Surge Impedance Determination of Transmission Line Towers Using Finite Element Method

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***Abstract* - The surge impedance of transmission towers is an important factor and its value, associated with impulsive currents, is essential to evaluate voltages that may cause dielectric disruption between the power cable and the tower structure. This work describes the analytical and experimental methods for the surge impedance computation and proposes a computational model, in three dimensions, of transmission towers. The model is then analyzed, using the finite element method (FEM), in order to obtain the parameter herein focused. Using experimental data, comparisons were performed to verify the modeling performance. Through the EMTP/ATPDraw simulator, the voltage were obtained considering an impulsive current source and the results have shown a good accuracy when compared with the field results.**

***Index Terms* - Surge impedance, Transmission tower, Transmission Line, Finite Element Method, EMTP/ATPDraw.**

I. Introduction

The strategic role of the transmission lines as infrastructure component for the economy of any country highlights the importance of providing a reliable power supply network. Therefore, the full understanding of the impacts due lighting strikes and its parametrization is vital.

One of the disturbances produced by lightning strikes is overvoltage. As is known, when a lightning strikes a tower or the ground system of a transmission line, the current flowing through the tower impedance causes a voltage increasing, which may cause an electric arc between the tower metal structure and one of the phase cables. This phenomenon is known as “back flashover”, and can result in unscheduled system shutdown.

In this way, the tower surge impedance is a significant parameter when determining the transmission lines performance. However, any divergence on the values estimation of this parameter can bring significant differences on determining disconnections of a power system segment.

The relative errors in methods for determining the tower surge impedance, for the same transmission tower, can vary from approximately from 5% to 46.5%[1]. For instance, the surge impedance values obtained by different methods to the same tower are shown in Table I.

Table I. Comparison of surge impedance values using different methods for the same tower [1].

Methods	Jordan [2]	Wanger [3]	Sargent [4]	Measurement [1]
Impedance (Ω)	92.92	207.30	165.90	174.22

As the current peak magnitude of a lightning strike is thousands of amperes, the calculated voltage on the tower higher point, based on the tower surge impedance, can diverge significantly for each surge impedance value from Table I, which can be critical for predicting a system shutdown.

The surge impedance measuring is a direct process and it may seem simple at first. However, there are different measuring methodologies, each one with its particularities. That said, there is no consensus on which one would be the best technique. Moreover, the towers with considerable dimensions make the impedance measurement a complex and expensive practice.

On the other hand, analytical formulation brings down costs when determining the tower surge impedance. The analytical method is related with equations based on geometric shapes similar to real towers. Cylindrical and conical shapes are some of the most frequently used geometries in order to obtain the analytical expressions. However, they are approximated forms, and the equations, applied to the size of the towers, have results with a considerable error. The results can be less accurate when the tower has a different structural form.

The proposed method combines low cost with the reliability of dimensional shapes of transmission towers. Computer modeling in three dimensions brings significant details from tower construction such as shape, length, height, thickness of steel plates, etc. These details are needed for the implementation of the Finite Elements Method (FEM) and have great impact on results.

To validate the consistency of the proposed technique, an experimental data will be utilized as reference. Furthermore, performance evaluation of both analytical and the proposed method will be analyzed.

II. Methods for surge impedance determination

A. Experimental method

The measurement of the tower surge impedance consists in a complex process, with many issues that make it impracticable. This is due to the large physical dimensions of the tower and the variables magnitudes involved in the lightning strike phenomenon. Two methods of surge impedance measurement can be highlighted: the direct and the indirect.

The direct method [5], [6] is applied through an impulse generator, using a current step-shaped source at the higher point of the tower. The potential difference between the current injection point and the tower base can be obtained. This measurement is a simple way to determine the line insulation voltage against lightning strikes.

The direct measurement has some complications in its implementation, as the difficulty of raising equipment to the top of the tower. The work of Yamada [6] shows the equipment elevation through balloons, using auxiliary cables for performing the measurement on the ground. In this case, the cable are parallel in relation to the ground and perpendicular in relation to the transmission line, thereby minimizing inductive coupling. However, it is still required to elevate the pulse generator at the top of the tower.

Furthermore, resistances were connected to the ends of the auxiliary cables, equivalent to their characteristic impedances, to avoid wave reflection, which in this case, could cause measuring errors. The measurements are made using optical transducers and digital oscilloscope. Fig. 1 shows the used configuration for the direct measurement [6].

