Influence of Tower Modeling on the Assessment of Backflashover Occurrence on Transmission Lines due to First Negative Lightning Strokes

Frederico S. Almeida, Fernando H. Silveira, Alberto De Conti, Silverio Visacro

***Abstract*— This paper assesses the influence of tower modeling on the calculation of voltages across insulator strings, critical currents and percentage of backflashover occurrence for typical 138-, 230- and 500-kV towers. Three different model types are considered: geometric, multistory and multiconductor models. The results are compared to those obtained with the Hybrid Electromagnetic Model (HEM), which is taken as reference. The extended Jordan model belonging to the multiconductor model type is responsible for the results closest to those provided by HEM. The geometric and multistory models also lead to consistent results but with some limitations. The former provides good results for tower-footing impedance above 20 Ω, for the 138-kV tower, and above 40 Ω for the 230- and 500-kV towers. The latter is more appropriate to represent towers with geometry close to the one adopted on the development of its formulation, such as double circuit transmission towers with heights above 60 m.**

***Keywords*: Backflashover, Lightning performance of transmission lines, Tower modeling.**

I. Introduction

LIGHTNING performance of transmission lines depends on the balance between the voltages across the insulator strings due to lightning strikes on the line and the insulation strength. For transmission lines with voltage level up to 500 kV, backflashovers related to lightning strikes to grounded elements of the line (shield wires and towers) are usually the main concern.

To estimate the probability of backflashover occurrence, it is necessary to determine the voltage across the insulator string, which corresponds to the voltage difference between the tower and the voltage induced at the phase conductor [1, 2]. The quality of the estimation depends on the selected calculation method, which can be analytical [3-5], circuit based [6, 7], or electromagnetic-field based [8]. It also depends on the accurate modeling of the transmission line elements, including the tower.

A complete review on the modeling of transmission line towers for the estimation of the lightning performance of transmission lines using electromagnetic transient-type programs is presented in [9]. Traditional methodologies proposed by CIGRE and IEEE [4,5] suggest the use of so-called geometric tower models. These models aim to determine the tower characteristic impedance by means of expressions derived assuming the tower as a solid with equivalent geometry [3, 10-12]. Other types of models [13,14] consider the subdivision of the tower into shorter elements, each represented with a particular set of characteristic impedances that take into account the height-dependent characteristics of the tower geometry.

The purpose of this work is to assess the influence of different tower models on the estimation of the lightning performance of transmission lines, with focus on backflashover occurrence due to first negative lightning strokes. Different towers typically used in 138-kV to 500-kV transmission systems are considered in simulations, which are performed in the Alternative Transients Program (ATP) [15]. Three different parameters are determined for each tower model as a function of the tower-footing impedance: voltage across insulator strings, critical current (I_C) and the corresponding percentage of backflashover occurrence $P(I \geq I_C)$ that is assumed as the percentage of currents larger than the critical current. The results are compared to those obtained with the application of the Hybrid Electromagnetic Model (HEM) [8], which is taken as reference.

II. Transmission Line Tower Models

In this section, some transmission line tower models following the classification proposed in [16] are presented. They are referred to as geometric, multistory, or multiconductor models.

A. Geometric Models

Geometric models represent the tower as a lossless single-phase transmission line with surge impedance corresponding to the geometry of the solid that more closely resembles the tower configuration. Cylinders, cones and a combination of solids are generally assumed [3, 4, 10, 11]. Such kind of model is mainly applied in the analytical procedures proposed by CIGRE and

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IEEE for evaluations of the lightning performance of transmission lines [4, 5], as well as in the well-known FLASH program.

Fig. 1 shows a typical 138-kV transmission line tower approximated by a cone. Its surge impedance is determined by (1), where H and r represent the height and radius of the cone, respectively. Fig. 2 illustrates the geometrical approximation typically considered for waist towers. Equation (2) is applied to determine the tower surge impedance. The term T is a function of the top (d_{tp}) and middle (d_{ms}) sections, the base diameter (d_{bs}), the tower height H and the distance h between middle section and tower top, as expressed in (3).

