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On the Effect of Current Front Time Representations on Evaluations of Backflashover Rate of Transmission Lines considering Deterministic and Probabilistic Approaches

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***Abstract*—This work presents an investigation on how current front time representation affects the evaluation of backflashover occurrence of transmission lines considering deterministic and probabilistic approaches. Representations assuming front time as a constant value equal to typical median Td30 of 3.8 μs and the correlation of this parameter with peak current are considered. Simulations assuming the deterministic approach HEM-DE and the probabilistic approach ATP-DE-MC with Monte Carlo method were developed taking as reference a typical 138-kV and 400-m span line configuration. The results obtained by both calculation procedures revealed BFOR probabilities estimated by the use of the median Td30 very close to those obtained by current front time represented as a correlated parameter, even when considering the application of Monte Carlo method. This behavior reinforces the consistence of the application of a constant front time equal to the median Td30, leading to the recommendation of the use of this kind of representation in computational analysis of the lightning performance of transmission lines.**

Keywords— Backflashover, Current front time, Deterministic and probabilistic methodologies, Lightning performance of transmission lines.

I. INTRODUCTION

The assessment of the lightning performance of transmission lines in terms of backflashover occurrence follows a common procedure comprising several articulated steps related to 1) modeling of line components (such as aerial conductors, tower, insulator strings, grounding, etc.), 2) definition of the lightning return stroke current assumed to be impressed on the transmission line (considering current waveform and parameters such as peak, front time and time-to-half value), 3) calculation of the resulting overvoltage across line insulator strings, 4) application of a flashover criterion to assess if the simulated event leads (or not) the insulator to flashover, and 5) estimation of the critical peak current and its probability of occurrence. The backflashover outage rate (BFOR) is estimated as the product of this percentage by the expected number of lightning strikes to the line [1].

In the past, CIGRE [2] and IEEE [3] proposed analytical approaches to be applied on the calculation of the lightning performance of transmission lines that have become very traditional. More recently, approaches based on the use of circuit-based modeling [4,5] and electromagnetic-field-based modeling [6,7] have been considered to calculate the overvoltages across line insulator strings. Also, the application of accurate flashover criteria [1,8] to assess backflashover occurrence has been a trend.

Several definitions related to transmission line modeling and the representation of the lightning return stroke current may affect the estimated lightning performance of the evaluated line. Concerning the latter, definitions in terms of current waveform and front time parameters directly affects the resulting overvoltage across line insulator strings. The balance between such overvoltage and line insulation withstand is what determines the lightning performance of transmission lines.

In literature, it is common the application of linearly rising current waveforms, such as the triangular waveform, on lightning performance evaluations, following the recommendation by CIGRE and IEEE [2,3] to reproduce an average front behavior. Recently, improved representations considering the wavefront concavity observed in first return stroke current measured waveforms have been also adopted, such as the CIGRE-concave [2] and Double-peaked [9] waveforms.

The investigation presented in [10] revealed that the influence of current waveform on the resulting backflashover rate is flashover model dependent. The consideration of linearly rising or concave wavefront profiles leads to similar BFOR when the Disruptive Effect and Leader Progression models are assumed as flashover criteria, for analyses assuming direct strikes to the tower.

One relevant aspect that may influence the estimating BFOR concerns the definition of the current front time and how it varies with peak current. According to the statistics developed from Berger's measurement at Mount San Salvatore, most of current front time of first return stroke currents (5%-to-95% probability of occurrence) varies in the 1.5-to-10 μs with a median value of 3.8 μs [11].

Fig. 1 presents calculated overvoltages across insulator string of a 138-kV transmission line for distinct current front time Td30 of a 31-kA-peak-triangular current, indicating the significantly impact of this parameter on the results. However, it

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is worth noting that, in practice, it is expected longer front time to be associated with larger peak currents. This trend is supposed to affect the resulting overvoltages, and, consequently, the estimated BFOR.

