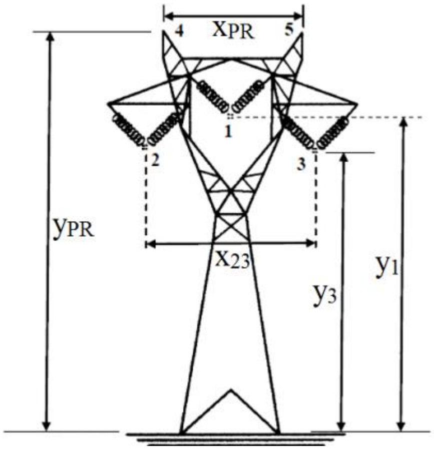

Fig. 3. Geometrical representation of the transmission line and tower.

TABLE I
GEOMETRICAL CHARACTERISTICS OF THE LINE SECTIONS

	Conventional	**Non-conventional**
$\boldsymbol{y_1}$	27.64 m	280 m
$\boldsymbol{y_3}$	24.04 m	255 m
$\boldsymbol{x_{23}}$	18.54 m	24.0 m
$\boldsymbol{y_{PR}}$	36.0 m	300 m
$\boldsymbol{x_{PR}}$	15.02 m	12.0 m

The bundled conductors of both line sections have a similar structure. They are composed of four *Grosbeak* conductors spaced 0.4 m from each other. The shield wires are EHWS-3/8” and implicitly included in the line modeling [9].

Another important technical description is the distance between two consecutive towers, which is 500 m for the conventional representation and 2 km for the line sections using the tall towers (non-conventional) [8].

The frequency-domain behavior of the electrical parameters of the non-conventional line section, described in table I, are analyzed as a function of the soil resistivity in reference [3] and [8].

B. *Transmission line modeling*

In computational models to study lightning performance of transmission lines, the shield wires should be included as well as towers and eventual nonlinear corona effect. Furthermore, the necessary computational model should differ in comparison with models applied for evaluation of electromagnetic transient resulted from switching operations in the systems [10]-[12]. The proposed phases and shield wires are modeled as frequency-dependent line sections using the mentioned computational line model. On the other hand, the metallic structure of the towers is modeled by horizontal and transversal transmission line sections, as described in reference [5].

The horizontal sections of the towers are modeled as horizontal transmission line where the parameters are obtained from standard line formulas. The vertical sections are also calculated using a specific formulation derived from the standard line formulas. The mutual coupling between any two parallel vertical transmission line sections is also taken into account [5].

The transmission tower in fig. 3 is represented using transmission line segments as follows in fig. 4.

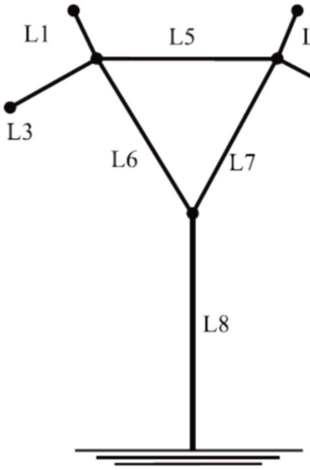

Fig. 4. Transmission tower modeled by line segments.

Based on the proposed tower modeling, the electromagnetic transient of each section can be expressed by the well-known Transmission Line Telegrapher's Equations [12]:

$$-\frac{\partial v(x,t)}{\partial x} = R(x)i(x,t) + L(x)\frac{\partial i(x,t)}{\partial t} \tag{1}$$

$$-\frac{\partial i(x,t)}{\partial x} = C(x)\frac{\partial v(x,t)}{\partial t} \tag{2}$$

The terms $L(x)$, $R(x)$ and $C(x)$ are per unit-length inductance, resistance and capacitance, respectively. The equations (1) and (2) do not take into account the frequency variations of the line parameters. However, since the skin depth is very small at high frequencies, the approach presented in [12] provides accurate results for fast and impulsive transients. Equations (1) and (2) were originally obtained for an infinite long line which means that end effects are neglected. Thus, for the case of the shortest truss segments this may not hold. Nevertheless, for the travel and the rise times of the waveforms involved in lightning, tower arms behave as long wires antennas. In this case, reflection analysis can be performed considering only the transmission line behavior [6].

