Modeling Guyed Towers of Transmission Lines in the Assessment of Backflashover Occurrence

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***Abstract*-- This paper evaluates the modeling of guyed towers of transmission lines in EMT-type programs to assess the backflashover occurrence of transmission lines and proposes a new modeling approach for this kind of towers. Two approaches to model the guyed towers by the revised Jordan model were evaluated: (i) the approach suggested by CIGRE Brochure 63 that represents the tower surge impedance as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling among them, and (ii) a new approach assuming the surge impedance of all the conductors in the tower section, guyed and mast conductors, and their mutual effect. The evaluations assumed the results provided by the Hybrid Electromagnetic Model (HEM) as reference for assessing the quality of the approaches. The approach (i) provided results of lightning overvoltage significantly lower than the reference, HEM model, leading to an underestimation of the probability of backflashover of the line. On the other hand, the approach (ii) was responsible for the results closest to those provided by HEM, indicating its quality, and the recommendation of applying this proposed approach for modeling guyed towers in the evaluations of backflashover occurrence.**

***Keywords*: Backflashover, Guyed towers, lightning performance of transmission lines, Tower modeling, Electromagnetic models, EMT-type programs.**

I. INTRODUCTION

THE assessment of the lightning performance of transmission lines (TLs) is of major importance to the protection engineering, since it provides elements that contribute to the development of protective measurements to adequate TL performance with the requirements demanded by the regulatory agencies.

Backflashover due to direct lightning strikes to grounded elements of the line is the main mechanism that governs lightning outages of transmission lines with voltage level up to 500 kV installed over moderate and high resistivity soils [1]. In this context, the resulting overvoltage across TL insulators is the key element to determine the occurrence of a backflashover.

Several parameters are capable to influence the resulting overvoltage across TL insulator strings, such as the transmission line elements, including the grounding system and the tower.

According with the physical characteristics of the tower, it may be classified as self-sustained tower and guyed tower. The latter is characterized by the presence of a central mast supported by four wires connected to the soil, as illustrated in Fig. 1. This peculiar configuration reduces the surge impedance of the tower and provides additional paths to the propagation of the lightning current to the ground, contributing to provide a better lightning performance in relation to those of self-sustained towers [2-4].

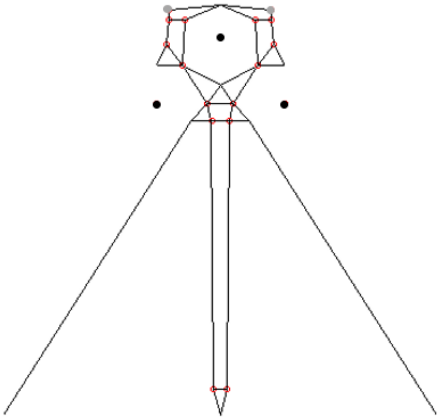

Fig. 1. Rough view of a transmission line guyed tower.

Several tower models are proposed in literature to be applied in electromagnetic transient (EMT)-type programs to assess the lightning performance of transmission lines [5-10]. However, such models are appropriate for self-sustained towers. In addition to the lack of tower models specifically to represent guyed towers, there are few references in literature of approaches to model this type of tower in EMT-type programs. CIGRE brochure 63 [2], for instance, suggests representing the tower surge impedance of guyed towers as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling among them. In spite of this recommendation, this type of approach has not been validated yet with results provided by electromagnetic field-based programs [11,12], which are more appropriate to model 3-D thin wire structures, since they directly represent the geometry and consider the electromagnetic coupling effects among all the conductors of the simulated system.

The purpose of this work is to assess the modeling of guyed

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towers of transmission lines in EMT-type simulations of backflashover occurrence, providing a quantitative evaluation of the quality of the CIGRE approach to represent guyed towers and proposing a new approach to model this type of towers based on the use of the revised Jordan formula [10]. The results provided by the two approaches in terms of voltage across insulator strings, critical current and the corresponding probability of backflashover are compared to those obtained with the application of the Hybrid Electromagnetic Model (HEM) [12], which is taken as reference.