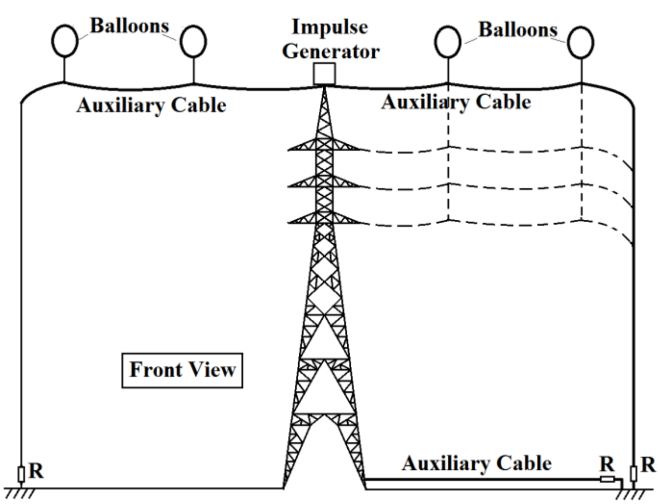

Figure 1. Configuration for the direct measurement described by [6].

In Fig. 1 three auxiliary cables are used: the cable on the left, for the current reading and two cables on the right to check the potential difference in the tower. The dashed lines indicate the possibility to move the cable to perform measurement of voltage at different points on the transmission tower.

The second method is also called reflection method [7], [8], which consists of applying a surge current at the end of an auxiliary cable which is connected to the top of the tower in a diagonal shape in a plane perpendicular to the transmission line and forming an angle of 45 degrees relative to the ground surface. Fig. 2 shows the configuration for this measurement methodology.

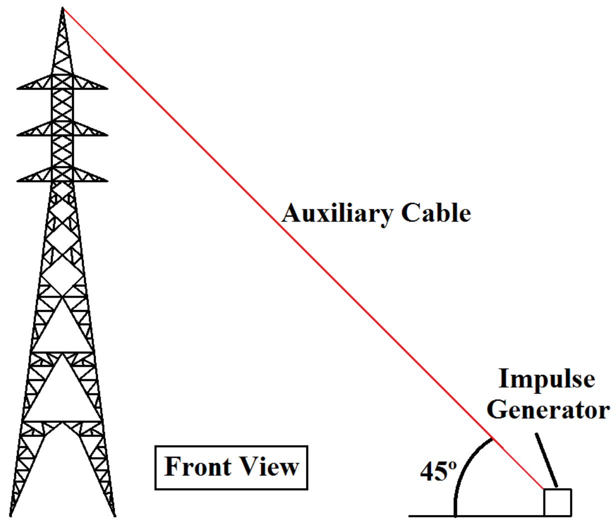

Figure 2. Configuration for indirect measurement or reflection method.

Through the measuring of wave reflections in the auxiliary cable connection with the pulse generator, and knowing the characteristic impedance of the cable, it is possible to determine the tower surge impedance.

Alternatively, reduced scale towers are used to simplify the measurement. Smaller towers facilitate the surge injection and the measurement of the quantities involved as well. Nevertheless, the analysis that involves wave reflections should pay special attention to the tower pulse frequency, due its frequency dependent behavior.

B. Analytical method

The use of mathematical equations as an alternative to measurements it is a simple way to obtain the required results. The low cost coupled with agility in the calculation is an undeniable advantage, and, in this context, becomes a viable option for determining the surge impedance of transmission towers.

However, the existing expressions have been based on approximate geometric shapes of some towers, such as cylinders and cones. This approach has a certain error, which can be greater if the basic geometric shape used to calculate it was different from the real tower. Fig. 3 shows some geometrical shapes used for the expressions development.

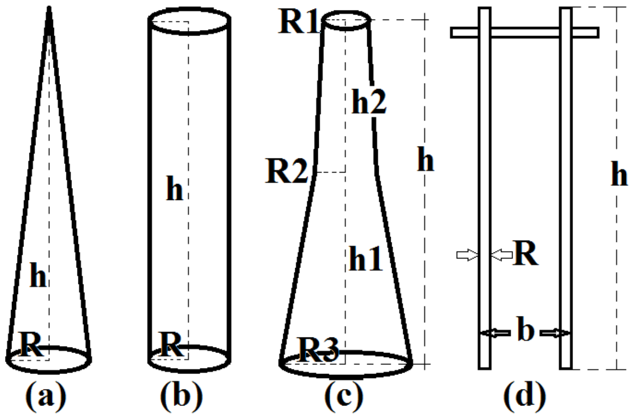

Figure 3. Some geometric shapes used for the development of towers surge impedance formulation.

