Performance of Transmission Line Tower Models used for Electromagnetic Transient Studies: Comparisons with Experimental Results

A. R. J. Araújo, A. Piantini and S. Kurokawa

Abstract— **The backflashover (BF) mechanism caused by direct lightning strikes to towers and overhead wires is one of the main causes of overvoltages on power systems outages. When lightning strikes a tower, the injected current travels its structure, causing an overvoltage. If the voltage between the phase conductor and cross arms exceeds the *Critical Flashover Voltage* (CFO) of the insulator strings, a BF will take place. The tower surge impedance is an important parameter on the determination of overvoltage and various models have been proposed for its calculation. This paper presents a comparison between measured and calculated surge impedances of a thin cylinder and a reduced-scale transmission tower built for this purpose. Different models have been considered for the calculations. This article also presents a brief literature review and some methods for measuring tower surge impedance.**

Keywords: **backflashovers, overvoltage, transmission tower modelling.**

I. Introduction

Lightning is one of the main causes of overvoltages in transmission lines and it may result in outages. Analyses of lightning strikes to transmission towers play a key role in protection and insulation coordination in power systems [1].

When lightning strikes either a tower top or an overhead ground wire, the surge current will split to the adjacent towers, via overhead ground wires, and travel down the tower structure to the ground. In this situation, the overvoltages will be greatly influenced by *tower surge impedance* which causes reflection waves at the top and bottom of the tower. If the voltage between the phase conductor and the cross arm exceeds the Critical Flashover Voltage (CFO), it will cause a *backflashover* (BF) [2]. BFs have an important influence on the performance of a transmission system; according to [3], 40% to 70% of the outages are caused by this phenomenon. These incidents occur mainly in regions with high ground flash densities, high resistivity soils and high terrains. Some factors may reduce b*ackflashovers* such as: installation of overhead ground wires, correct dimensioning of tower structure and insulator strings and a low tower footing resistance values.

Overvoltages caused by lightning depend on the tower surge impedance, which is directly related to the tower geometry, and also on the amplitude and direction of the injected current at tower top, soil resistivity and footing resistance [3-6]. The higher tower impedance, the larger the voltage between the tower top and phase conductors.

The tower surge impedance and propagation speed can be obtained by different methods, such as: (i) measurements in real or (ii) reduced-scale transmission towers, (iii) equations developed from simple solid approximations or (iv) numerical methods such as FDTD or MoM [7].

In (iii), transmission towers are approximated by simplified geometric solids such as cones, cylinders or a combination of them. From this representation, the tower surge impedance is obtained by simple equations [4] which however present some errors, since the cross arms and the slant bars (trusses) are not considered.

In order to obtain the surge impedance using the electromagnetic field theory, the tower should be divided into small segments. Once the position and orientation of each segment is known, along with information about the source which excites the tower, it is possible to calculate the electromagnetic field around the tower. This method allows to calculate the surge impedance of any type of tower, taking into account its geometrical characteristics, including cross arms and slant bars.

After presenting a brief description of BFs and a literature review on this topic, this article compares some simplified equations proposed in the literature, based on geometric solids to represent a reduced-scale transmission tower. A thin aluminum cylinder was also used for measuring its surge impedance. These comparisons will show what might be a best geometrical approximation for the reduced-scale tower to estimating its tower surge impedance and its accuracy.

II. Literature Review on Transmission Tower Modelling

When lightning strikes a tower or a ground wires, voltage surge waves propagate through the tower structure. These waves are reflected back and forth between the top and bottom

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of the tower. This surge also propagates on the cross arms, increasing the potential difference across the insulator strings. If the voltage difference between phase conductors and cross arms exceeds the CFO, a BF will occur from the structure to one or more of the phase conductors, as depicted in Fig. 1-(a) and (b). Many studies have been conducted to evaluate the overvoltage caused by lightning and some transmission tower models have been developed in frequency or directly in time domain [5-11].