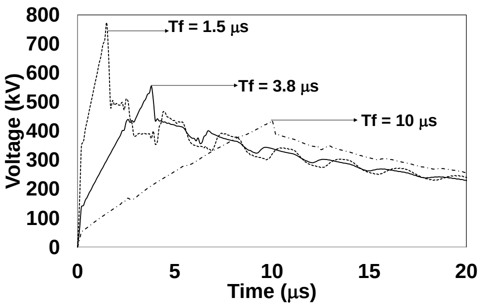


Fig. 1. Effect of varying current front time on resulting overvoltage across the insulator string of a 138-kV transmission line with adjacent towers. Tower-footing grounding impedance (Zp) of 20 Ω. Simulated current waveform: Triangular, Ip = 31 kA, Td30 front time varying from 1.5 to 10 μs.

Deterministic approaches to estimate BFOR of transmission lines commonly assumes front time constant [11] for peak current varying up the flashover condition is reached. On the other hand, probabilistic approaches based on Monte Carlo method [12] are appropriate to consider the correlation between front time and peak current observed in measured currents according to well-stablished expressions.

The aim of this work is to exam how the representation of current front time may influence the assessment of backflashover occurrence of transmission lines considering deterministic and probabilistic approaches to represent front time as an independent parameter and as a parameter correlated to the peak current, giving elements to delimit the application of each method of representation.

The application of the HEM-DE (deterministic) and ATP-DE-MC (probabilistic) methodologies are considered. Both methodologies assume Disruptive Effect (DE) method [8] to assess backflashover occurrence. The resulting overvoltages across line insulator strings are calculated by means of the Hybrid Electromagnetic Model (HEM) [13] and the Alternative Transient Program (ATP) [14], respectively. MC stands for Monte Carlo method.

Simulations considered a typical configuration of a 138-kV single circuit transmission line, including adjacent towers, as case study, for distinct values of tower-footing grounding impedance. The obtained backflashover probabilities are related to the CIGRE cumulative peak current distribution of first strokes [2].

II. Traditional Lightning Return Stroke Current Parameters for Lightning Performance Evaluation of Transmission Lines

Traditionally, lightning protection standards suggest the use of first return stroke current parameters of negative cloud-to-ground lightning in lightning performance studies of transmission lines. Also, they recommend the use of lightning current parameters derived from the measurements at Mount San Salvatore station, since it is considered the most complete database obtained in instrumented towers installed in temperate regions, comprising 101 first strokes measured events.

According to [15], lightning protection standards commonly adopt two main 'global' distributions of lightning peak currents for negative first strokes: the CIGRE and IEEE distributions, as illustrated in Fig. 2. To constitute such global distributions, Berger's data is complemented by some current measurements obtained in different countries.

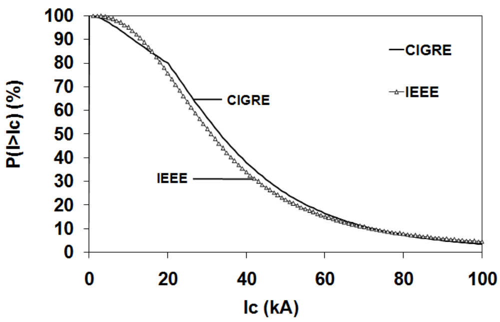


Fig. 2. Traditional cumulative first stroke current distribution: CIGRE and IEEE.

Also considering lightning return stroke current measurements in temperate regions, current parameters obtained from 120 measured negative first return stroke currents of direct strikes to transmission towers in Japan from 1994 to 2004 were recently published by Takami and Okabe [16]. The median peak current of 31 kA and Td30 front time parameter of 3.8 μs of Berger's measurement are also obtained from Takami and Okabe measurements, as denoted in [16].