The conical model and the cylindrical model, shown in Fig. 3 (a) and (b) has been studied by several researchers [1]–[4], and it considers the tower either conic or cylindrical, respectively, requiring only its height and radius to determinate the average surge impedance. In [4] the parameter calculation for conical representation is given by (1). The expression considering cylindrical geometry is given by (2) [3].

$$Z_t = 60 \ \ln\left(\frac{\sqrt{2*(h^2+R^2)}}{R}\right) \quad (1)$$

$$Z_t = 60 \ \ln\left(\sqrt{2} * \frac{2*h}{R}\right) - 60 \quad (2)$$

The model seen in Fig. 3 (c) [4], [8], [9] is more detailed, allowing greater similarity to actual towers, when compared to previous models. The considered radius in the calculation is given by an average weighted given by (3).

$$R_m = \frac{(R_1 h_2 + R_2 h + R_3 h_1)}{h} \quad (3)$$

The impedance calculation is performed according (4).

$$Z_t = 60 \ln\left\{\cot\left[\frac{1}{2}\tan^{-1}\left(\frac{R_m}{h}\right)\right]\right\} \quad (4)$$

The model seen in Fig. 3 (d) [9], has specific arrangements of a real structure. The surge impedance from that model can be obtained using (5).

$$Z_t = \frac{1}{2}(Z_s + Z_m) \quad (5)$$

Where:

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

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

Due the large number of different structures, with different shapes and sizes, it is hard to obtain a general equation. Thus, it may induce an error on the surge impedance value and it is relatively high when using basic shapes to represent constructive tower details with unusual shapes.

As it can be seen in Fig. 3, the models consider the radius tower silhouette for the impedance calculation. However, the towers typically have a rectangular base (not circular). Another important detail in many types of towers and is not considered in the analytical methods are called "tower arms". They are responsible for supporting the insulators and cables, being important in the analysis because they can influence the surge impedance value [10].

C. *Proposed computational method*

The tower surge impedance can be calculated through its capacitance (C_t) and the surge travel time (T_t) [11], [12], as shown in (6).

$$Z_t = \frac{T_t}{C_t} \quad (6)$$

Considering the relationship of the travel time, the tower height (*h*) and the surge propagation speed (*v*), it is possible to obtain (7).

$$Z_t = \frac{h}{v * C_t} \quad (7)$$

Thus, the tower surge impedance can be directly related to the tower height, making it possible to check the parameter variation through the tower size.

However, the tower capacitance must be known so, through this methodology, the impedance can be determined. In this context, the FEM can be applied to a 3D model of the tower and the simulation can consider the physical characteristics of the tower structure.

Using this methodology, the simulation can obtain the stored energy in the electric field surrounding the tower. Therefore, a unit-voltage is applied in the tower so it is possible to obtain the electric potential energy. From this energy is possible to get to the tower capacitance using (8).

$$C_t = 2\frac{E_e}{U^2} \quad (8)$$

Where:

U – Applied voltage,

E_e – Stored energy in the electric field.

Thus, replacing (8) in (7) and considering the unitary voltage, it is found (9):

$$Z_t = \frac{h}{2vE_e} \quad (9)$$

Another parameter checked in (9) is the surge speed. There are several references on this subject but the most common accepted value is equal to the speed of light (300 m / μs) [2], [3], [6], [7], [10]. Other authors consider its value below the speed of light [4], [5], [8]. In this work, all the simulations will consider the speed of light for this parameter.

III. Case Study

The analysis of the proposed method performance will be made by comparing the obtained results from the simulation in Flux3D software and the results from the analytical method. Additionally, the results will be compared with experimental data as well. The same tower will be adopted for all analysis.

Due the complexity involved with measurements, as the difficulty to obtain equipment, this study will consider the experimental results from [1]. In such reference it is specified both the silhouette of the tower and dimensions, as shown in Fig. 4.