II. COMMENTS ABOUT THE MODELING OF TRANSMISSION LINE TOWERS

In literature, transmission line tower models applied for evaluations of the lighting performance of transmission lines are commonly classified as geometric, multistory, and multiconductor models [13]. The quality of the results provided by the main tower models proposed in literature for assessing the backflashover occurrence for typical 138, 230 and 500 kV self-sustained towers is evaluated in [14], taking the results of the Hybrid Electromagnetic Model (HEM) as reference [12].

Geometric models assume the tower as a lossless single-phase transmission line with surge impedance of the solid whose geometry closely resembles tower configuration, such as cylinders, cones, and a combination of solids [5-7]. This type of modeling is very simple, but strongly dependent on the adopted geometrical approximation of the tower.

Multistory models assume the tower as a set of short sections composed by lossless single-phase transmission lines. The multistory model proposed by Ishii et al. [8] considers the tower divided 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. It was proposed based on measurements for 500-kV self-sustained double-circuit transmission lines towers with average height of around 60 m.

Multiconductor models also consider the tower divided into sections 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.

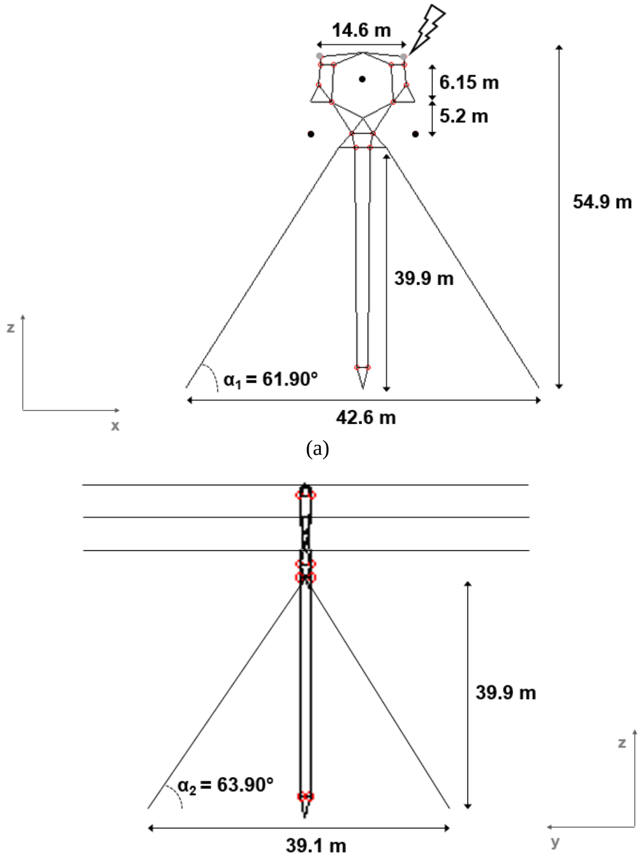
Based on the analysis of typical configurations of guyed towers, it is noted that geometric models and their associated solids would not be appropriate enough to reproduce the geometry and arrangements of guyed towers. Furthermore, the results presented in [14] for self-sustained towers indicated that this type of model is preferable applied for tower geometries that closely resembles the tower that originated the model proposed in [8]. According to [14], the revised Jordan model [10] that belongs to the multiconductor model type is responsible for the results closest to those provided by the Hybrid Electromagnetic Model (HEM) [12], for self-sustained towers modeling.

Since the geometry of guyed towers is characterized by a set of sections composed by several segments (the central mast and the guyed wires as slanted conductors), the use of the revised Jordan model seems to be a better option to model this kind of tower, mainly to represent the electromagnetic coupling among the mast and guyed wires in each section of the tower.

