Power Line Tower Lightning Surge Impedance Computation, a Comparison of Analytical and Finite Element Methods.

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Abstract. The aim of this work is to compare methods for the computation of transmission line tower surge impedance, that are: traditional analytical method using simplified equations; and the Finite Element Method for the mapping of electromagnetic fields surrounding the tower[9]. In the latter were used two different software, the public domain FEMM, and the commercial software FLUX3D. The first is able to perform calculations based in a 2D representation of the problem while the second uses a 3D representation of the problem to perform computations. It is also verified the impedance variation along the tower height, phenomenon that most of the time is not considered, and that can provide a direct impact in the performance of transmission lines facing the atmospheric discharges. With this purpose it was used the software ATP-EMTP, where it was modeled a simple case who brought results for immediate comparison.

Keywords: surge impedance, transmission line, tower, finite elements, ATP-EMTP.

1. Introduction

The electrical system is constantly affected by several phenomena, such as: transformer magnetization currents, sustained faults, large motors starting currents, capacitance switching effects in transmission lines and lightning. So, the electrical system is always tested concerning its continuity in service, and its capacity to endure and minimize such phenomena.

The surge impedance of structures that are part of transmission lines is a key factor concerning their performance analysis facing atmospheric electric discharges. Such analysis can be weakened when this parameter is not considered or inadequately considered.

As a rule three methods are used to obtain surge impedances

of transmission line towers, namely: through measurements, by way of analytical calculation taking advantage of equations based in ordinary tower geometric models; and through numerical methods based on the electromagnetic field theory.

In a simple way, the measurement consists in the injection of a current surge at the top of the tower and evaluates the voltage waveform produced for the determination of surge impedance. However, this method brings some drawbacks as the needs to de energize the line for its completion. By other way, sometimes it is needed the knowledge of the tower surge impedance for the consummation of the line design, even before the construction of the tower.

Despite its importance, the tower surge impedances is estimated many times through approximated equations, and not taking in consideration all the structure geometric details. The large variety of structures with many different geometric forms makes the creation of a generic method for the calculation of surge impedances very complex, with every structure format having a different set of equations to perform this calculation. Commonly, the set of equations for the surge impedance takes in consideration structures with simplified formats as cylinders and cones, or a combination of both. As a result, in cases of towers with very distinctive formats of the approximated shapes, relevant imprecision can occur. Furthermore, it is known that the surge impedance varies along the structure length, and this method presents an average value for this parameter.

This work is based in a method that makes the estimate of the tower surge impedance value from simulations in the software FEMM and FLUX3D, both take advantage of the Finite Element Methods for the solution of electromagnetic problems. From the structure representative drawing the tower capacitance is obtained, and from this value it is computed the surge

impedance. In such a way it is possible to estimate the surge impedance for any type of tower, being sufficient only to know its geometric characteristics for the representation in this kind of software. Still it can be verified the variation of the structure surge impedance along of its length, what is not possible in another methods.

The importance in this study is verified in simulated cases where is used values of transmission line towers surge impedances obtained through different methods. With this purpose the software ATP-EMTP is used for the simulation of effects caused by lightning in the proximity of a transmission line.

2. Methodologies

This work could encompass only one methodology for the calculation of tower impedance surge, however, it is important the application of other methods for the comparison of obtained results, a method to validate the methodology used. So, firstly it is presented the methodology that uses analytical equations for the calculation of tower surge impedance. In sequence are presented the models using Finite Elements, with respectively the software FEMM and FLUX3D.

A. Analytical Method

The tower surge impedance is deeply related to their geometric shapes. However, the existence of complex transmission line structures it is not easy to compute its surge impedance. Furthermore, the variety of structures, with different shapes and sizes makes impossible to have a general equation, which encompasses all the cases. In this way were developed equations obtained from simple geometric shapes, as cylinders and cones [1, 2], representing various types of towers. Some of the existing models [1, 2, 3] can be seen in Fig. 1.

Fig. 1. Simple geometric shapes used to establish the set of equations of transmission line towers impedance surge.

Each of the shapes in figure 1 has specific formulation for the computation of surge impedance. Equation (1) is obtained from figure 1(a).

$$Z_t = 30 \cdot \ln \frac{2 \cdot (H_t^2 + r^2)}{r^2} \quad (1)$$

Where:

Z_t is the surge impedance;

H_t is the height of the tower;

r is the radius in the base of the tower.

Equations (2) and (3) were developed from the geometric

shape of figure 1(b).

$$Z_t = 60 \cdot \ln \left\{ \cot \left[0,5 \cdot \tan^{-1} \left(r_{avg} / H_t \right) \right] \right\} \quad (2)$$

$$r_{avg} = \frac{r_1 h_2 + r_2 H_t + r_3 h_1}{H_t} \quad (3)$$

Where:

r_{avg} is the average geometric radius;

r_1, r_2, r_3 are the radius presented in figure 1(b).

