Time-Domain Analysis of Surge Impedance Formulations based on Cylindrical Representation of 200 meters Tall Transmission Towers

E. C. M. Costa, L. F. N. Lourenço, C. E. M. Pereira, M. B. Perotoni, J. R. Cardoso and C. A. F. Sartori

Abstract—**A discussion on conventional surge impedance formulations, by means of the cylindrical approach of the tower, is promoted in order to verify if these well-known analytic methods are also valid for transmission towers with 200 meters height. The study is carried out based on surge impedance reference values obtained by using the Finite Element Method – FEM for towers up to 200 meters height and then compared to results obtained using well-established formulations based on the simplistic geometrical representation by a cylindrical structure. The reference model is developed using a FEM-based multiphysics software in which the tower can be drawn following the original design of its steel structure. The comparison between these two different modeling techniques is presented for a 200 m tower height, surge impedance calculation and electromagnetic transient simulations in the time domain. From this evaluation, the most adequate tower models can be determined for analysis of the lightning performance in power transmission systems composed of tall line sections**

***Keywords*: power transmission towers, time-domain simulation, atmospheric impulse, electromagnetic transients.**

I. Introduction

THE computational modeling of metallic towers is an important subject for analysis of lightning performance in power transmission lines. The analysis of the electromagnetic transients in tall metallic towers during an atmospheric surge is usually achieved based on the transmission line theory or antenna theory [1]. In the transmission line approach, currents and voltages are obtained from solving the well-established Telegrapher's equations of transmission lines as a function of the distributed electrical parameters of the tower. In the approach using the antenna theory, the towers are modeled based on the numerical analysis of full wave electromagnetic fields, *i.e.*, the tower structure is modeled as an antenna. These two categories provide a general classification for most of the models available in the technical literature on the modeling of tall tower/objects for simulation of electromagnetic transients.

In the modeling from the transmission line approach, tower is basically represented as a constant impedance, calculated from a simplified geometry of the tower structure [2], or a combination of a series of vertical and horizontal short transmission lines that represent each section and crossarm of the tower [3]. In this last modeling technique, the currents and voltages at each segment can be calculated using the Telegrapher's equations which represent the transmission line model of the tower. However, r tower as a system of short line segments has some restrictions for tall towers/structures because it does not take into account the successive wave reflections between the sending and receiving ends of each segment and from the top to the tower foot. Thus, for tall towers, these equivalent line segments could be too long to neglect the current and voltage wave reflections between terminals [1, 4].

On the other hand, modeling towers using the antenna approach is based on the solution of the full wave Maxwell's equations, which is more general than transmission line approach where the transverse electromagnetic (TEM) is assumed to be the only propagation mode. The existing models of towers using transmission line or antenna theories are limited to simplistic geometries, such as cone or cylindrical forms. However, even with such simplification the results cannot be properly evaluated without an accurate numerical procedure [5].

In this context, the proposed evaluation presents an analysis of the most important analytic tower models for surge impedance calculation using the cylindrical geometry approach for towers with 200 meters height. The objective of this study is to verify if these conventional analytic techniques are also suitable for determination of the surge impedance of tall transmission towers.

II. Different Definitions of Surge Impedance

The surge impedance is one of the most important characteristics in the tower modeling for analysis of the lightning performance. However, there are different definitions of surge impedance in the technical literature. Although surge impedance is a well-defined electrical parameter, the same denomination has been used to describe differently formulations in the literature on electromagnetic transient in transmission lines and towers [6].

For example, the literature presents the definition of transient surge impedance as a time-domain function expressed as [7]:

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$$z(t) = \frac{v(t)}{i(t)} \tag{1}$$

Where $v(t)$ is the time-varying voltage between the top and foot grounding of the tower, and $i(t)$ is the current impulse injected at the top, as shown in fig. 2.

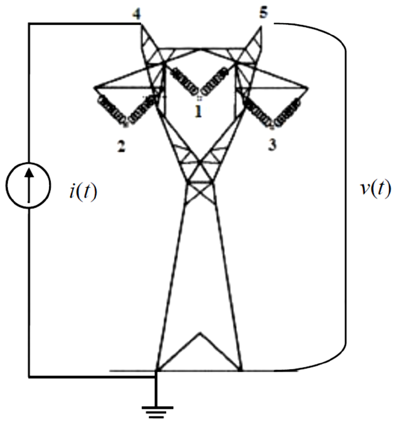


Fig. 2 Time-varying current impulse and voltage on the tower.