Several correlation expressions among lightning return stroke current parameters are presented in literature [2,11,15,16]. In this work, the correlation expressions relating peak current and current front time of first stroke currents proposed in [2,16] are considered. They are described next, where Ip and Tf stands for the peak current in kA, and the front time in μs.

$$Tf = 0.906 * Ip^{0.411} \quad (Ip > 20\ A) \quad [2] \tag{1}$$

$$Tf = 1.39 * Ip^{0.25} \quad [16] \tag{2}$$

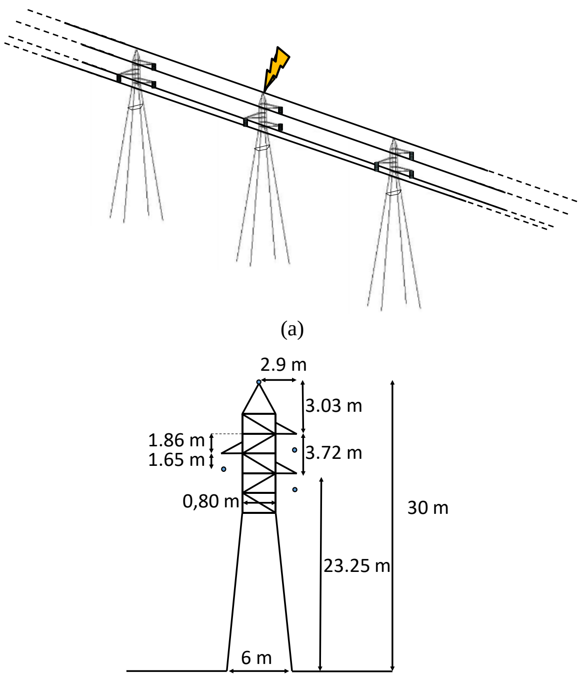
III. Developments

A. Simulated system

The computational simulations developed in this work considered a typical configuration of a 138-kV transmission line as case study. The 400-m span length reference line is composed by self-sustained towers with average height of 30 m with a single shield wire and a nonuniform arrangement of phase conductors. The line has a critical flashover overvoltage (CFO) of 650 kV. Fig. 3 illustrates the simulated system and a rough view of the tower.

Tower-footing electrodes were represented as first-stroke impulse grounding impedances Zp_{1st} [17], varying from 10 to 40 Ω. The use of this simplified representation of grounding is supported by the analyses provided in [18] that demonstrate that considering the impulse impedance as a concise representation of tower-footing electrodes yields practically the same backflashover rate obtained under the physical representation of grounding electrodes.

All the analyses refer to direct strike at tower top and the resulting performance of the stricken tower as function of the assumed tower-footing impulse impedance Zp. The triangular current representation was assumed as the lightning current waveform.



(b)

Fig. 3. Simulated system: 138-kV-and-400-m span transmission line (a), Rough view of the simulated tower (b).

B. Implemented approaches

Computational simulations were developed assuming both deterministic and probabilistic approaches, named as HEM-DE and ATP-DE-MC, respectively. Both procedures assess backflashover occurrence by means of the Disruptive Effect (DE) method [8].

The deterministic approach HEM-DE adopts the Hybrid Electromagnetic Model (HEM) [13] to calculate the resulting lightning overvoltage across line insulator strings. The HEM model is an electromagnetic model traditionally applied for lightning performance evaluations of transmission lines [1,6,10,13] that models the simulated physical system directly from the geometry of the problem and the constitutive parameters of the media. The solution automatically takes into account the electromagnetic coupling between all system elements as well as propagation effects.

The probabilistic approach considers the Alternative Transient Program (ATP) [14] in the calculation of overvoltages across line insulators. Shield wire and phase conductors are represented assuming JMarti model [19] following cables location indicated in Fig. 3. Tower modeling assumes transmission line representation and the adoption of the modeling proposed in [20], that consists of using the revised Jordan's formula to calculate surge impedance for vertical multiconductor systems.

A Monte Carlo procedure [12] is implemented in MATLAB and interfaced with ATP in order to provide current peak and front time parameters to be simulated following a triangular current waveform representation. In the MATLAB environment, random numbers are generated to define peak current according to the probability distribution function presented in [2]. Front time for each event is determined following correlation expressions (1) and (2). Those lightning current parameters are used by ATP to calculate voltages across line insulator strings. Each event that leads insulator to flashover increases the MATLAB counter in order to determine the backflashover probability of the line.