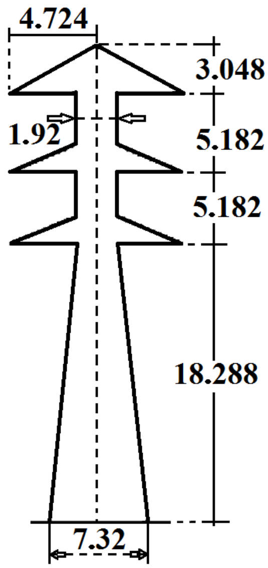

Figure 4. The tower dimensions, in meters.

From these details, the tower surge impedance will be determined by other methods, for later comparison.

A. Results

In [1], the measurement results were obtained from the direct method approach, using a real tower with dimensions and geometry shown in Fig. 4. The value of the surge impedance was 165 ohms.

It is important to notice the obtained impedance represents an average value, not considering the variation of the parameter by the height of the tower.

For analytical solution is assumed the cylindrical model shown in Fig. 3 (b). Substituting the values of the tower base radius and its height in (2):

$$Z_t = 60\ \ln\left(\sqrt{2} * \frac{2 * 31.7}{3.66}\right) - 60$$

$$Z_t = 131.91\Omega$$

The results of these two methods have considerable difference in surge impedance value.

B. Proposed Method

The proposed method requires a 3D modeling of the transmission tower. The dimensions shown in Fig. 4 were used for the 3D modeling. The computational model took into account two aspects: the physical dimensions and the boundary conditions of the problem.

Regarding the physical dimensions of the tower, several work in this area consider only the height, width and shape of the tower silhouette. However, in the proposed method, all details are represented, such as height, width, thickness of the metal profiles, dimensions and arrangement of the truss.

Due to the tower details found in [1], a typical design of a similar tower from that studied was adopted. The 3D model of the tower is shown in Fig. 5.

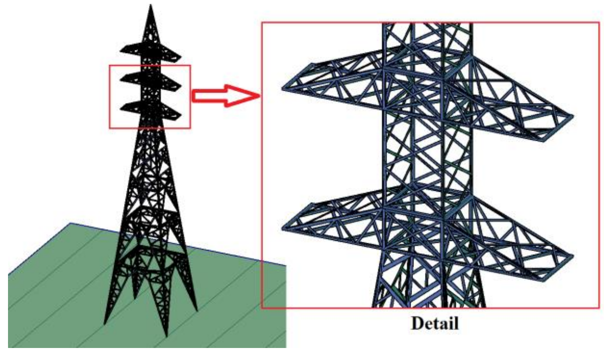

Figure 5. Model in Flux3D software, tower under review.

This model follows the specifications of FIG. 4 in addition to consider the arrangement of lattices as shown in Fig. 5. Similarly, it was considered the tower was comprised of steel angles with equal flanges, with two types of profiles, as shown in Fig. 6.

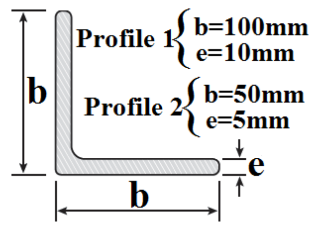

Figure 6. Steel profiles used for 3D modeling.

The second aspect is related with the solution of the problem by the FEM. The problem is from electrostatic nature, and quantifies the stored energy in the electric field surrounding the tower. Physical boundaries conditions are needed to solve the problem by FEM.

The adopted boundary condition is based on a method known as “external limits truncation”. This approach chooses a boundary condition usually five times greater than the tower dimensions [13].

Therefore, using this method, it was considered an external virtual cube, with dimensions at least 5 times the distance between the tower outer surface and its center. A zero potential is then adopted in the cube boundaries. Fig. 7 shows the tower with the adopted limits.

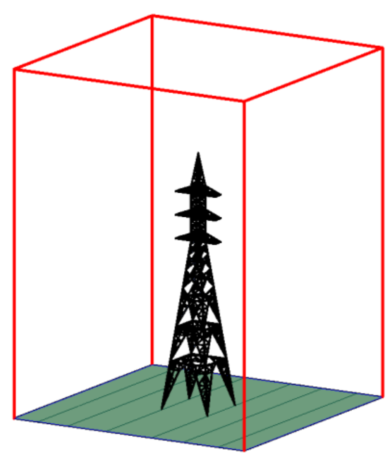

Figure 7. Tower model in Flux3D software, with boundaries.

From the performed simulations, the energy stored in the electric field was $359.32*10^{-12}$ joules.