Geometric models are quite simple and their implementation is really intuitive, but strongly dependent on the adopted geometrical approximation. Also, the direction of lightning strike to the tower influences the resulting tower surge impedance, and distinct formulations have to be considered for lightning performance evaluations related to direct strikes to the tower and at line midspan [10,11].

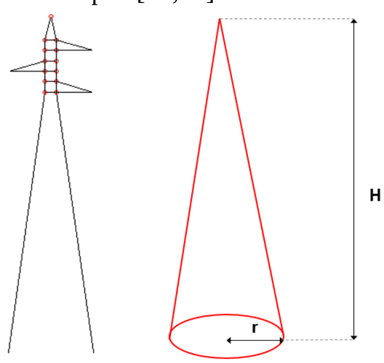

Fig. 1. Geometrical model of a 138-kV tower: representation as a cone.

$$Z = 60 \cdot \ln\left(\sqrt{2} \cdot \frac{\sqrt{H^2 + r^2}}{r}\right) \tag{1}$$

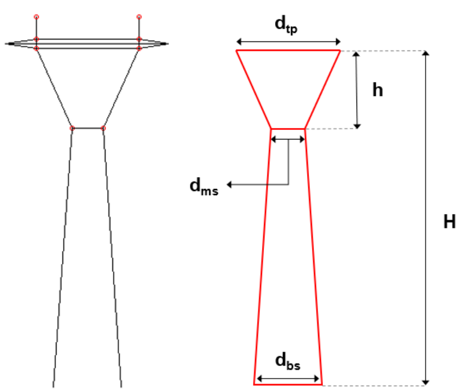

Fig. 2. Geometrical model of a 230-kV waist tower.

$$Z = \sqrt{\frac{\pi}{4}} \cdot \left[60 \cdot \ln\left(\frac{1}{\tan T}\right) + 60 \cdot \ln(\sqrt{2})\right] \tag{2}$$

$$T = \frac{1}{2} \cdot \tan^{-1}\left(\frac{d_{tp} \cdot h + d_{ms} \cdot H + d_{bs} \cdot (H - h)}{2 \cdot H^2}\right) \tag{3}$$

B. *Multistory Model*

The multistory model represents the tower as a set of short sections composed of lossless single-phase transmission lines. An example of multistory model is the one proposed by Ishii et al. [13], which divides the tower into four sections, each one represented as lossless line in series with an RL-parallel circuit that is responsible for the effects of surge attenuation and distortion. Fig. 3 illustrates a typical 138-kV transmission line tower model considering Ishii et al.'s model [13].

According to [13], the surge impedance Z_i of each section presents fixed values, given by (4) and (5). The *i*-th resistance, R_i, depends on the section length (l_i) and on the propagation constant (γ), given by (6) and (7). The *i*-th inductance, L_i, is defined by the relationship between the travel time (τ) and R_i related to the section, given by (8). The travel time (τ) is given by (9), where v is the propagation velocity defined in [13] as 300 m/μs. This model was proposed based on measurements in 500-kV transmission lines towers with average height around 60 m, hence the model accuracy may be influenced by the tower height. Furthermore, different values of the propagation constant γ are presented in literature, such as in [17], and this can have some influence on the results. One of the most noticeable features of this model is the smoothing provided by the RL circuit to the voltage waveforms.

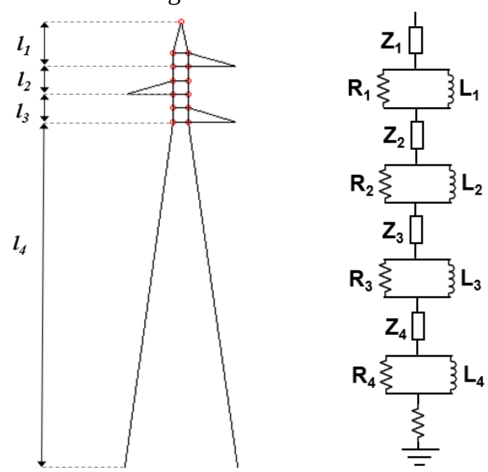

Fig. 3. Multistory model of 138-kV tower.