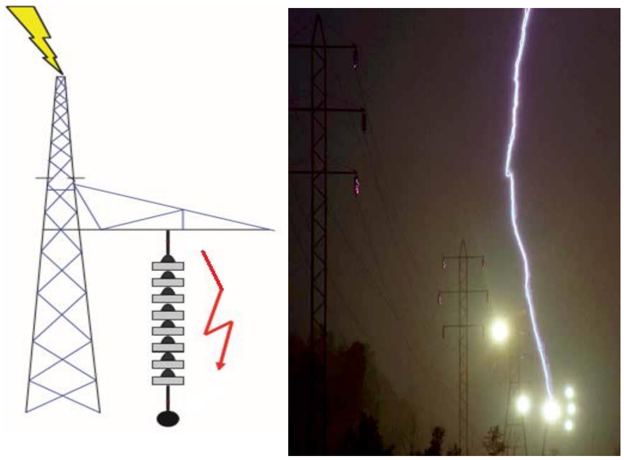

Fig. 1. (a) BF illustration (b) BF in real tower.

A. Models based on geometrical approximations

The first theoretical formulation for tower surge impedance was proposed by Jordan [11]. In his work, a transmission tower was approximated by a vertical cylinder with the same height as the actual tower and a radius equal to the mean equivalent radius of the tower base. In the Jordan’s formulation, the image method was applied, however it was considered the wrong direction for the image current, resulting in an underestimation of tower surge impedance. Latter, Jordan’s equation was corrected by Takahashi [12]. Recently, De Conti et al. [13] also presented an equation for tower surge impedance for cylindrical representation.

In the 1960s, using the electromagnetic field theory and simplified geometric solids, several authors proposed equations for calculating the tower surge impedance [14-16], which depends on: current waveform and also on the way it is injected into the tower top. The wave speed along the tower is considered the speed of light [14-16]. Although these formulas are attractive and easy to use, the problem consists on how to represent properly the tower structure by solids. Furthermore, some important parts as cross arms and slant bars (trusses) are disregarded, leading to errors.

In these formulations, it is assumed that the current is uniformly distributed over the structure from the base to the tower top and the propagation speed along is equal to speed of light. Fig. 2 shows an example of a transmission tower and some simple geometric representations.

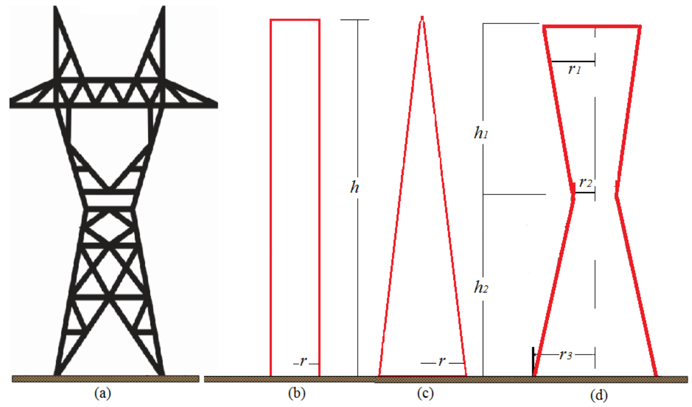

Fig. 2. (a) Tower Profile. Approximations by: (b) cylindrical (c) conical (d) combination of solids.

The following assumptions are made: the ground is perfectly conducting, the cylindrical conductor is perpendicular to the ground plane and the conductor is lossless. In (1) - (7), h and r are the height and the base radius of the tower, respectively.