The geometric shape of figure 1(c) is the origin of equation (4) for the surge impedance calculation.

$$Z_t = 60 \left[\ln \left(\sqrt{2} \frac{2h}{r} \right) - 1 \right] \quad (4)$$

Where:

r is the radius presented in figure 1(c).

So, with such equations it is possible to estimate analytically the approximated value for the tower surge impedance. It is legitimate to remember that the obtained impedance with these equations is an equivalent value that doesn't take in consideration the impedance variation along the height of the tower.

B. FEMM

The FEMM software takes advantage of the finite element method for the solution of magnetic, electrostatic and thermal problems[5]. With this aim, it is employed the triangularization technique for the representation of the problem, that is to say, the two-dimensional representation of the case is subdivided in a triangular mesh.

The fact of the software to be using representations in two dimensions implies in greater care that should be taken when choosing the view of the drawing, in such a way that important details were not ignored. In the case of a transmission tower, this was represented in such a way that the conductors are orthogonal to the plane of the figure.

An important parameter for the representation in this software is the problem depth representing the third dimension. For the representation of three-dimensional models in FEMM the plane of the figure is considered the front view of the model, making an extrusion of the figure in its plane orthogonal axis is obtained the third dimension, to which we refer here as depth. Thus, to obtain consistent results, it is needed to choose the depth of the problem in such a way that its volume is the same as the real three-dimensional volume.

From the simulation is obtained the tower capacitance, and through equation (5) the surge impedance can be obtained.

$$Z_t = \frac{1}{C \cdot v} \quad (5)$$

Where:

C is the tower capacitance;

v is the propagation speed of the voltage wave along the tower.

The surge speed in the tower is considered the speed of light[6] – 300 m/μs.

C. FLUX3D

Similar to FEMM, the FLUX3D also applies FEM in the solution of electromagnetic problems[7]. Its large difference is the use of three-dimensional representation and due to this fact; the mesh is made of tetrahedral components, pyramids, cubes, parallelepipeds or prisms. There is the program an automatic choice of such elements for the mesh generation in such a way to get as close as possible of the drawing shape.

In the case of FLUX3D, an important parameter is the boundary condition to be adopted. The desired results obtained in this study are related with the space involving the tower, which in practice is limited to the electric field interaction radius, for the results to be coherent with reality. The boundary condition to be used is established by references [5]-[7] used in an especial case, presented ahead, and taken as reference for the comparison of results.

3. Results for the surge impedance

The surge impedance was obtained from the methods in three different cases, being the first of them a theoretical situation created for the obtaining of boundary conditions, as mentioned previously. From this step two more cases were simulated, where real transmission line structures were considered.

A. First case – Representation of the structure by a cone

Approximations of the analytical computation allied to a variety of shapes of transmission line towers can bring large disagreement in the results of adopted methods. To promote a standard in the implementation of models in the software, the cone shape was chosen due to its simplicity and its well defined analytical formulation. Figure 2 shows the representation of a cone 30 meters high and 10 meters of diameter in the base respectively in software FEMM and FLUX3D.

Fig. 2. Tower representations in the shape of a cone in software (a) FEMM and (b) FLUX3D.

In the FEMM (two-dimensional), the depth of the problem is set in way that its product by the area of the triangle representing the cone in the software corresponds to its volume. In this example it is as if the FEMM “view” was a wedge instead of a cone, but both with the same volume.

In the cone representation with FLUX3D, to achieve the value on Table I, the rule of thumb is that the distance from the centre of the problem to the external limit must be five times the distance from the centre to the external surface of the object of interest[5]. As the centre of the problem is inside the cone, the adopted boundary condition is an external cone with radius and

height 4.8 times the respective dimensions for the cone under investigation. This procedure will be adopted in the following simulations, as a standard procedure.

Table I shows the results of surge impedance obtained in the three methods.

Table I. – Results of suge impedance for a tower in the shape of a cone.

	Analytical	FEMM	FLUX3D
Surge impedance in Ohms	129.12	155.77	125.94

B. Second case – 230 kV transmission line and single circuit.

The tower under consideration corresponds to a standard structure of single circuit 230 kV power line.

For the analytical calculation it was considered the figure 1.(c) as a standard for the representation of the structure, using equation (4) to find its surge impedance, being the height 37 meters and radius represented in figure 1.(c) of 1.8 meters. In the simulation with FLUX3D the adopted boundary condition is a wedge of radius and height equal to 4.8 times the respective dimensions for the tower under study.