$$Z_1 = Z_2 = Z_3 \;\; 220\,\Omega \tag{4}$$

$$Z_4 = \; 150\,\Omega \tag{5}$$

$$R_i = \frac{2 \cdot Z_i \cdot \ln\left(\frac{1}{\gamma}\right) \cdot l_i}{l_1 + l_2 + l_3}, i = 1,2,3 \tag{6}$$

$$R_4 = 2 \cdot Z_4 \cdot \ln\left(\frac{1}{\gamma}\right) \tag{7}$$

$$L_i = R_i \cdot \tau \tag{8}$$

$$\tau = \frac{2 \cdot H}{v} \tag{9}$$

C. *Multiconductor Model*

Similarly to the multistory model, multiconductor models also divide the tower in sections that are modeled by single-phase lossless transmission lines. The surge impedance of each tower section considers both the self and the mutual impedance associated with the vertical conductors belonging to the section. A multiconductor model was proposed by Ametani et al. in

[18]. Recently, a multiconductor model based on a revised and extended version of Jordan's formula [19] was proposed by De Conti et al. [14]. This model is named here extended Jordan model. According to this model, the surge impedance of each tower section depends on the section height (h), the equivalent radius (r) of the vertical conductors and their relative distances (d_{ij}), as illustrated in Fig. 4.

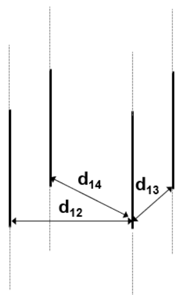

Fig. 4. Relative distance between the vertical conductors to the calculation of the mutual impedances in the multiconductor model.

The self and mutual impedances of each section are determined by (10) and (11), respectively [14]. Equation (12) provides the equivalent impedance (Z_i) representative of an *n*-conductor section.

$$Z_{ii} = 60 \cdot \ln\left(\frac{4 \cdot h}{r}\right) - 60 \tag{10}$$

$$Z_{ij} = 60 \cdot \ln\left(\frac{2 \cdot h + \sqrt{4 \cdot h^2 + d^2}}{d}\right) + 30 \cdot \frac{d}{h} - 60 \cdot \sqrt{1 + \frac{d^2}{4 \cdot h^2}} \tag{11}$$

$$Z_i = \frac{Z_{ii} + Z_{ij} + \cdots + Z_{in}}{n} \tag{12}$$

The accuracy of the extended Jordan model may be improved by the number of sections adopted to segment the tower. However, special attention is needed to model line sections characterized by conductors that are not vertically aligned, such as those close to the tower base, requiring the adoption of average distances among the conductors.

III. Developments

The analyses of this work are based on ATP simulations considering the geometric, multistory and extended Jordan models to represent transmission line towers of 138-, 230- and 500-kV transmission systems. Fig. 5 shows the dimensions of the simulated towers. The 138-kV tower is 30-m-high and has a non-uniform arrangement of insulator strings and one shield wire. The 230-kV tower is 40-m-high and has a horizontal arrangement of insulator strings and two shield wires. The 500-kV tower is 64-m-high and has a double-circuit vertical arrangement and two shield wires. In the simulations, a direct lightning strike was assumed at the tower top.