III. DEVELOPMENT

The results of this work are based on systematic computational simulations using ATP [15] to calculate lightning overvoltages across the insulator strings of the 500 kV TL guyed tower illustrated in Fig. 2, due to direct lightning strike to tower top. The tower is 54.9 m high and has two shield wires. The guyed wires are connected to the mast at height of 39.9 m.

The simulation assumed one stricken tower and two adjacent towers positioned at a distance of 530 m from the stricken tower. After the 530 m long span, a 10 km long section was assumed to avoid the effect of surge reflections. Shield wires and phase conductors with radii of 0.4 cm and 1.13 cm, respectively, were represented with the JMarti model [16]. The critical flashover overvoltage (CFO) of the TL is 1750 kV.



(a)

(b)

Fig. 2. Rough view of the transmission line guyed tower. Front view (a). Side view (b).

First-stroke grounding impulse impedance (Z_P) varying from 10 to 80 Ω was assumed to represent tower-footing as a concentrate circuit parameter. This representation leads to practically the same probability of backflashover obtained under the physical representation of grounding electrodes in electromagnetic-field based programs [17].

The lightning current waveform is represented by triangular current waveform with front time of 3.8 μs and tail time of

75 μs, following the median values of first stroke currents measured at Mount San Salvatore station [18]. In simulations, the front time is maintained as a constant parameter for peak current varying up to the occurrence of backflashover and the determination of the corresponding critical current. The adoption of this approach is supported by the sensitivity analysis developed in [19], that addressed the impact on the backflashover occurrence in transmission lines of two different assumptions for representing the front time of return-stroke currents, namely a constant parameter, set as the median Td30 front time, and a varying parameter, determined from expressions correlating the front time and the peak current. The results showed that the two methods of representing the current front time led to almost the same critical currents and, therefore, percentages of backflashover, mainly on the 1.5-to-10 μs range that most of current front time of first return stroke currents (5%-to- 95% probability of occurrence) varies.

The critical current (I_C), defined as the minimum value of lightning current able to lead line insulators to flashover, is assessed by means of the integration method, assuming the disruptive effect (DE) with model parameters proposed by A.R. Hileman in [20]. The probability of backflashover is determined as the percentage of currents that exceeds the critical current in the CIGRE two-slope cumulative probability distribution of peak current of first negative strokes [2].

In this work, the guyed tower is modeled following the revised Jordan model, applying equations (1)-(3) to calculate the self (Z_{ii}), mutual (Z_{ij}) and the equivalent surge impedance (Z_S) of each tower section. In equations, h, r, d, and n are, respectively the height, radius, distance, and number of conductors in the tower section.

$$Z_{ii} = 60 \cdot \ln\left(\frac{4 \cdot h}{r}\right) - 60 \tag{1}$$

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

$$Z_S = \frac{Z_{ii} + Z_{ij} + \cdots + Z_{in}}{n} \tag{3}$$

Two approaches were assumed to model the guyed tower:

(i) the approach proposed by CIGRE brochure 63 [2] that suggests representing the tower surge impedance of guyed towers as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling among them. Fig. 3 illustrates the circuit model of the guyed tower following CIGRE approach;

(ii) the new approach proposed in this work that considers the mutual coupling among the mast and guyed wires in each section of the tower. Fig. 4 shows the circuit model related to this proposed approach.

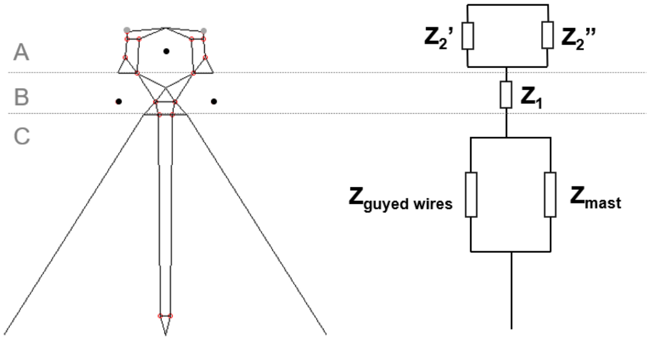


Fig. 3. Representation of the circuit model of the guyed tower by the revised Jordan model, assuming the approach suggested by CIGRE brochure 63 [2].