Wagner and Hilleman [15] represented the tower by a vertical cylinder and its surge impedance is given by:

$$Z_H = 60\, ln\left(2\sqrt{2}\frac{h}{r}\right) \quad (1)$$

Sargent and Darveniza [16] calculated the tower by a cylinder and its surge impedance for cylindrical representation is given by:

$$Z_S = 60\left[ln\left(\sqrt{2}\frac{2h}{r}\right)-1\right] \quad (2)$$

Hara [1] performed different experiments on cylinders and obtained the empirical equation expressed by:

$$Z_{Ha} = 60\left[ln\left(\sqrt{2}\frac{2h}{r}\right)-2\right] \quad (3)$$

Jordan represented a transmission tower as a cylinder and considering that the depth of true ground below earth’s surface can be disregarded and h>>r, its surge impedance is simplified and given by [13]:

$$Z_J = 60\left[ln\left(\frac{h}{r}\right)-1\right] \quad (4)$$

CIGRE also proposes an equation based on geometric solids [17]:

$$Z_{CI} = 60\, ln\left[\cot\left(0.5\tan^{-1}\left(\frac{r}{h}\right)\right)\right] \quad (5)$$

Chisholm *et al*. introduced (6) for horizontal current at the top of the cylinder [4,25]:

$$Z_{Ch} = 60\left[ln\left(\frac{h+\sqrt{h^2+r^2}}{r}\right)-1\right] \quad (6)$$

Ametani considered a multiconductor system above an imperfect conducting ground, taking into account the equivalent radius of the tower structure [22] given by:

$$Z_A = 60\left[ln\frac{\left(h+\sqrt{h^2+r_{eq}^2}\right)^2}{r_{eq}\left(2h+\sqrt{4h^2+r_{eq}^2}\right)} + \frac{3r_{eq}+\sqrt{4h^2+r_{eq}^2}-4\sqrt{h^2+r_{eq}^2}}{2h}\right] \quad (7)$$

In (7), r_{eq} is the equivalent radius of a multiconductor system [23]. The surge impedance of the conical representation, depicted in Fig.1-(c), proposed by Sargent and Darveniza [16] is given by:

$$Z_{Scone} = 60\,ln\left(\sqrt{2}\,\frac{\sqrt{r^2+h^2}}{r}\right) \quad (8)$$

Chishom *et al.* [16] also calculated the surge impedance of a transmission towers represented by a combination of solids, as depicted in Fig.2-(d):

$$Z_{comb} = 60\,ln\left[\cot\left(0.5\tan^{-1}\left(\frac{r_1h_2+r_2(h_1+h_2)+r_3h_1}{(h_1+h_2)^2}\right)\right)\right] \quad (9)$$

In (9), h_1 and h_2 are the heights from base to middle and from middle to top of the tower structure, respectively and r_1, r_2 and r_3 are top, middle and bottom radii respectively. Fig.3 shows the surge impedance obtained using (1)-(7) as function of the ratio h/r.

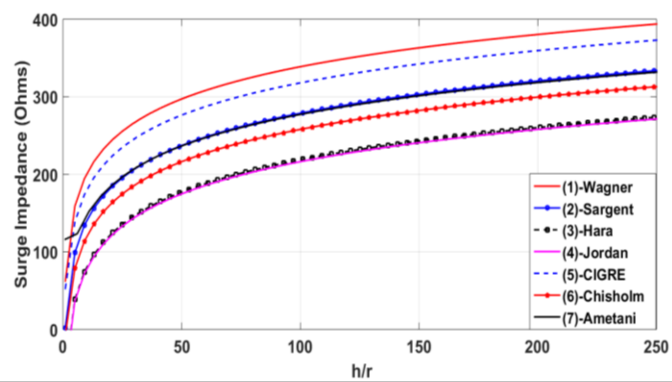

Fig. 3. Tower surge impedance for cylinders as function of *h/r*.

For the same ratio *h/r*, the surge impedance varies significantly depending on the adopted model and this illustrates the importance of this investigation. The geometric model may be used as an estimate of the tower surge impedance and it is clearly affected by the geometric approximation used.

B. Models based on measurements

Methods based on measurements on real towers and reduced-scale models are also frequently used for the estimation of the tower surge impedance measurements [4, 6, 9, 18].Two methods can be applied: direct or indirect.