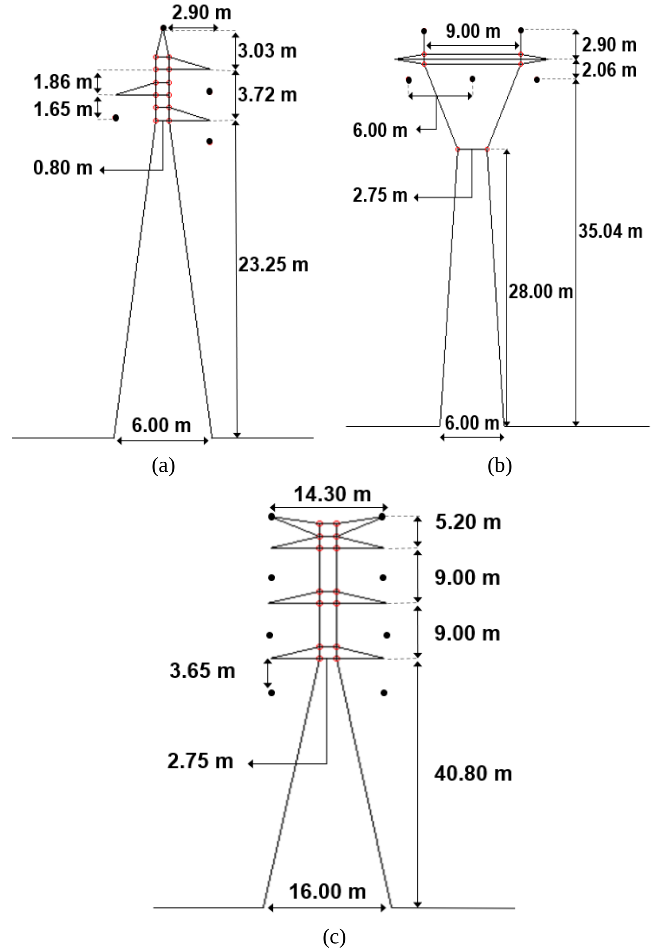

Fig. 5. Tower geometries and their respective dimensions: 138-kV(a), 230-kV(b) and 500-kV(c) transmission towers.

The effect of adjacent towers was considered assuming representative span lengths of 400 m for the 138-kV and 230-kV transmission lines, and 500 m for the 500-kV transmission line. Shield wires and phase conductors with radii of 0.4 cm and 1.13 cm, respectively, were represented with the JMarti model [20] following the distances indicated in Fig. 5. The critical flashover overvoltages (CFOs) of the 138-, 230- and 500-kV lines are of 650 kV, 1200 kV and 1750 kV, respectively. In the analyses, the steady-state voltage at power frequency was neglected.

The application of the geometrical model considered the conical approximation for representing the 138-kV and 500-kV towers and the waist approximation for representing the 230-kV tower, following the dimensions indicated in Fig. 5. The extended Jordan model assumed the 138-kV and 500-kV towers to be divided into four sections with heights h_1 to h_4 of 7.75 m, 15.5 m, 23.25 m, and 30 m (138 kV), and 13.6 m, 27.2 m, 40.8 m, 64 m (500 kV), respectively. The 230-kV tower was divided into five sections with heights h_1 to h_5 of 10 m, 19 m, 28 m, 37.1 m, and 40 m, respectively. A conductor radius of 1 cm was assumed. The use of the multistory model considered towers segmented into four sections with the following lengths: l_1 = 3.03 m, $l_2 = l_3$ = 1.86 m and l_4 = 23.25 m for the 138-kV tower; l_1 = 2.9 m, $l_2 = l_3$ = 4.55 m and l_4 = 28 m for the 230-kV tower; and l_1 = 5.2 m, $l_2 = l_3$ = 9 m and l_4 = 40.8 m for the 500-kV tower.

The tower-footing was represented as first-stroke impulse grounding impedances Z_P varying from 10 Ω to 80 Ω [21]. Such grounding representation is supported by analyses provided in [22] that demonstrate that the use of grounding impulse impedance leads to nearly the same percentage of backflashovers obtained under the physical representation of grounding electrodes in electromagnetic-field based programs.

The lightning current waveform assumed in the simulations has a linearly rising front with current front time (Td30) and tail time (T50) values equal to median parameters of first stroke currents measured at Mount San Salvatore station [23]. The adoption of such current waveform and parameters is supported by the analyses presented in [24, 25].

The critical current I_C, defined as the minimum current that is able to lead line insulators to flashover, is determined by means of the integration method with model parameters proposed by Hileman in [2]. The probability of backflashover occurrence is determined as the percentage of currents that exceed the critical current $P(I \geq I_C)$ considering the cumulative peak current distribution proposed by IEEE [5].