Some simulations were made to evaluate the influence of the presence of the lattice girder in the tower surge impedance. It was found an insignificant decrease, around 0.35%, when the lattice girder is not considered in the tower. Thus, in the subsequent simulations, to facilitate the software representation such details won’t be considered. However all the structure boundary real dimensions will be considered in simulations, exception made to the simulation in FEMM, where the depth is obtained by the volume equivalence.

Figure 3 shows the single circuit tower representations made in the software.

Fig. 3. Tower representation for the 230 kV TL, single circuit, in software (a) FEMM and (b) FLUX3D.

From equation 4 and model simulation were obtained the results presented in Table II.

Table II. – Results of surge impedance for a single circuit tower.

	Analytical	FEMM	FLUX3D
Surge impedance in Ohms	183.77	198.03	117.42

It can be realized that the result obtained with FLUX3D is the one that has the larger difference when compared with others, however, this must be considered the closest to the real value, since no approximation is made relatively to its geometric dimension.

C. Third case – 138 kV transmission line and double circuit tower.

In this case study was used a tower in a 138 kV transmission line, which has two circuits and is 44 meters high.

In this case, the impedance analytical calculation is made having as a basis the standard profile of figure 1(b) using equations (2) and (3).

Figure 4 shows the representations for this tower made in FEMM and FLUX3D.

Fig. 4. Representation of the 138 kV TL tower, double circuit in software (a) FEMM and (b) FLUX3D.

After simulations and analytical calculations were obtained the results presented in Table III.

Table III. – Results of surge impedance for a double circuit tower.

	Analytical	FEMM	FLUX3D
Surge impedance in Ohms	187.62	284.65	163.91

As can be seen in tables I, II and III, the results with FEMM are the largest values. The reason for that fact is based in the depth obtained by the equivalence of volumes. This operation imposes an increase in the volume at the top of the tower in contrast with a reduction in the base. This results in a reduction in the structure equivalent capacitance, that is, an increase in the impedance.

Results obtained by FLUX3D must be considered close to real values, since that no approximation is made relatively to the structure geometric profile. It is observed that in the case of the structure representation by a cone that has a well defined analytical formulation, the simulation in FLUX3D and the analytical method presented similar results.

4. Variation of the surge impedance along the transmission line tower

Inductance and capacitance are variable according to their relative distance to the ground; consequently the impedance will be as well. Thus, to the extent that an outbreak pervades the extension of the tower, from top to the ground, this current wave

is the subject of variable impedance and, by the travelling wave's theory, reflected waves will be present. The computation of overvoltage that the tower is subject must take in consideration this aspect. However the continuous variation of such parameters, in the present work, won't be taken in consideration. Here will be considered the structure split along its height in equal parts, where will be determined the surge impedance. With the capacitive coupling with the soil increasing with the proximity of the surge wave, it is expected that the surge impedance presents a reduction in this sense.

The computation methods presented take in consideration the tower as a whole, and the estimated impedance refers to an equivalent value for the variable impedance.

Under this aspect, the tower will be split in three equal parts along its height, for the verification of the surge impedance for each part, being possible the analysis of its variation.

It is important to mention that the software FEMM could also be used; however, approximations made in the computation of depth may lead to meaningful discrepancies of results, being necessary a greater care with the representation of such models in the software.

Single and double circuit transmission line towers, already studied previously, will be used in this case.

A. Surge impedance variation in the single circuit TL tower.

This tower, 37 meters high, was split in three parts with 12.33 meters, as can be seen in Figure 5.

Fig. 5. 230 kV TL tower, single circuit, split in three parts.

The computation of capacitance in each part is made considering the electrical energy stored.

From this procedure, made in FLUX3D, it is obtained the tower surge impedance for each part of the tower. Table IV show such results.

Table IV. – Results of surge impedance, in ohms, in three parts of the single circuit transmission line tower.

TOP	MIDDLE	BASE	Z equivalent
1510.33	690.25	156.12	117.42

As can be seen the equivalent impedance was also calculated as a combination of the found impedances. For such computation it was considered a parallel connection of these impedances, since the impedances are estimated relatively to the ground. Comparing the equivalent impedance of Table IV with the impedance found with the complete representation for the tower (Table II), can be verified the coherence of the adopted

methodology.

A. Surge impedance variation in the double circuit TL tower.

The double circuit tower was split in three equal parts 14.67 meters high, representing its 44 meters height, as can be seen in Figure 6.

Fig. 6. 138 kV TL tower, double circuit, split in three parts.

Results of surge impedance obtained for each of these parts are presented in Table V.

Similarly to the previous case, was estimated the equivalent impedance for the whole structure. The result is also coherent with the values in Table III.

Table V. – Results of surge impedance, in ohms, in three parts of the transmission line double circuit tower.