Another well-established time-varying definition of surge impedance is [1]:

$$Z(t) = \frac{v(t)}{max\ [i(t)]} \tag{2}$$

The surge impedance is established in (2) at the maximum value of the current wave $i(t)$, which can be defined as a constant. However, the most conventional surge impedance definition is presented in (3) [8].

$$Z = \frac{max\ [v(t)]}{I} \tag{3}$$

The current I is a constant value at the instant when the voltage $v(t)$ is maximum. Thus, the surge impedance Z is also a constant.

An important issue is that the surge impedance varies as a function of the current wave form, which may be represented by a double exponential, ramp, step or unitary impulse. Thus, since the current and voltage are time varying, the surge impedance is also frequency dependent, as described in (4).

$$Z(\omega) = \frac{V(\omega)}{I(\omega)} \tag{4}$$

An alternative definition for surge impedance that depends only on the tower geometry and electromagnetic propagation characteristics is the denominated as harmonic impedance [9]. This definition presents a frequency-domain surge impedance that does not depend on the excitation input signal, such as expressed in (5).

$$Z(\omega) = \frac{V_h(\omega)}{I_h(\omega)} \tag{5}$$

The harmonic impedance is given as a function of $V_h(\omega)$, since the harmonic current is represented by an unitary impulse $I_h(\omega) = 1$. Thus, the harmonic impedance comprehends to a very wide range of frequencies, which represents an excellent approach for electromagnetic transient analysis. The voltage $v(t)$ can be obtained in the time domain by using inverse transforms.

III. Analytic formulations

As demonstrated in the prior section, the surge impedance is a time and frequency function. This issue leads to some misunderstanding about the adequate current and voltage values for calculation of the surge impedance. Even the frequency-domain definition of harmonic impedance leads to uncertainty about the appropriate formulation for the surge impedance. Thus, analytic geometric models represent an alternative procedure for the surge impedance calculation based on the tower representation by simplistic geometrical shapes (cylindrical or conical). However, these models are not able to represent properly nonlinear phenomena, such as the corona effect [10].

Most analytic models were established in the 1960s, by means of experimental data and validation based on the electromagnetic field theory. Results obtained from these models indicated that the tower may be accurately represented as a transmission line with a constant characteristic impedance (surge impedance) and propagation function. Other assumptions for analytic models are that the earth and tower assume an infinite conductivity, wave propagation equal to the light velocity and the current waves maintain the shape during propagation [1, 10].

There are three principal analytic tower models in the literature: the *Jordan model*, the *Jordan revised model* and the *Darveniza model*. These three models are based on the cylindrical tower representation, as described in fig. 3.

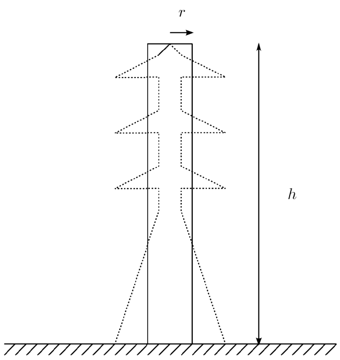


Fig. 3 Cylindrical representation of a steel lattice tower.

The Jordan model was one of the first analytic models developed for analysis of lightning performance on power transmission towers [7, 12]. This model is based on the static-field theory and the surge impedance is calculated from the analytic formulation in (6).

$$Z = 60\ ln\left(\frac{h}{r}\right) + 90\frac{r}{h} - 60 \tag{6}$$

The term h is the tower height and r is the radius of the cylindrical tower representation in fig. 3.

Although the Jordan model has been widely used for analysis of atmospheric impulse on steel towers, the analytic formulation provides underestimated values for the surge impedance [11]. This way, the revised Jordan formulation was developed by deriving the same formulation through a different path [8, 11]. The analytic formation obtained from the revised Jordan formulation is expressed in (7).

$$Z = 60\ ln\left(\frac{4h}{r}\right) - 60 \tag{7}$$

The Darveniza model was proposed based on the Wagner and Hileman representation, which was developed from the surge impedance obtained from an impressed rectangular current wave, resulting in impedance values greater than those obtained experimentally by measuring [7, 10]. The analytic formulation for the Darveniza model is expressed in (8).

$$Z = 60\ \left[ln\left(\sqrt{2}\frac{2h}{r}\right) - 1 + \frac{r}{4h} + \left(\frac{r}{4h}\right)^2\right] \tag{8}$$

If $h >> r$, (8) can be reduced as follows:

$$Z = 60\ ln\left(\sqrt{2}\frac{2h}{r}\right) - 60 \tag{9}$$

These three formulations are widely used for analysis of the lightning performance of power transmission towers during studies on insulation coordination and electromagnetic compatibility in power transmission systems. This research proposes to evaluate if these analytic models, based on simplistic cylindrical representation of transmission towers, are also valid for towers higher than 50 meters. A tower model using FEM is proposed for calculation of the reference surge impedance, which is a function of the current and voltage values on the tower during time-domain simulation of an atmospheric impulse on the tower.