Simulations were also performed with the HEM model [8] to validate each tower model. HEM is an electromagnetic-field based model traditionally applied for calculating the lightning performance of transmission lines [8, 22, 24, 26]. The formulation and implementation of HEM is discussed in detail in [8,27].

IV. Results and Analyses

Figs. 6, 7 and 8 illustrate insulator string voltages calculated for the 138-kV, 230-kV and 500-kV transmission line towers assuming a 31-kA lightning strike at their top and considering Z_P varying from 10 Ω to 80 Ω.

It can be observed that the influence of the tower model on the resulting overvoltages reduces as the grounding impedance increases. Similar behavior is observed for double-circuit transmission line towers of 77 kV [28] and of 150 kV and 400 kV [29]. This is explained as follows. When the tower-footing grounding impedance is small, the grounding potential rise (GPR) is low and the resulting overvoltage across insulator string is mainly ruled by the tower. On the other hand, for increasing values of grounding impedance, the GPR increases and its effect becomes predominant on the establishment of the insulator string overvoltage, reducing the influence of the tower.

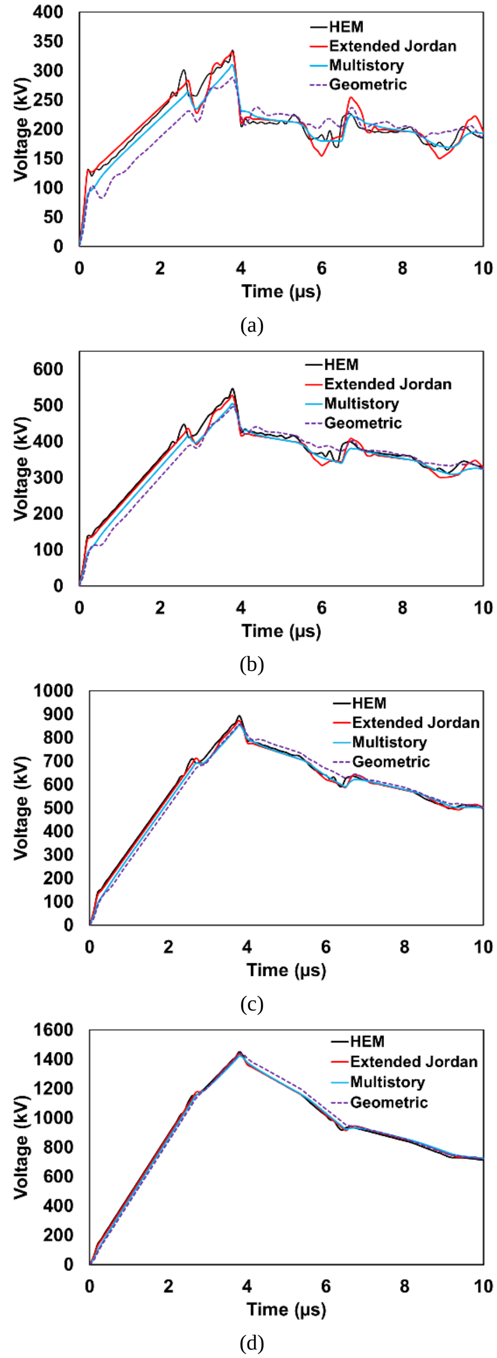

Fig. 6. Lightning overvoltages across the lower insulator string of the 138-kV transmission line for different tower models. Tower-footing impedance Z_P: 10 Ω (a); 20 Ω (b); 40 Ω (c) and 80 Ω (d). [Ip = 31 kA, Td30 = 3.8 µs, T50 = 75 µs]. Geometric tower model assuming equation (1).