IV. Results and Analysis

A. Deterministic approach: HEM-DE methodology

Results calculated by the HEM-DE methodology in terms of critical current and the probability of backflashover occurrence as function of tower-footing grounding impedance for constant front time assumed as the median Td30 of 3.8 μs are summarized in Table I. As expected, backflashover probability diminishes for decreasing grounding impedance.

TABLE I. Critical Currents and associated probability of Backflashover Occurrence for a Constante Front Time (T_{D30} = 3.8 μs).

Zp (Ω)	Critical current Ic (kA)	%I >Ic
10	83.7	7.03
20	50.5	21.9
40	31	54.7

In order to check the influence of current front time variation on the resulting performance of the line, additional simulations considering the injection of the triangular current waveform at tower top for current front time varying in the 1-to-10-μs range was performed. For each chosen current front time, the corresponding voltages across insulators, the critical currents and the backflashover probability were determined.

Figs. 4 and 5 illustrate the resulting critical current and backflashover probability as function of the front time, considering different tower-footing impedances. The results corresponding to the 3.8-μs front time are indicated by a black circle in each curve for the sake of comparison.

The obtained results show critical currents varying from 61.7 to 92.1 kA, 42.8 to 55.2 kA, and 27.6 to 36.3 kA in the 1-to-10 μs range for tower-footing grounding impedance of 10, 20, and 40 Ω, respectively. In terms of backflashover probability, the corresponding percentage ranges are 15.4% to 4.6%, 33.9% to 20.2%, and 62.2% to 44.4%. However, it is important to note that the extreme points of the current front time range have very low expected frequency of occurrence, and so the events related to such condition. With this perspective, it is worthen to consider the correlation between current front time and peak current to avoid assuming lightning current events that are not expected to occur in fact. If such correlation is considered, part of the curves illustrated on the graphics would not be valid, mainly for those cases related to very low front time and large peak current. Fig. 6 denotes such analysis.

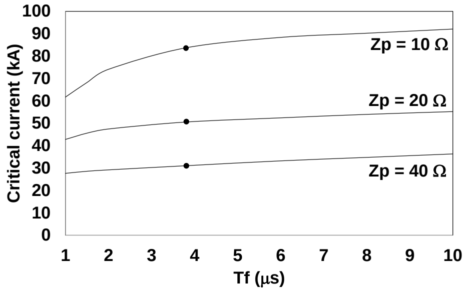


Fig. 4. Critical current (Ic) as function of the current front time calculated assuming the independent variation of such parameter.

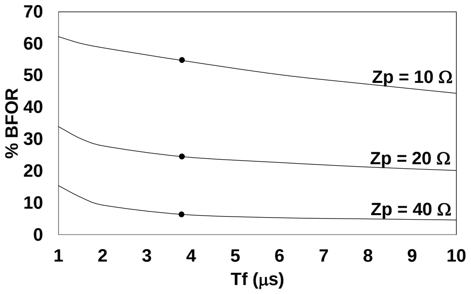


Fig. 5. Percentage of backflashover occurrence in the stricken tower as function of the current front time calculated assuming the independent variation of such parameter.

The intersection points of the curve given by expressions (1) and (2) with the critical current curves for each tower-footing grounding impedance, indicated as square and triangular symbols, respectively, indicate the minimum peak current able to lead the insulators to flashover. For the sake of comparison, the critical currents corresponding to the 3.8-µs front time are indicated by a black circle. As can be noted, critical currents assuming correlated parameters are very close to those obtained following the representation of constant value equal to the median Td30, and so the expectation of backflashover occurrence. The obtained results in terms of critical currents and backflashover probability for both current front time representation are summarized in Tables II and III.

Considering correlation expression (1) and (2), only currents larger than about 85, 51, and 31 kA are expected to lead line insulator to flashover, for Zp in the 10-to-40 Ω range. Such currents are related to front time values about 4.2-to-3.3 µs and 5.7-to-3.7 µs, both intervals very close to the median 3.8 µs.

This behavior corroborates the quality of using a constant front time as the Td30 median front time in evaluations of backflashover occurrence for deterministic approaches.