IV. SURGE IMPEDANCE CALCULATION USING FEM

The reference values for the proposed evaluation are obtained using the CST Microwave Studio (CST MWS). The CST is a commercial software for high-frequency 3D electromagnetic field simulations based on the time domain solution by using several different methods including the Method of Moments (MoM), Multilevel Fast Multipole Method (MLFMM), Shooting Boundary Ray (SBR) and also the Finite Element Method (FEM). All boundary conditions and the steel lattice tower can be modeled in details by using the 3D CST interface.

Figure 4 shows the steel lattice tower modeling enclosed into a box whose boundary conditions provide a closed path for the electric current and the ending surfaces of the box represent a perfect match layer. The tower is excited by a current signal with wave front of 1.2 µs (double exponential represented by the Heidler function), which covers the frequency range of interest up to approximately 2 MHz [12].

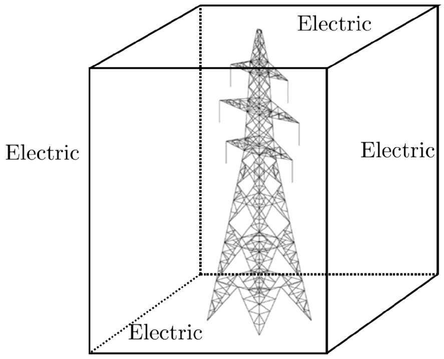


Fig. 4 Boundary conditions applied to the tower modeling using the CST.

The tower modeling is properly limited to some boundary conditions, such as electric permittivity of the air, soil conductivity and tower grounding, as resumed in fig. 4. The tower is modeled based on the approximate lattice structure of the transmission tower, in which the surge impedance is calculated as a function of the tower height. The tower foot is grounded considering a constant resistance of 3 Ω, as indicated in fig. 2.

The proposed surge impedance analysis is carried out based on the geometrical characteristics of a conventional double-circuit tower, as described in fig. 5 [3]:

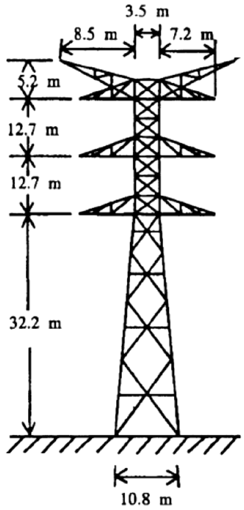
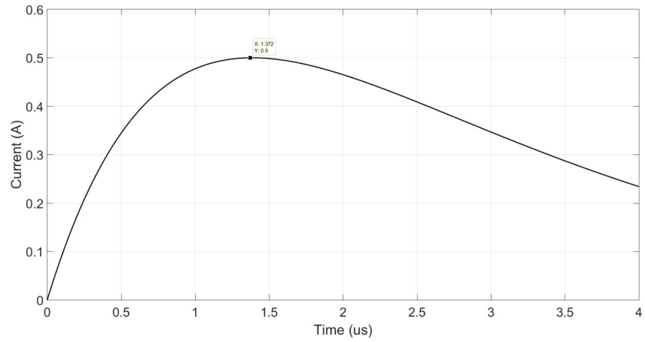
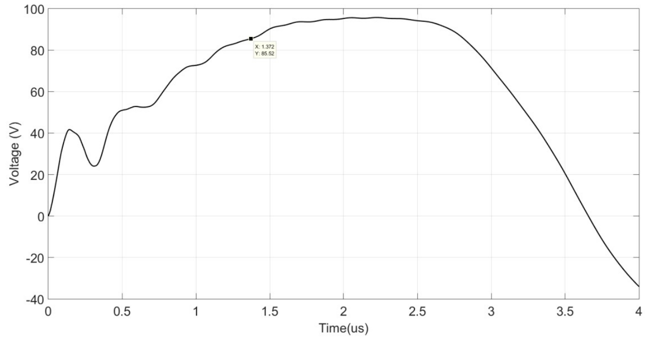


Fig. 5 Geometrical characteristics of a conventional double-circuit tower.