Replacing the electrical energy value, the tower height and the surge propagation speed in (9), it can be obtained the tower surge impedance (Z_t):

$$Z_t = \frac{31.7}{2 * 3 * 10^8 * 359.32 * 10^{-12}}$$
$$Z_t = 147.04\Omega$$

C. Results anlysis

In order to compare the results and evaluate the method accuracy, the analytical and experimental data were used. Table II shows the results and their relative errors.

Table II. Values obtained and respective relative errors.

Methods	Analytical	Proposed	Measurement
Impedance Zt (Ω)	131.91	147.04	165
Relative error (%)	20.05	10.88	-

As it can be seen, the analytical method has the high relative error because it considers a characteristic silhouette tower, with a simple geometric shape. Ignored details may influence considerably in the tower capacitance value, thereby affecting the surge impedance calculation.

The proposed method has the smallest relative error (10.88%). The error is almost half of error obtained through analytical method [1]. It highlights the proposed method accuracy.

To verify the impact of those differences in surge impedance value, a second analysis was performed using the Alternative Transients Program (ATP). The system configuration and its electrical representation are shown in Fig. 8.

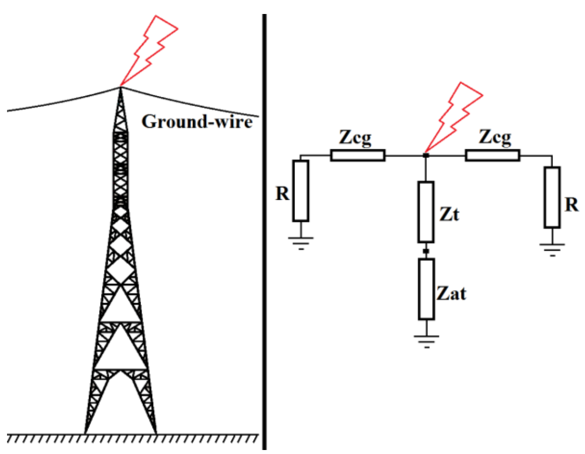

Figura 8. Physical configuration (side view of the tower) and corresponding electrical circuit modeled on the ATP.

The tower impedances and the ground system were represented using the equivalent transmission line, with distributed parameters, on ATP. It was considered the characteristic impedance of the ground system (Z_{cg}) and the tower grounding resistance (Z_{at}) with typical values of 455Ω and 15Ω, respectively. The ground wire ends were connected using resistances (R) with appropriate values to avoid wave reflections. The lightning strike has been represented using the double exponential expression [14], with a peak of 10 kA, rise time and decreasing time of 1.2 and 50 microseconds, respectively. Simulations were then performed for each surge impedance (Z_t) of Table II and the results are shown in Fig. 9.

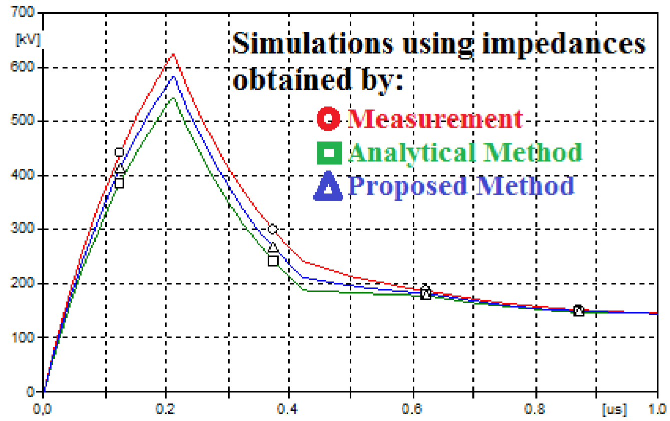

Figure 9. Voltage results at the top of the tower.

The voltage peaks at the top of the tower considering the impedance Z_t obtained from the measurement, from the analytical method and from the proposed method is 623.18kV, 544.07kV, and 581.98kV, respectively. It is noticed a difference of up to 79.11kV between methods, which can cause considerable impact on transmission line projects.

IV. Conclusions

The surge impedance is an important parameter for the study of transmission lines performance, and its value must be carefully determined. Several methods for determining the surge impedance can be found, either theoretical or experimental. However, the difference between the techniques reflects outlying results, which brings uncertainty in this study field and highlights the need and importance of the analysis of this parameter.