The *direct method* consists on measurements carried out using cables, supported by balloons, positioned in the vertical or horizontal. An impulse current is injected through the cable into to the tower top. The currents have usually a rectangular or exponential waveforms with different rise times. Currents in any part of the tower can be measured by means of current transformers (CTs); voltages on cross arms or any other part of the structure are transmitted to recording equipments by optical-fiber cables and optical-electro converters [24]. In the *indirect method*, an auxiliary cable connects diagonally the tower top to the impulse generator on the ground. Using the measured current and voltage using the auxiliary cables and knowing the surge impedance of the cable, it is possible to determine the tower surge impedance. Current and voltages are measured as in the direct method. Using these methods different tower models (based on lumped circuit parameters have been proposed and are implemented in electromagnetic transient software [5,6].

Methods based on reduced-scale measurements are more economical than the methods in real-size towers, as well as being more flexible and easy to implement, considering the various types of structure that can be built. Another factor is the good accuracy when the direct method is applied. However, the size of measuring equipments is relatively big compared to the reduced-scale tower and electromagnetic induction may affect the measurements [23]. In the next section, experimental results are a compared with the classical equations.

III. Results

Two experiments were performed at a high voltage laboratory. The first one consisted on applying a dc voltage to the top of a vertical aluminium cylinder, measuring the reflected pulse and computing the surge impedance and propagation speed through it. The height *h* and radius *r* of the cylinder were 1.52 m and 8 mm (*h/r*= 190), respectively. In the second one, the cylinder was replaced with reduced-scale tower. The measured surge impedances of the vertical cylinder and the reduced-scale tower were compared with calculations using by classical formulations (1) - (9).

A. Vertical cylinder

A 12 V battery was connected to one of the cylinder ends through a coaxial cable with surge impedance of 50 Ω, (confirmed by experiments) and a switch. When the switch was closed, at t = 0 s, the voltage was measured at the point (point A) at which the cylinder was connected at the cable. The voltage measured at this point as depicted in fig. 6 (blue curve). Fig. 5 shows a picture of experimental setup.

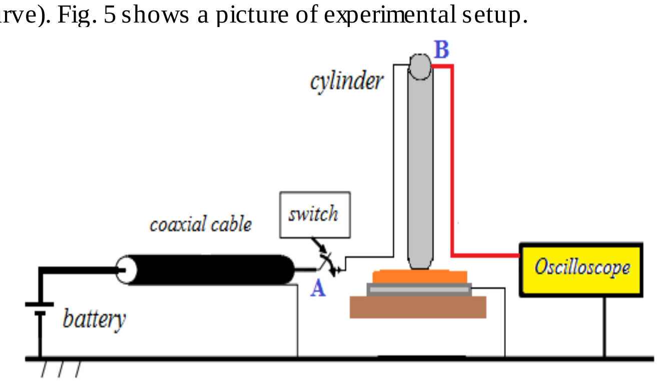

Fig. 4. Scheme of the experiment.

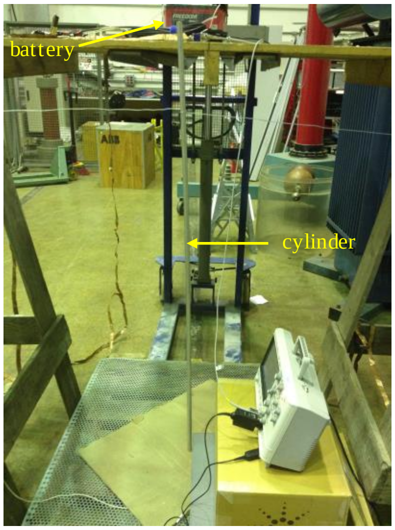

Fig. 5 Experimental set-up.