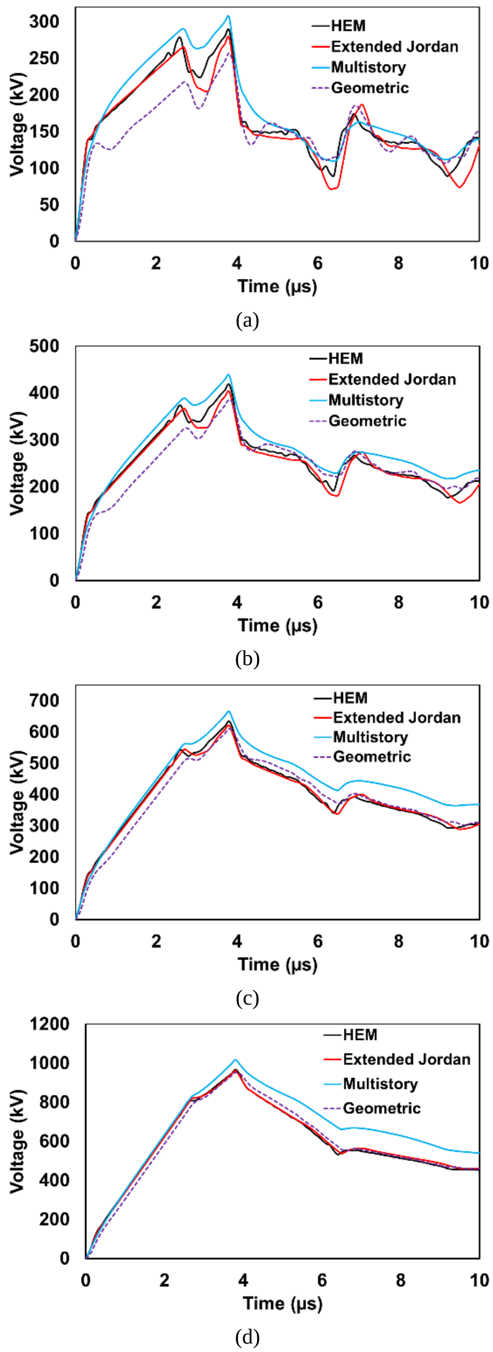

Fig. 7. Lightning overvoltages across the lateral insulator string of the 230-kV transmission line for different tower models. Tower-footing impedance Z_P: 10 Ω (a); 20 Ω (b); 40 Ω (c) and 80 Ω (d). [Ip = 31 kA, Td30 = 3.8 µs, T50 = 75 µs]. Geometric model assuming equations (2) and (3).