A case study revealed a discrepancy between the results of the techniques, with the relative error of 20.05%. The proposed method obtained better results, with relative error of 10.88%, showing the methodology accuracy. With low cost, fast simulations and efficiency, the proposed method can be a viable alternative in determining the parameter herein studied.

However, there is still the possibility of decrease the relative error found in the results of the proposed method. In the case study, the 3D modeling similar to the tower present in [1], may have influenced the result. The use of a similar tower is justified because a structure with greater level of detail would be needed.

Based on the simulations results on ATP software, there is an impact in the surge impedance obtaining. A difference of up 79.11kV can be crucial in predicting shutdowns and it can influences the transmission lines performance when submitted to lightning strikes.

Another point of future analysis is the surge propagation speed through the tower. Its value is important for surge impedance calculation but there is a disagreement concerning it and there is no consensus on its value.

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REFERENCES

[1] Zhijing Zhang, Wenxia Sima, Yongji Zhang, and Lichun Shu, "The simulation model for calculating the surge impedance of a tower," in *Conference Record of the 2004 IEEE International Symposium on Electrical Insulation*, 2004, no. September, pp. 331–334.

[2] C. A. Jordan, "Lightning Computations for Transmission Lines With Overhead Ground Wires, Part II," *Gen. Electr. Rev.*, vol. 37, no. 4, pp. 130–137, 1934.

[3] C. F. Wagner and A. R. Hileman, "A New Approach to Calculation of Lightning Performance of Transmission Lines-Ii," *Trans. Am. Inst. Electr. Eng. Part III Power Appar. Syst.*, vol. 78, no. 4, pp. 996–1020, Dec. 1959.

[4] M. Sargent and M. Darveniza, "Tower Surge Impedance," *IEEE Trans. Power Appar. Syst.*, vol. PAS-88, no. 5, pp. 680–687, May 1969.

[5] M. Kawai, "Studies of the Surge Response on a Transmission Line Tower," *IEEE Trans. Power Appar. Syst.*, vol. 83, no. 1, pp. 30–34, Jan. 1964.

[6] T. Yamada, A. Mochizuki, J. Sawada, E. Zaima, T. Kawamura, A. Ametani, M. Ishii, and S. Kato, "Experimental evaluation of a UHV tower model for lightning surge analysis," *IEEE Trans. Power Deliv.*, vol. 10, no. 1, pp. 393–402, 1995.

[7] G. D. Breuer, A. J. Schultz, R. H. Schlomann, and W. S. Price, "Field Studies of the Surge Response of a 345-Kv Transmission Tower and Ground Wire," *Trans. Am. Inst. Electr. Eng. Part III Power Appar. Syst.*, vol. 76, no. 3, pp. 1392–1396, Apr. 1958.

[8] W. a. Chisholm, Y. L. Chow, and K. D. Srivastava, "Travel Time of Transmission Towers," *IEEE Trans. Power Appar. Syst.*, vol. PAS-104, no. 10, pp. 2922–2928, 1985.

[9] J. R. Ooyle, L. E. Zaffanella, F. J. Ellert, S. A. Miske, C. J. Truax, J. R. Ooyle, J. J. LaForest, T. S. Lauber, M. G. Comber, O. W. Oeno, and R. J. Nigbor, *Transmission Line Reference Book*, 2nd ed. Palo Alto : Electric Power Research Institute, 1982.

[10] T. Hara and O. Yamamoto, "Modelling of a transmission tower for lightning-surge analysis," *IEE Proc. - Gener. Transm. Distrib.*, vol. 143, no. 3, p. 283, 1996.

[11] Working Group 33.01-Lightning (CIGRÉ), "Guide To Procedures For Estimating The Lightning Performance Of Transmission Lines," *CIGRE Broch. 63*, vol. 01, 1991.

[12] T. X. Cao, T. Pham, and S. Boggs, "Computation of tower surge impedance in transmission line," in *2013 IEEE Electrical Insulation Conference (EIC)*, 2013, no. June, pp. 77–80.

[13] Qiushi Chen and A. Konrad, "A review of finite element open boundary techniques for static and quasi-static electromagnetic field problems," *IEEE Trans. Magn.*, vol. 33, no. 1, pp. 663–676, 1997.

[14] W. Jia and Z. Xiaoqing, "Double-Exponential Expression of Lightning Current Waveforms," in *The 2006 4th Asia-Pacific Conference on Environmental Electromagnetics*, 2006, pp. 320–323.