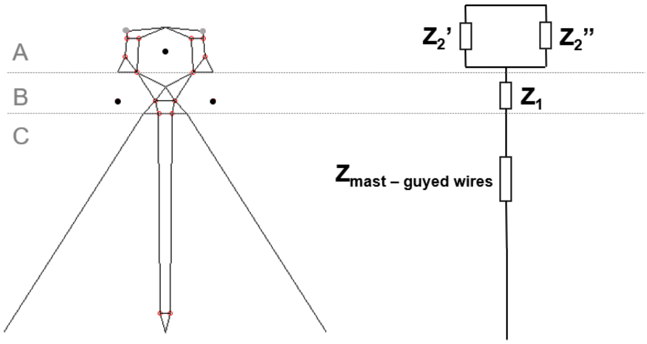


Fig. 4. Representation of the circuit model of the guyed tower by the revised Jordan model, assuming the proposed approach that considers the mutual coupling among mast and guyed wires for each tower section. Tower modeling assumes the tower divided into parts A, B, and C.

Considering the tower dimensions indicated in Fig. 2, the revised Jordan model was applied to calculate the surge impedance of each section of the guyed tower according to equations (1)-(3) and considering approaches (i) (proposed by CIGRE brochure 63 [2] and illustrated in Fig. 3) and (ii) (proposed in this paper and illustrated in Fig. 4) for guyed tower modeling. In this work, the tower is divided into parts A, B, and C, as illustrated in Figs. 3 and 4. The number of sections of each part is a decision of the user. In the simulated case, it was assumed one section for part A, one section for part B and three sections for part C. Since Part C has the longer length and is composed by the mast and the guyed wires, more sections are needed to improve the quality of tower modelling. The surge impedances of each section are calculated assuming equations (1)-(3) and the obtained values are summarized in Table I for each approach. It is worth noting that both approaches present the same values for impedances Z_1, Z_2' and Z_2" since they correspond to the region of the tower that is equally modeled by both approaches. The only difference between the modeling approaches resides on the tower section that contains the guyed wires.

The results provided by the electromagnetic field-based model HEM were taken as reference to assess the quality of the two approaches to model guyed towers in EMT-type programs.

The power-frequency voltage effect was not considered in simulations in order to maintain the focus of the work only on the influence of the modeling approaches of guyed towers of transmission lines. Since this effect is the same for both tower modeling approaches, the quality of the results is not affected. Details about the influence of the power-frequency voltage effect on the assessment of the lightning performance of transmission lines are presented in [21].

TABLE I
SURGE IMPEDANCE OF EACH TOWER SECTION CALCULATED BY THE APPLICATION OF THE REVISED JORDAN MODEL CONSIDERING APPROACHES (I) AND (II) FOR GUYED TOWER MODELING

Approach (i)		Approach (ii)	
Z_{mast}	988.77 Ω	$Z_{mast\text{-}guyed\ wires}$	807.30 Ω
$Z_{guyed\ wires}$	130.17 Ω		
Z_1	238.70 Ω	Z_1	238.70 Ω
Z_2’	1158.00 Ω	Z_2’	1158.00 Ω
Z_2”	1158.00 Ω	Z_2”	1158.00 Ω