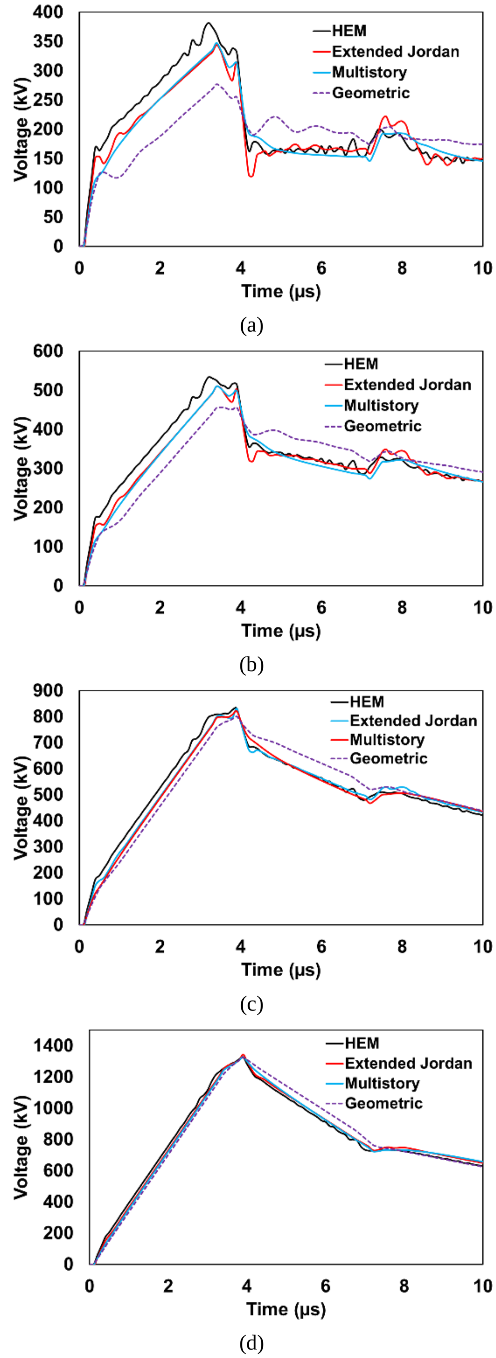

Fig. 8. Lightning overvoltages across the lower insulator string of the 500-kV transmission line for different tower models. Tower-footing impedance Z_P : 10 Ω (a); 20 Ω (b); 40 Ω (c) and 80 Ω (d). [Ip = 31 kA, Td30 = 3.8 µs, T50 = 75 µs]. Geometric model assuming equation (1).

In general, for grounding impedances greater than 20 Ω, the results of the simulated tower models converge to those provided by the HEM model.

Among the simulated models, the extended Jordan model is the one that leads to voltage waveforms closest to those provided by the reference model, HEM, considering the three simulated transmission lines. The geometric model also leads to accurate results when considering Z_P greater than 20 Ω for the 138-kV line and in the 40-to-80 Ω range for the 230- and 500-kV lines.

Another relevant aspect refers to the multistory tower model.

As noted from Figs. 6-8, the waveforms calculated with this model agree better with the reference model, HEM, for the 138- and the 500-kV towers. The results related to the 230-kV waist tower present larger differences in terms of voltage amplitudes. This is explained by the fact that the geometry of this tower is quite different from the one assumed by Ishii et al. [13] on developing the multistory model.

All points above have an impact on the line performance in terms of critical current and percentage of backflashover occurrence. Considering the voltages across the insulator strings and the application of the DE method, the critical currents I_C as function of tower-footing impedance were determined for each tower model. The results are presented in Tables I, II and III for the 138-, 230- and 500-kV lines, respectively, along with the probability of currents to exceed such critical currents $P(I \geq I_C)$ taking the IEEE cumulative peak current distribution of first strokes as reference. The results related to the overvoltages calculated by the HEM model are included for the sake of comparison.

TABLE I
CRITICAL CURRENT (I_C) AND BACKFLASHOVER PROBABILITY DEPENDING ON TOWER MODEL – 138-KV TRANSMISSION LINE

Z_P	Model	I_C (kA)	$P(I \geq I_C)$ %
10 Ω	HEM	90.12	5.9
	Extended Jordan	89.59	6.0
	Multistory	92.38	5.5
	Geometric	91.83	5.6
20 Ω	HEM	51.24	21.3
	Extended Jordan	52.43	20.3
	Multistory	52.99	19.9
	Geometric	52.05	20.6
40 Ω	HEM	30.62	50.8
	Extended Jordan	30.94	50.1
	Multistory	31.09	49.8
	Geometric	30.55	50.9
80 Ω	HEM	19.00	78.1
	Extended Jordan	18.98	78.1
	Multistory	19.02	78.1
	Geometric	18.78	78.6

TABLE II
CRITICAL CURRENT (I_C) AND BACKFLASHOVER PROBABILITY DEPENDING ON TOWER MODEL – 230-KV TRANSMISSION LINE

Z_P	Model	I_C (kA)	$P(I \geq I_C)$ %
10 Ω	HEM	193.48	0.9
	Extended Jordan	198.40	0.8
	Multistory	176.08	1.1
	Geometric	222.01	0.6
20 Ω	HEM	131.41	2.3
	Extended Jordan	134.85	2.1
	Multistory	122.45	2.7
	Geometric	137.95	2.0
40 Ω	HEM	83.81	7.0
	Extended Jordan	85.25	6.7
	Multistory	77.19	8.5
	Geometric	84.94	6.8
80 Ω	HEM	54.26	18.9
	Extended Jordan	54.56	18.7
	Multistory	49.91	22.5
	Geometric	54.25	18.9

Following the behavior observed for voltages waveforms, in general the critical currents and the probability of backflashover occurrence calculated with the different tower models become closer for increasing values of tower-footing grounding impedance.