In reference [12], an interesting analysis is presented comparing the modeling of tall towers using transmission line and antenna theories. The same reference assumes that the principal propagation mode is transverse electromagnetic (TEM) and the voltage difference can be obtained between any pair of points in the same transversal plane. Although the TEM representation is an approximation, it provides a practical method using the well-established transmission line theory to model transmission towers. Furthermore, the frequency- and time-domains analyses prior discussed in reference [12], in which tower modeling using line and antenna theories were compared, proves that the transmission line representation is accurate enough to model towers to study impulses with time to maximum up to 1 µs (typical of subsequent return strokes). Thus, assuming an atmospheric impulse with a front-wave time of 2.6 µs, the tall tower modeling using transmission line theory shows to be physically consistent.

C. Atmospheric impulse

The atmospheric impulse is modeled as a double exponential current wave, characterized by a front time of 2.6 µs and a tail time of 65 µs. Usually, in agreement with the *International Electrotechnical Commission* (IEC), a normalized atmospheric impulse is represented by a 8/20 µs current wave [7]. However, a front-wave rise of 20 kA/µs (*di/dt*) given by a 2.6/65 µs current wave has been widely used to simulate atmospheric surges on transmission towers [3]. Furthermore, this wave shape represents a more conservative situation because of the steeper front time, greater front-wave rise and a longer tail time if compared to the IEC-normalized atmospheric impulse [7].

The current source representing the atmospheric impulse is applied at the top of a tower in the middle of the line length. The transient voltage is measured on this same tower.

D. Surge arrester modeling

The first step to model surge arresters for a power transmission system is to calculate the nominal voltage of the arresters. This technical characteristic is obtained as a function of the maximum system voltage and based on the temporary overvoltage (TOV) capability at 60 Hz for 1 and 10 seconds. For both 440-kV systems compared in this research, the maximum operation voltage is 462 kV and the TOV capabilities for 1 and 10 seconds are 1.4 p.u. and 1.25 p.u., respectively [13]. Based on these technical characteristics and according with the information available in a given manufacturer database, 360-kV ZnO surge arresters are usually installed for nominal 440-kV systems with the given maximum voltage operation and TOV. The tower surge arresters used for the conventional and the non-conventional lines are the same, since the nominal voltages of both systems are the same.

The line surge arresters are modeled in the time domain following the well-established IEEE reference model (fig. 5), which is approached in several researches and technical references in power system lightning protection [2, 9, 10].

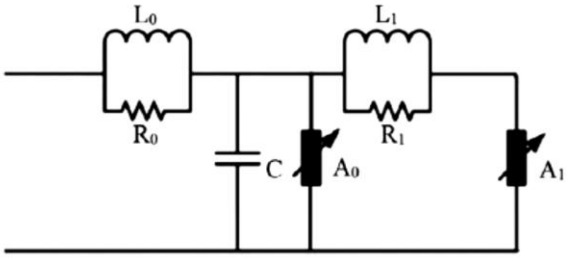

Fig. 5. IEEE reference model for metal-oxide surge arresters.

The value of the elements L_0, R_0, L_1, R_1 and C are calculated based on the number of varistor columns and the physical height of the surge arrester. The magnitude of the residual voltage from an atmospheric impulse (20 kA 8/20 µs current wave) and from a switching operation (2 kA 30/80 µs current wave) are necessary to calculate the nonlinear resistances A_0 and A_1. The residual voltages of the 360-kV surge arrester used in the current analysis are 856 kV for atmospheric impulse and 712 kV for switching operation. The *L*, *R* and *C* elements of the electric circuit in fig. 3 are obtained based on the database provided by the manufacturer. More details on modeling of surge arresters are given step-by-step in reference [6].

III. ELECTROMAGNETIC TRANSIENTS AND SIMULATIONS

A conventional and a non-conventional infinite line segment are considered according with the given descriptions of the line, towers, wires and distance of two consecutive towers. The surge impedance of the towers and the current surge representing an atmospheric impulse are also previously described. Based on these technical descriptions, the time-domain simulations are carried out from an atmospheric impulse applied on a steel tower located at the middle of the line segments. A critical and more conservative situation is simulated, considering a total failure in the insulation coordination of the power transmission system (backflashover). The transient overvoltages on the tower struck by the atmospheric impulse are evaluated for the two line sections, with and without the presence of line surge arresters.

Figure 6 shows the transient voltages on the conventional tower struck by the atmospheric impulse, without (curve 1) and with line surge arresters at the three phases (curve 2).