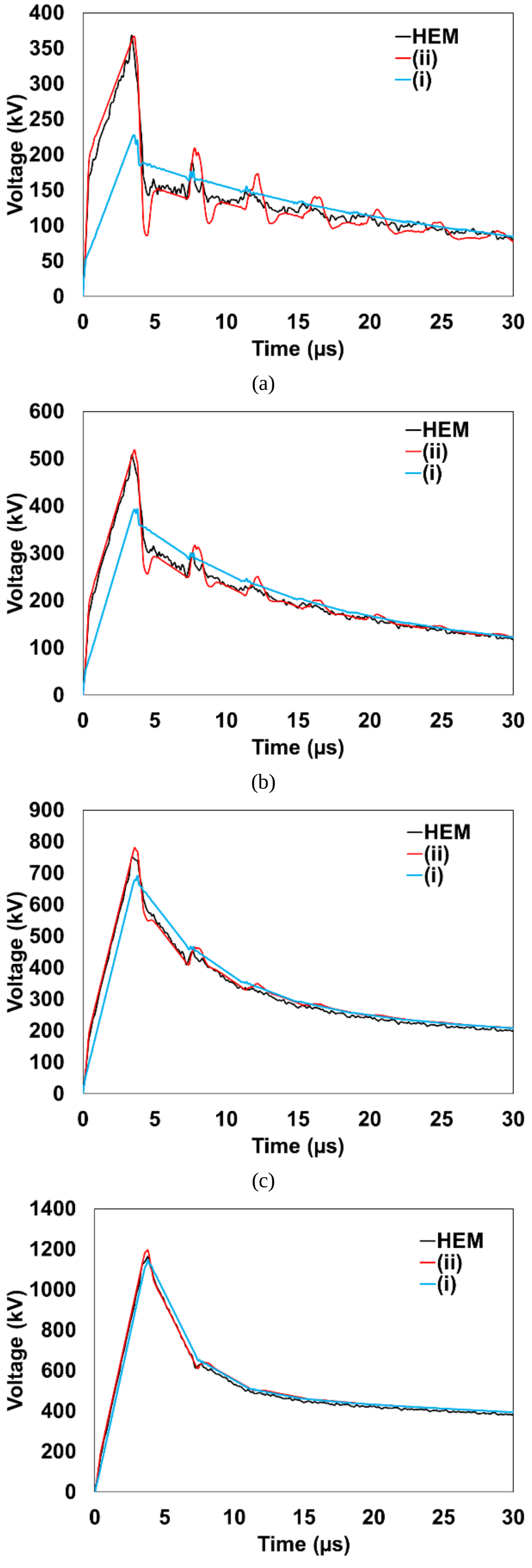
IV. RESULTS AND ANALYSIS

A. *Lightning overvoltages across insulator strings*

Figs. 5 to 7 illustrate the resulting overvoltage developed across the right, central and left insulator strings of the simulated 500 kV transmission line guyed tower as function of tower-footing grounding impedance Zp varying from 10 to 80 Ω, considering a 31 kA peak and 3.8 µs front time, triangular current waveform assumed to be injected at tower top. The results related to the CIGRE approach (i) are presented as solid blue lines, whereas the results related to the proposed approach are presented as solid red lines. For the sake of comparison, the overvoltage waveforms obtained by the HEM model are also included in the figures and are presented as black solid lines.

The results indicated that the overvoltages obtained by the approach suggested by CIGRE brochure 63 (i) are significantly lower than the reference results provided by HEM for tower-footing grounding impedance of 40 Ω and lower. Only for 80 Ω grounding impedance, the obtained overvoltages are closer to the one of the HEM model. However, as discussed in [14], for increasing values of grounding impedance, the grounding potential rise (GPR) increases, and the influence of the tower to establish the overvoltage across TL insulators decreases, diminishing the importance of the model of the tower.

On the other hand, the approach herein proposed to model guyed towers (ii) leaded to accurate overvoltages in relation to HEM’s results for all simulated cases, even those related to lower values of tower-footing impedance, denoting the quality of the proposed approach.