The surge impedance values are calculated from a current signal with wave front of 1.2 µs and resulting surge voltage on the tower, considering the impedance definition in (2). For example, the procedure for the surge impedance calculation of the tower in fig. 5 is described as a function of the current signal injected at the top of the tower (fig. 6*a*) and surge voltage (fig. 6*b*). Figure 6*c* shows the impedance $Z(t)$ in which the constant surge impedance is calculated from the current peak at 1.37 µs, such as pointed in fig. 6*a*. The correspondent voltage value is obtained on the maximum current value, as also described in fig. 6*b*. Thus, fig. 6*c* is the time-variable impedance $Z(t)$, where the constant surge impedance is also obtained at 1.37 µs (171 Ω), in agreement with the surge impedance concept stated in (2). This same procedure is carried out for a conventional tower with 50 meters height and for a tall tower with 200 meters height, maintaining the geometric proportion of the tower in fig. 5, i.e., vertical and horizontal geometrical characteristics of cross arms, grounded base and central column of the tower.



(*a*)



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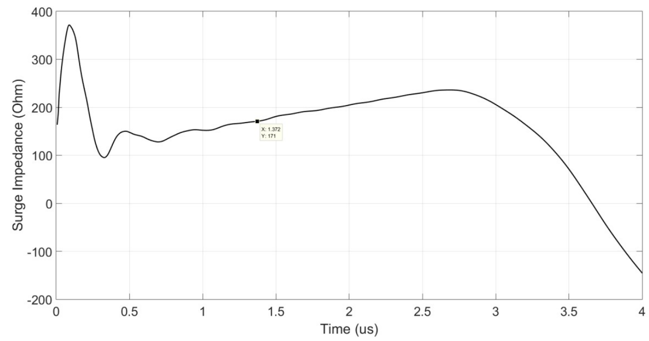


(*c*)

Fig. 6. Current signal (*a*), voltage on the tower (*b*) and surge impedance (*c*) calculated using the CST.

V. Transient simulations in the time domain

The well-established cylindrical tower representations are evaluated based on time-domain results obtained from the reference model using the CST. The surge impedance values are calculated from the analytic formulations for the cylindrical tower representations (section 3), while the reference value of surge impedance is obtained based on FEM using the CST platform. The surge impedance values are calculated using analytic and FEM-based methods for towers with 50 and 200 meters height and then modeled using the transmission line representation by distributed parameters in the well-established Alternative Transient Program – ATP.

Since the various analytic tower representations and the reference FEM-based model can be properly simulated by using the ATP, the lightning performance of each tower representation can be evaluated from an atmospheric impulse applied at the top of the tower that is grounded with a foot resistance of 3 **Ω**, as illustrated in fig. 2. The atmospheric impulse is represented by 8/20 μs current signal with peak of 10 kA (fig. 7), as suggested by the *International Electrotechnical Commission* – IEC for high-voltage tests of electric power components and systems [12].

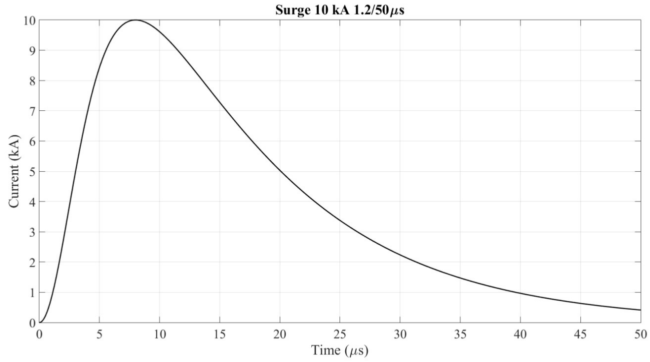
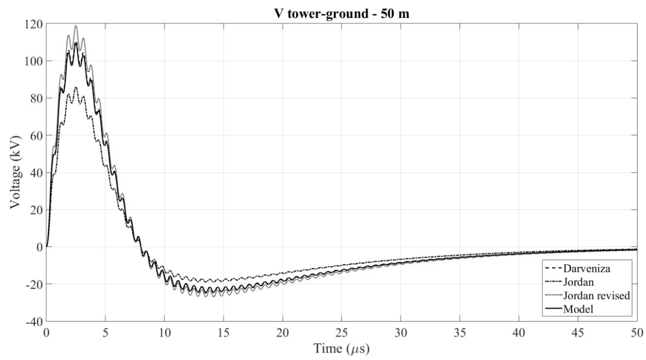


Fig. 7 Atmospheric impulse of 10 kA 8/20 μs.

Three well-established tower models based on simplified cylindrical representations are evaluated by comparison with the reference model in the CST: Jordan, Jordan revised and Darveniza formulations [7, 10].