The specifications for the oscilloscope: bandwidth was from dc to 350 MHz and its sampling rate was 4GSamples/s. The input resistance and capacitance of the probe were 10MΩ and 11 pF, respectively and its bandwidth was from dc to 500 MHz.. The injected voltage pulse propagates along the cylinder and reflects back to the top, when it arrives at the other extremity (open). The reflected pulse arrives at the measuring point after Δ*t* nanoseconds as in Fig. 6 (red curve). The blue curve is the voltage at the same point with the switch open. From Fig. 6, Δt =12.20 ns the surge impedance of the cylinder can be calculated by:

$$E_{step} = \frac{Z_{cyl}}{Z_{cyl} + Z_{cable}} V_{op} \quad (10)$$

Where V_{op} is the voltage at the battery (with the switch open), E_{step} is the voltage at the connection point of the cylinder with the cable before Δ*t* and Z_{cyl} and Z_{cable} are the cylinder and cable surge impedances respectively. The surge impedance of the cable is 50 Ω. From the test, V_{op} = 12.0 V and E_{step} = 10.40 V, so that Z_{cyl} = 320 Ω. The propagation speed is given by:

$$v = \frac{2h}{\Delta t} \quad (11)$$

From Fig. 6, Δt =12.20 ns and therefore propagation speed through the cylinder is 0.250 m/ns (83% of the speed of light). In [1], Hara and Yamamoto obtained 320 Ω of surge impedance for a steel-pipe pole of 15 m in height and 51 mm in diameter and the speed of light for the propagation speed. The measured speed obtained by Chisholm, Chow and Srivastava [4] was 96% of the speed of the light. Table I shows a comparison between measured surge impedance and the calculated using (1) - (6). The smallest error was obtained using (2), proposed by Sargent and Darveniza [16].

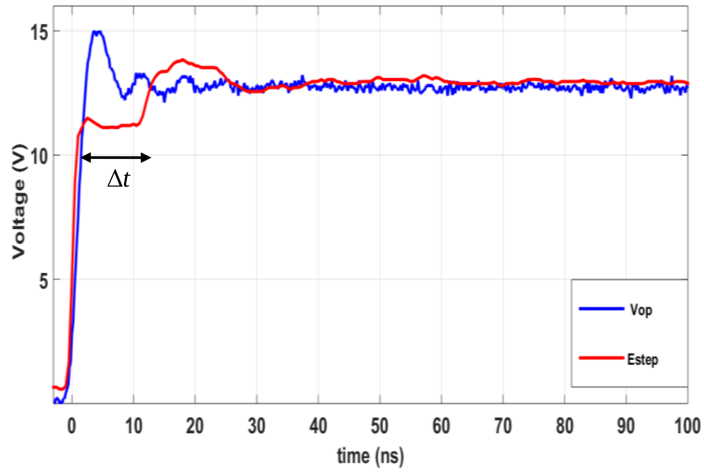

Fig. 6. Voltages V_{op} and E_{step} -vertical cylinder.

Table I. Comparison between measured and calculated surge impedances (aluminum cylinder h/r=190).

AUTHOR/EQUATION	SURGE IMPEDANCE (Ω)	| ERROR | (%)
Wagner and Hileman-(1)	376	17.60
Sargent and Darveniza-(2)	316	1.17
Hara and Yamamoto-(3)	256	19.90
Jordan-(4)	253	20.67
CIGRE-(5)	355	11.08
Chisholm, Chow and Srivastava-(6)	295	7.67

B. Reduced scale tower

The surge impedance of the reduced scale tower was measured using the same setup of the cylinder but the current was injected at the base of the tower. Fig. 7 shows a picture of the reduced-scale tower in the measurements.

In Fig. 7, the tower dimensions were: height *h*=1.36 m, cross arms distance = 0.90 m and legs distance= 0.50 m. The measured voltages are V_{op}= 12.V and E_{step}=7.20 V are shown in Fig. 8. The time interval Δ*t* =12.0 *ns* and propagation speed along the tower is approximately 0.223 m/ns (75% of the speed of the light). The calculated surge impedance is using (11) is Z_{tower}=75 Ω.

Table II presents the surge impedance of the tower model calculated for the case of its representation by a vertical cylinder, cone and a combination of solids, as shown in Fig. 2, considering the different formulations given in Section II. The differences in relation to the measured surge impedance are also presented.

Fig. 7. Experimental set-up reduced-scale tower.