(a)

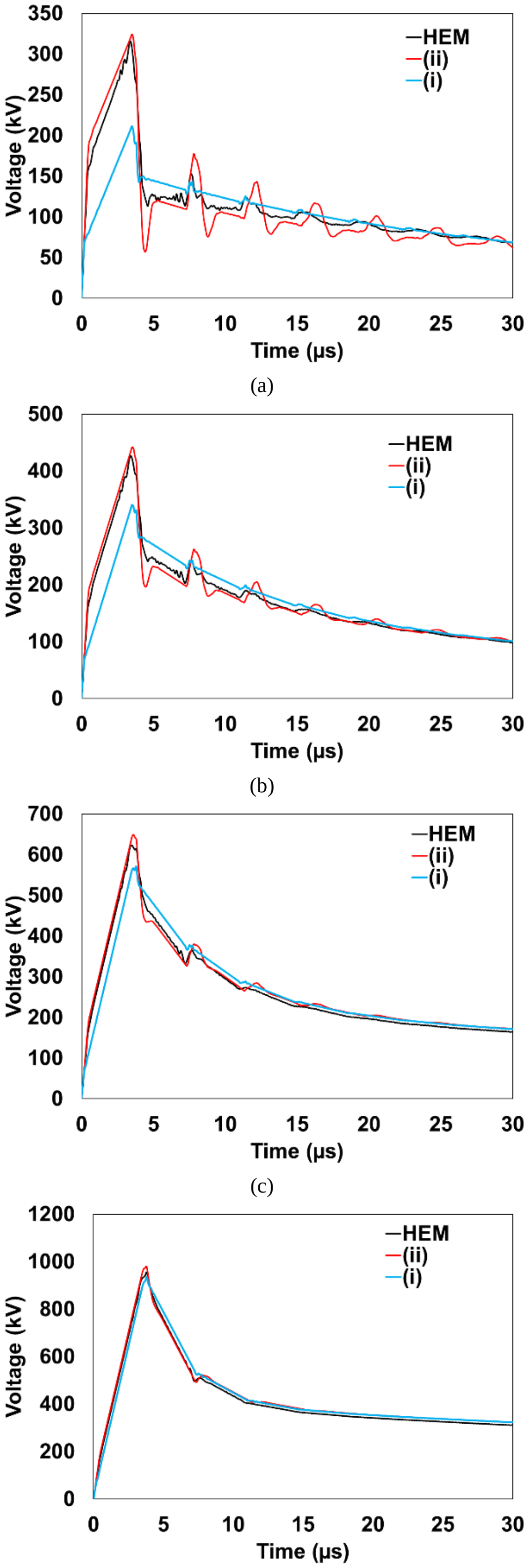
(b)

(c)

(d)

Fig. 5. Lightning overvoltage across the right insulator string of the guyed tower. Overvoltages obtained by HEM (black solid line), approach (i) (tower surge impedance of guyed towers as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling between them - blue solid line) and approach (ii) (tower surge impedance of guyed towers as the combined surge impedance mast-guyed wire considering the mutual coupling among the elements of each section of the tower - red solid line). Simulated lightning current: 31 kA peak and 3.8 µs front time, triangular waveform. TL span: 530 m. Tower-footing grounding impedance (Z_P) of 10 Ω

(a), 20 Ω (b), 40 Ω (c) and 80 Ω (d).