The larger percentage difference in comparison with the critical currents related to the application of the HEM model occurs for the 500-kV tower with 10-Ω-grounding impedance. In this case, the modeling of such tower by the extended Jordan, geometric, and multistory models leaded to critical currents about 10%, 19%, and 9% larger. However, it is worth noting that such condition is related to very high critical currents with very low expectation of occurrence. So, it is reasonable to assume that the observed variation would not influence the estimated performance of the lines in terms of backflashover occurrence.

TABLE III
CRITICAL CURRENT (I_C) AND BACKFLASHOVER PROBABILITY DEPENDING ON TOWER MODEL – 500-KV TRANSMISSION LINE

Z_P	Model	I_C (kA)	$P(I \geq I_C)$ %
10 Ω	HEM	221.29	0.6
	Extended Jordan	242.78	0.5
	Multistory	242.18	0.5
	Geometric	262.52	0.4
20 Ω	HEM	147.61	1.7
	Extended Jordan	153.84	1.5
	Multistory	153.79	1.5
	Geometric	151.11	1.6
40 Ω	HEM	91.01	5.7
	Extended Jordan	92.12	5.6
	Multistory	92.36	5.5
	Geometric	89.65	5.9
80 Ω	HEM	57.27	16.9
	Extended Jordan	57.03	17.0
	Multistory	57.12	17.0
	Geometric	55.89	17.8

The obtained results show that the extended Jordan model leads to critical currents in good agreement with the ones obtained by the HEM model in all investigated cases. The best performance of such model is observed for the 138- and 500-kV tower configurations, which are characterized by almost vertical conductors. This type of tower geometry contributes to a better result of this model.

Results presented by the geometric models adopted in this work are as good as those provided by the extended Jordan model for tower-footing grounding impedance greater than 20 Ω, especially for the 138- and 230-kV transmission line towers. Such results indicate that, despite their simplicity, geometric models may lead to consistent results in evaluations of the lightning performance of transmission lines.

The multistory model leads to critical currents and corresponding backflashover probabilities very close to those obtained with the HEM model for 138-kV and, especially, for 500-kV transmission line towers. Also, in such cases the results are almost the same as those obtained by the extended Jordan model. However, this conclusion does not hold for the 230-kV line. The backflashover probability for the multistory model is about 20% higher than the one obtained by the HEM model. Considering the 230-kV waist tower, the application of the multistory model should be avoided, being recommended its use for modeling towers with geometric configuration similar to those of Fig. 5(c).

Additional simulations considering a lightning current waveform with median current parameters of subsequent negative lightning strokes [23] revealed results provided by the three evaluated tower models even closer to those related to HEM. However, for the conditions simulated in this work, it is important to note that the percentage of backflashover occurrence due to subsequent strokes is very low and does not influence the outage rate of those lines.

V. Conclusions

This paper assesses the influence of tower modeling on the backflashover occurrence on 138-, 230-, and 500-kV transmission lines using ATP. Three different tower models were implemented: geometric, multistory and the extended Jordan model. Voltages across line insulator strings, critical currents and percentage of backflashover occurrence related to each tower model are compared to those associated with the application of the Hybrid Electromagnetic Model.

Considering the three tower configurations assumed in this work, the analyses revealed that the extended Jordan model presents the best agreement with HEM for the simulated tower-footing impedances. This model is thus recommended for the evaluation of the lightning performance of transmission lines with such tower geometries using circuit-based calculation methods.

The application of the geometric model traditionally applied by CIGRE and IEEE procedures presented consistent results, especially for tower-footing grounding impedances greater than 20 Ω for the 138-kV tower and above 40 Ω for the 230- and 500-kV towers. Its use is also recommended for such cases.

The multistory model proved to be more sensitive to tower geometry, leading to better results when considering tower geometries similar to the one considered on its development, such as double circuit transmission towers with heights above 60 m. For the application of the multistory model to tower geometries such as the 138-kV and 230-kV towers assumed in this work, the adjustment of the surge impedance Z_i of each section is needed, following the computed response by electromagnetic models.

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