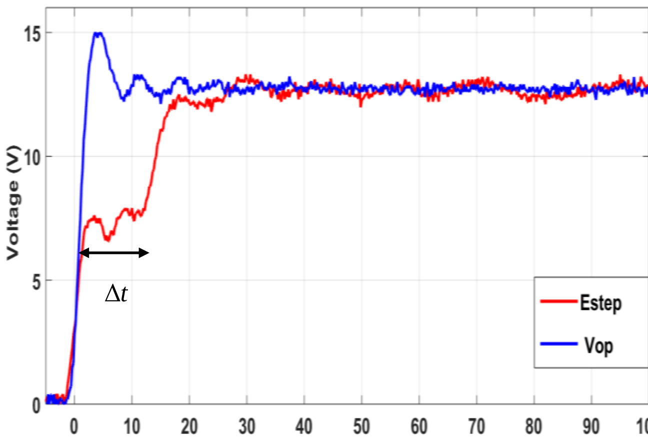

Fig. 8. Voltages V_{op} and E_{step} -reduced scale tower.

In table II, (*[2]) is the equivalent radius of the vertical cylinder calculated considering empirical formulation for multi-conductor systems proposed by Hara and Yamamoto [1]; in (*[3]) is the equivalent base radius of the cone inside a square base.

Some observations must be done about the measurement procedure and methods. For example: The surge impedance of the coaxial cable (50 Ω) was measured before the experiment since this parameter affects the accuracy of the measurements. The set-up can influence the results of cylinder/reduced-scale tower under test and thus its surge impedance. In this experiment, it was used copper strips to create a small loop, such as Faraday's cage, for minimizing induced currents. Objects near the system under test may also affect the capacitance of the cylinder/ tower model. Measurements using real tower are based on methodology as described in section II-B by direct and indirect methods. The reduced-scale tower is not an exact replica of a high-voltage transmission tower, the analysis is expected to be valid also for real towers with similar structure.

Table II. Surge impedances of the tower model calculated assuming different approximations and calculated differences in relation to the measured value.

GEOMETRY/ PARAMETERS	AUTHOR/ EQUATION	SURGE IMPEDANCE (Ω)	ERROR (%)
Cylinder r=0.25 m*[2] h=1.36 m	Wagner-(1)	159	112.0
	Sargent and Darveniza-(2)	99	32.0
	Hara and Yamamoto-(3)	39	48.0
	Jordan-(4)	36.50	51.20
	CIGRE-(5)	138.75	85.0
	Chisholm, Chow and Srivastava-(6)	78.75	5.0
	Ametani-(7)	115.90	54.50
Cone r=0.35 m*[3] h=1.36 m	Sargent-(8)	103	37.0
Combination of solids r_1=0.48 m r_2=0.28 m r_3=0.45 m h_1=0.61 m h_2=0.75 m	Chisholm, Chow and Srivastava -(9)	81	8.30

IV. CONCLUSIONS

This paper presented a brief literature review about tower models and methods for measuring tower surge impedances. The geometric model is the basic formulation to evaluate the tower surge impedance and depending on the formula proposed, it presents a good approximation for the tower.

Various equations to calculate tower surge impedance were compared with experimental results. For the case of a vertical cylinder the smallest difference between measured and calculated surge impedance was about 1% obtained when (2), proposed by Sargent and Darveniza [16] was proposed. The surge impedance measured is Z_{cyl} = 320 Ω, which is in accordance with the results obtained by Hara and Yamamoto [1].

The measured surge impedance of the reduced-scale transmission tower was equal to 75 Ω and the best model to represent it, considering a vertical current injection, was the composition of solids, which yielded a difference of about 8% between measured and calculated tower surge impedances. If a horizontal current injection is assumed, the use of (6) yields the smallest difference (about 5%). Thus, both the considerations proposed by Chisholm, Chow and Srivastava [4] of a cylinder, using (6) and a combination of solids, using (9), have been shown to be reasonable to estimate tower surge impedances.

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