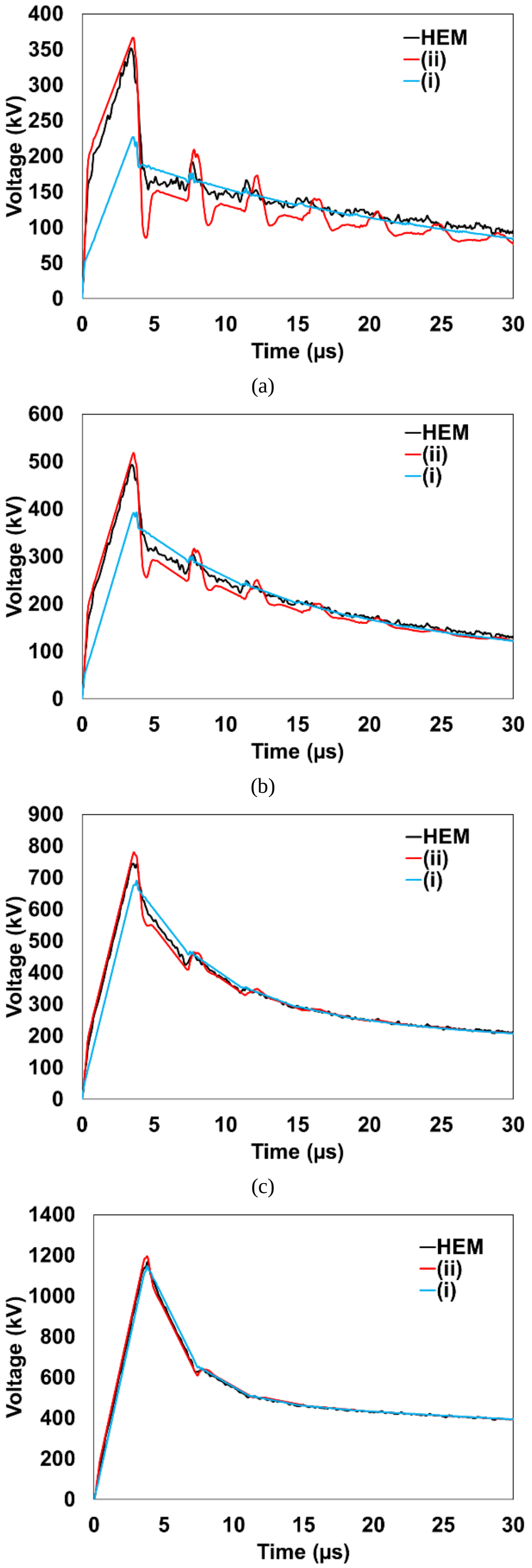
(a)

(b)

(c)

(d)

Fig. 6. Lightning overvoltage across the central insulator string of the guyed tower. Overvoltages obtained by HEM (black solid line), approach (i) (tower surge impedance of guyed towers as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling between them - blue solid line) and approach (ii) (tower surge impedance of guyed towers as the combined surge impedance mast-guyed wire considering the mutual coupling among the elements of each section of the tower - red solid line). Simulated lightning current: 31 kA peak and 3.8 µs front time, triangular waveform. TL span: 530 m. Tower-footing grounding impedance (Z_P) of 10 Ω (a), 20 Ω (b), 40 Ω (c) and 80 Ω (d).



(a)

(b)

(c)

(d)

Fig. 7. Lightning overvoltage across the left insulator string of the guyed tower. Overvoltages obtained by HEM (black solid line), approach (i) (tower surge impedance of guyed towers as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling between them - blue solid line) and approach (ii) (tower surge impedance of guyed towers as the combined surge impedance mast-guyed wire considering the mutual coupling

among the elements of each section of the tower - red solid line). Simulated lightning current: 31 kA peak and 3.8 µs front time, triangular waveform. TL span: 530 m. Tower-footing grounding impedance (Z_P) of 10 Ω (a), 20 Ω (b), 40 Ω (c) and 80 Ω (d).

B. *Assessing the lightning performance*

The results of critical current (I_C) and backflashover probability related to the two approaches to model guyed towers by the revised Jordan model are presented in Table II, along with the reference results of the HEM model.

TABLE II
Critical current I_C and probability of backflashover occurrence for the evaluated approaches to model guyed towers.