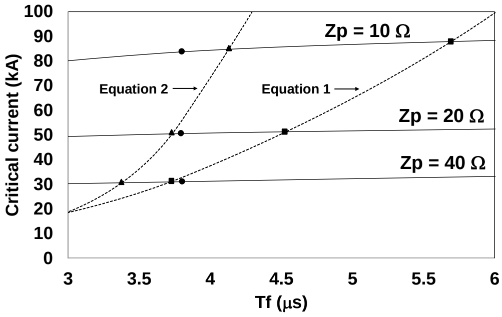


Fig. 6. Critical current as function of Td30 front time following correlation expressions (1) and (2) for triangular current representation as function of tower-footing grounding impedance.

TABLE II. CRITICAL CURRENTS ESTIMATED BY CONSTANTE FRONT TIME (TD30 = 3.8 µS) AND ASSUMING CORRELATION EXPRESSIONS (1) AND (2).

Zp (Ω)	Critical current Ic (kA)		
	Median front time 3.8 µs	Correlated front time Eq. (1)	Correlated front time Eq. (2)
10	83.7	84.5	88
20	50.5	50.5	51
40	31	30.5	31

TABLE III. BACKFLASHOVER PROBABILITY OF THE 138-KV LINE UNDER THE ASSUMPTIONS OF CONSTANT AND CORRELATED FRONT TIME: DETERMINISTIC APPROACH.

Zp (Ω)	BFOR (%)		
	Median front time 3.8 µs	Correlated front time Eq. (1)	Correlated front time Eq. (2)
10	7.03	6.2	5.4
20	21.9	24.6	24.1
40	54.7	55.8	54.7

B. *Probabilistic approach: ATP-DE-MC methodology*

The ATP-DE-MC methodology was applied considering two different scenarios in terms of current front time representation: (i) Monte Carlo method generating current events with a constant front time of 3.8 µs, and (ii) Monte Carlo method generating events considering correlation expressions (1) and (2). The probability of backflashover occurrence is obtained from the relation between the number of events that leaded the insulators to flashover and the total number of events. Table IV summarizes the results in terms of backflashover probability.

TABLE IV. BACKFLASHOVER PROBABILITY OF THE 138-KV LINE UNDER THE ASSUMPTIONS OF CONSTANT AND CORRELATED FRONT TIME: PROBABILISTIC APPROACH.

Zp (Ω)	BFOR (%)		
	Median front time 3.8 µs	Correlated front time Eq. (1)	Correlated front time Eq. (2)
10	5.3	4.6	5
20	23.8	23.3	23.9
40	56.3	57.2	57.6

The obtained results show the agreement between BFOR estimated considering both scenarios of current front time representation when applying a probabilistic approach, confirming the behavior presented in section IV-A for a deterministic approach.

The larger percentage variation consists of the 10-Ω-grounding impedance case that presented BFOR differences about 13% and 6% in relation to the result assuming median current front time. However, it is important to note that such comparison is related to very low BFOR, of the order of 5%, and thus it has low contribution on the total backflashover rate of the line, in comparison to the contribution to those towers with larger grounding impedance. So, the effect of this variation tends to be negligible. The comparison for 20 and 40 Ω grounding impedance reveals even lower differences of the order of just 1%-to-2%.

This set of results reinforces the use of the median Td30 current front time as a consistent representation in computational evaluations of backflashover occurrence even for those following probabilistic approaches.

V. Conclusions

This work examined how current front time representation affects the assessment of backflashover expectation of transmission lines considering deterministic and probabilistic approaches. The analyses involved the representation of the front time as a constant value equal to typical median Td30 of 3.8 μs and the adoption of correlation expressions between front time and peak current.

Simulations considering the deterministic approach HEM-DE and the probabilistic approach ATP-DE-MC were developed taking as reference a typical 138-kV and 400-m span line configuration.

The application of both methodologies revealed very close BFOR probabilities related to the two methods of current front time representation, reinforcing the quality of the approach that represents current front time by the median Td30.

Such conclusion is valuable for computational analysis of the lightning performance of transmission lines, even for those based on probabilistic approach. The recommendation of the use of median Td30 front time leads to consistent results and contributes to decrease the computational effort to be applied in such evaluations.

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