Figure 8 shows the voltage transient simulated from an atmospheric impulse on a transmission tower with 50 meters height.



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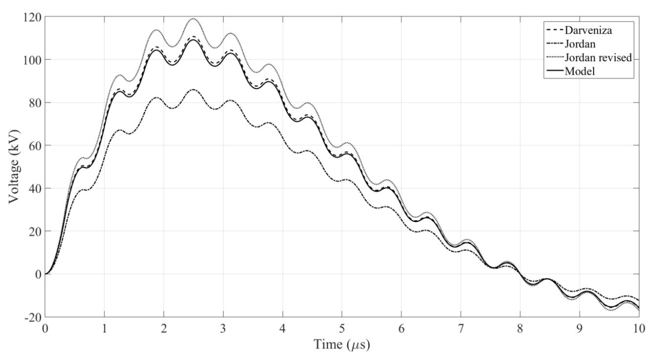

(*b*)

Fig. 8 Voltage profile on the tower with 50 meters height.

The voltage profiles during atmospheric impulse on the tower are described in details in fig. 8*b*. The voltage profile obtained from the Darveniza model is practically similar to the reference model, while the Jordan and Jordan revised models show significant variations during voltage peak between 2 and 3 µs.

Figure 9 shows the voltage profile for the analytic and reference models for a tower with 200 meters height.

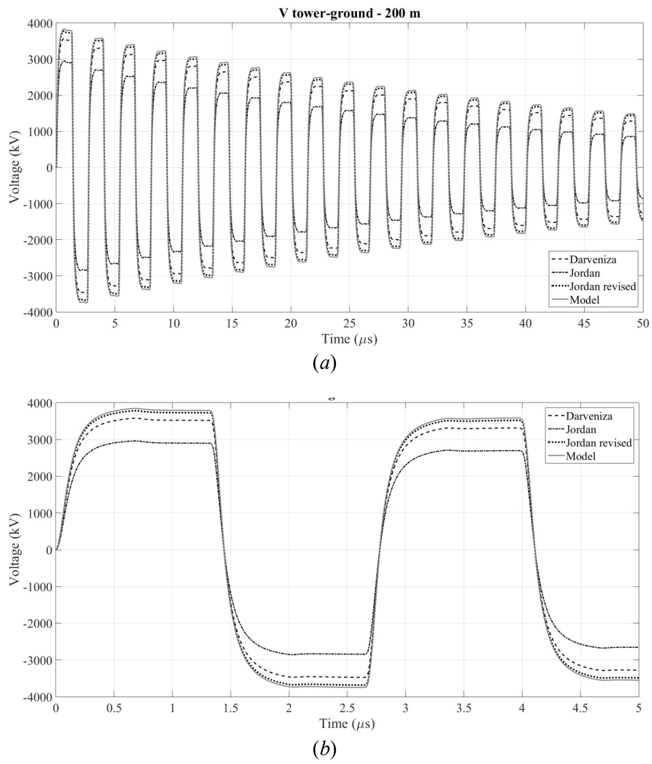

Fig. 9. Voltage profiles on the tower with 200 meters height.

Differently from a transmission tower with 50 meters height, the tower with 200 meters presents successive wave reflections between the foot grounding and top of the tower, as verified in figs. 8 and 9. This issue was previously raised in the technical literature and then verified by means of electromagnetic transient simulations in this paper [1, 6]. However, the principal conclusion from figs. 8 and 9 is that the Jordan revised model is more accurate than Darveniza model for towers with 200 meters height, although this second model shows acceptable performance as well. The Jordan model shows significant discrepancies in the transient voltage profile for both towers, especially during voltage peak.

VI. Conclusion

The performance of analytic formulations is evaluated from the well-established cylindrical representation of power transmission towers. This simplistic approach is widely used for surge impedance calculation of lattice towers providing good results for conventional towers with approximated 50 meters height, as well discussed in the technical literature. However, a practical analysis based on electromagnetic transient simulations in the time domain is required for validation of these conventional models for nonconventional tall towers that have been widely used in several countries in Asia and South America in order to overcome natural and geographic barriers.

Two of the three analyzed models presented accurate results for towers with 200 meters height when compared to the reference model developed on the CST platform. The Jordan revised and Darveniza formulations present accurate results in the time domain, during simulation of an atmospheric impulse whereas the original Jordan formulation prove to be inefficient even for conventional tower with 50 meters high. The Darveniza model and formulation shows a better performance for conventional towers with 50 meters height whereas the Jordan revised proves to be more accurate for nonconventional tall towers with 200 meters.

VII. References

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