TOP	MIDDLE	BASE	Z equivalent
4552.04	1252.70	196.74	163.91

5. Analysis of results for the surge impedance with ATP-EMTP software

The aim is to verify the impact of the variation of impedance along the tower height in the overvoltage caused by a lightning discharge; it is presented the simulation results obtained from the ATP program. To comply with the proposed objective, it was considered a single phase transmission line; it is composed of 11 towers equally spaced with 200 meters between towers. In the study it is represented only the towers and the guard cables for the TL, to which was applied a typical electrostatic discharge.

Each tower is represented by three single phase lines, with distributed parameters, each of it with one third of the tower height and the respective values of impedance (top, 2/3 and 1/3 of the height) in such a way that its variation could be reproduced.

The tower foot impedance was represented by purely resistive impedances with typical values of 6.5 Ohms [8].

The characteristic impedance of the guard cable is 455 Ohms, and to avoid undesirable reflections, the cable extremities were connected to ground resistances of the same value.

The atmospheric discharge is represented by a surge source based in a double exponential format [9], reach the 10 kA maximum in 1.2 μ s and with the tail time (half of the maximum) of 50 μ s (1.2x50 μ s).

The discharge is applied in the sixth tower, where it is

analyzed the overvoltage in the three marked points as can be seen in Figure 7.

Fig. 7. ATP array for the transmission line protection cable.

In order to compare, it was used also the values obtained in analytical calculations. In this case was kept the representation of three lines for one tower, each line with one third of the height, however with values of impedance equal to the ones calculated by the analytical method.

Firstly were used values obtained for the single circuit TL tower from the analytical calculation and simulation with FLUX3D. The voltage registered along de tower is as can be seen in Figure 8.

Fig. 8. Registered overvoltages using impedances obtained from (a) analytical method, and (b) FLUX3D, for the single circuit TL tower.

Fig. 9. Registered overvoltages using impedances obtained from (a) analytical method, and (b) FLUX3D, for the double circuit TL tower.

Other simulated case was the double circuit TL tower. Similarly, the tower was represented by single phase lines with their respective impedances. Figure 9 shows the results.

In the case of the double circuit TL tower, it is noticed larger differences in the peak voltage values. Table VI shows the numeric results obtained from ATP simulations.

Table VI. – Overvoltage results for the model in ATP software

Structure type	Single circuit					
Analysis point	37 meters (top)		24.67 meters		12.33 meters	
Method to obtain surge impedance	Analytical	FLUX3D	Analytical	FLUX3D	Analytical	FLUX3D
Voltage peak [kV]	540	1200	425	530	250	140
Structure type	Double circuit					
Analysis point	44 meters (top)		29.33 meters		14.66 meters	
Method to obtain surge impedance	Analytical	FLUX3D	Analytical	FLUX3D	Analytical	FLUX3D
Voltage peak [kV]	725	1630	580	500	360	100

Table VI shows that differences in overvoltage values found in different points of the tower are significant and upon on the type of transmission line tower and of the point of analysis can lead the observer to erroneous interpretations.

6. Conclusion

This paper approach is to show some ways to find the value for the surge impedance of transmission lines through analytical equations or the simulation using finite elements software. Due to the high value of surge current that the towers can be submitted to, imprecision in the estimative of its surge impedance can have the meaning of overvoltage values very different from expected. In that way it is important to take in consideration all the design details of the tower in order to all the TL components related to the performance in face of atmospheric discharges are designed correctly.

FEMM is a free software easy accessible that works only in 2D, making possible to use the depth as the third dimension in three dimensional problems. The greater difficulty is to find an ideal value for the depth that could be adequate to the problem characteristics. In this work equivalence was made between the real volume of the tower and the volume of its representative figure in FEMM. This procedure revealed less satisfactory, presenting higher results for the impedances due to the increase in volume in the higher part of the tower in contrast with the reduction in volume in its lower portion.

The FLUX3D software works with three dimensional representations being more adequate to the problem under investigation. By other hand, it is a restrict use software, that requires much more knowledge from the user. The boundary conditions and the borders of the problem are of fundamental importance to have trustable results. In this case was used the simulation of a special case (cone) to find the ideal boundary condition for the problem. In this way, the results for the different cases can be trusted, since the model representation in 100% in accordance with the real geometric dimensions.

It is shown in this study that the tower surge impedance present significant variations concerning the point of analysis and ground. Thus, the analysis of overvoltage caused by current surge is much more compromised if is not considered correctly.

As a coincidence or not, it is worth to note that in the proposed format the overvoltage at 2/3 of the height is similar in both cases of constant and variable impedance. However, large discrepancies were observed for the two other points.

Simulation in ATP used a simple model for the immediate analysis of the impact caused by variable impedance in the structure. More elaborated line models considering one or more circuits, phase conductors, and the real number of lightning protection cables are available in this software and can be easily used.

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