Right insulator string								
Z_P (Ω)	HEM model		(i)		P^I_{Hem} %	(ii)		P^{II}_{Hem} %
	I_C (kA)	$P(I \geq I_C)$ %	I_C (kA)	$P(I \geq I_C)$ %		I_C (kA)	$P(I \geq I_C)$ %	
10	233	0.06	305	0.01	80.2	222	0.09	34.9
20	163	0.43	174	0.31	27.8	161	0.45	4.4
40	102	3.15	103	3.07	2.6	102	3.19	1.3
80	65	13.4	64	13.7	2.5	65	13.7	2.3
Central insulator string								
Z_P (Ω)	HEM model		(i)		P^I_{Hem} %	(ii)		P^{II}_{Hem} %
	I_C (kA)	$P(I \geq I_C)$ %	I_C (kA)	$P(I \geq I_C)$ %		I_C (kA)	$P(I \geq I_C)$ %	
10	264	0.03	363	0.00	87.3	248	0.05	46.1
20	193	0.18	212	0.11	39.2	189	0.20	11.0
40	124	1.46	127	1.34	7.7	124	1.47	0.6
80	80	7.4	79	7.5	0.7	79	7.5	1.5
Left insulator string								
Z_P (Ω)	HEM model		(i)		P^I_{Hem} %	(ii)		P^{II}_{Hem} %
	I_C (kA)	$P(I \geq I_C)$ %	I_C (kA)	$P(I \geq I_C)$ %		I_C (kA)	$P(I \geq I_C)$ %	
10	236	0.06	304	0.01	78.9	222	0.09	42.6
20	161	0.46	174	0.31	31.2	161	0.45	0.7
40	101	3.26	103	3.07	5.8	102	3.2	2.1
80	64	13.56	64	13.70	1.0	64	13.67	0.8

P^I_{Hem}: Percentage difference between the backflashover probability calculated by approach (i) and HEM model.
P^{II}_{Hem}: Percentage difference between approach (ii) and HEM model.

The results of Table II confirm the ones presented by the overvoltage waveforms. The critical current and backflashover probability calculated for the approach (ii) leads to results closer to the ones obtained by the HEM model. The percentage difference is in the range of 46%-to-0.6%, being the largest percentage difference observed related for a very low backflashover probability of 0.05%, and such difference is meaningless in terms of the TL performance.

The approach (i) suggested by CIGRE brochure 63 resulted in backflashover probability always lower than the HEM model, in the range of 87-to-0.7%, the results obtained by (i) not only present larger percentage differences, but also the differences correspond to lower backflashover probabilities, meaning that the use of this approach to model guyed towers would underestimate the lightning performance of the transmission, and its application should be avoided.

V. Conclusion

Guyed towers are frequently used in transmission lines, especially for those of high voltage level. The modeling of this kind of tower for computational evaluations of the lightning performance of transmission lines is a topic that still deserves developments. Models based on circuit parameters for guyed towers are of interest for this type of study and may be applied in EMT-type programs.

The revised Jordan model presents capabilities that indicated its use for model guyed towers by considering a set of surge impedance of tower sections. Two approaches for model guyed tower by the revised Jordan model were investigated: (i) the approach suggested by CIGRE brochure 63 that considers the tower surge impedance as the parallel of the surge impedances of the mast and the guyed wires, disregarding the mutual coupling among them; (ii) a new approach proposed in this work that considers the mutual coupling among all the conductors of the mast and the guyed wires in each tower section.

The obtained results of lightning overvoltage, critical current and backflashover probability indicate that the proposed approach of considering the mutual impedance between the mast and guyed conductors (ii) leads to almost the same results obtained by the HEM model in all simulated cases. This approach is thus recommended to be applied on the modeling of guyed towers of transmission lines by means of EMT-type programs. For cases of intermediate grounding impedance (20 Ω), the percentage difference in terms of the probability of backflashover occurrence was not greater than 11%.

On the other hand, the approach proposed by CIGRE brochure 63 leaded to underestimate probabilities of backflashover, mainly for intermediate and low grounding impedance values, and should be avoided for this kind of assessment.

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