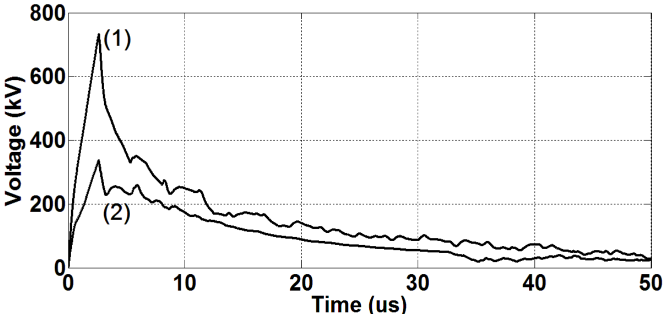

Fig. 6. Transient voltages on the conventional tower without surge arresters (1) and with line surge arresters (2).

The voltage profiles described in fig. 6 show an adequate performance for a conventional 440-kV transmission system equipped with 360-kV line surge arresters connected directly at the towers. Curve 2 shows that the voltage surge is maintained far below the maximum operation voltage of 462 kV. Otherwise, without the protection apparatus using line surge arresters, the voltage peak is approximately 700 kV (curve 1).

The same simulation is carried out considering the geometrical and physical characteristics of the transmission line section composed of towers with 300 meters high, as described in table I. A 2.6/65 µs current wave is applied at the top of the metallic structure of a tower located at the middle of an infinite line section. The transient voltages on the tall tower, with and without the insertion of line surge arresters, are shown in fig. 7.

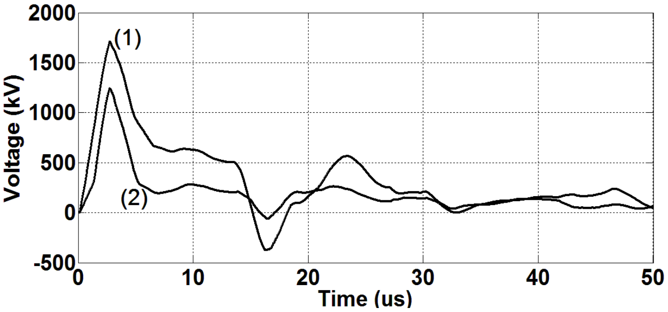

Fig. 7. Transient voltages on the non-conventional tower without surge arresters (1) and with line surge arresters (2).

For the non-conventional line section in fig. 7, the voltage peak without line surge arresters is more than 1500 kV (curve 1), two times higher than the voltage peak observed in the conventional system in fig. 5. Curve 2 shows that the 360-kV ZnO arresters are not able to maintain the system voltage below the maximum operational voltage of 462 kV, taking into account that both transmission lines are characterized by the same nominal voltage.

IV. DISCUSSION AND CONCLUSIONS

The two line sections compared in this research are based on existing systems or transmission lines under construction, as discussed in this paper and other technical literatures. Both systems have the same operational voltage of 440 kV and different geometrical and physical characteristics. However, the lightning performance and the transient behavior of the two line sections showed significant differences. Possible causes and technical characteristics can be listed as follows:

i. Previous researches have described variations in the transversal and longitudinal parameters of the conventional and non-conventional line sections evaluated in this research. Most of these variations were observed at high frequencies which mean a direct influence on the lightning performance observed for the non-conventional system.

ii. The distance of two consecutive towers of the non-conventional line section is approximately four times longer than the same distance for the conventional line. This characteristic results in a minor flow of shunt current through the towers to the ground along the line. Each tower is grounded at the base, thus the surge current has a better surge current flow to the ground with a greater number of towers per length. The quantity of tower per length in the conventional line is greater than for the non-conventional one, consequently the conventional line section has a better flow of the surge current through the tower to the ground. By contrast, the line sections with tower higher than 200 meters have a minor number of tower per length which represents less flow of the surge current wave to the ground and thus greater surge voltage values at the tall towers.

iii. Variations on the surge inductances of the conventional and non-conventional towers could result the major transient voltage observed on the 300-m-high tower.

iv. The proposed tower modeling by line segments could not be suitable for the non-conventional towers because of the high height. The tower modeling using line segments is suitable for conventional towers because they can be represented by a set of short line segments, as discussed in the paper. Otherwise, the tall towers are modeled by several short and also long segments, which could not represent an accurate approach for the non-conventional towers.

v. An evaluation is necessary on the discharge channel of the atmospheric impulse. The significant difference in the line height of conventional and non-conventional towers may result variations on the magnitude and wave shape of the atmospheric impulse, resulting variations in the transient behavior of the towers.

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