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Calculation of the Lightning Performance of Transmission Lines: A Study of the Impact of Current Waveform and Front Time

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***Abstract*—This work presents a contribution on the effect of return stroke current representation and associated front time on the calculation of the lightning performance of transmission lines. Two types of current wavefront representations were considered: linearly rising wavefront (triangular waveform) and concave wavefront (double-peaked waveform). Sensitivity analyses were developed by means of computational simulations using the Hybrid Electromagnetic Model (HEM) to calculate overvoltages across the insulator strings of a high-voltage transmission line and the Disruptive Effect Model (DE) to assess the flashover condition of such insulators. The results indicated larger outage rate by adopting the linearly rising wavefront. Also, it was shown that the variation of the current front time for the double-peaked current representation practically does not affect the resulting outage rate, in comparison to the results calculated assuming the variation of the current front time.**

Keywords - backflashover, current waveform, front time, lightning performance of transmission lines.

I. INTRODUCTION

The calculation procedure of the lightning outage rate of high-voltage transmission lines involves the definition of several parameters related to the transmission line itself (geometrical configuration, span length, critical flashover overvoltage, arrangement of tower-footing grounding electrodes, etc.), soil characteristics (soil resistivity and permittivity), and to the lightning return stroke current (waveform and front-time parameters).

Due to the complexity involved in the definition of such quantities, it is common the adoption of some simplifications on the calculation procedure. One aspect that is usually simplified concerns the representation of the return stroke current.

In spite of the knowledge of the typical features of measured first stroke current waveforms, such as the pronounced initial concavity followed by an abrupt rise around the half peak and, the presence of subsidiary peaks [1,2], as illustrated in Figure 1, the calculation of the lightning performance of transmission lines is commonly performed considering linearly rising current waveforms. Since the current representation influences directly the resulting overvoltage across insulator strings, such simplification has potential to affect the calculated outage rate.

Furthermore, the definition of the current front time to be simulated is a topic under continuous discussion in the literature. Some references consider the current front time given by the relation between the current peak and the maximum wavefront steepness, as suggested by Anderson [3]. Such approach is closely related with the use of linearly rising wavefront representation. Other works claim to reproduce all wavefront median parameters in the current wave, resulting on the use of concave wavefront representation [4-6]. Following this context, the aim of this work is to present a study of the effect of both current waveform and front time on the calculated outage rate of a high voltage transmission line in terms of backflashover occurrence, considering linearly rising and concave wavefront current representations.

II. DEVELOPMENTS

A. Analytical representations of first stroke current waveforms

As it is extensively presented in the literature, measurements of first return stroke current waveforms indicate the existence of two important features: the concave profile at the wavefront and the presence of subsidiary peaks after the first peak. Figure 1 illustrates current waveforms measured at Mount San Salvatore (MSS) and Morro do Cachimbo (MCS) stations that contemplate such characteristics.

According to CIGRE Guide to Procedures for Estimating the Lightning Performance of Transmission Lines [4], representations of first stroke current waveforms applied on computational simulations of the lighting performance of transmission lines should consider "the highest steepness close to the peak amplitude and the front time as the Td30". Also, it is suggested the representation of the concave profile at the wavefront. Current representations that follow such recommendation are CIGRE concave waveform [4] and the double-peaked waveform [7]. The former uses two independent expressions to represent, respectively, the wavefront and the

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wavetail of the current waveform. The latter is based on the sum of a set of Heidler's functions [8] to allow the representation of the wavefront concavity and the presence of a second peak. Figure 2 illustrates such waveform considering median parameters of MSS.

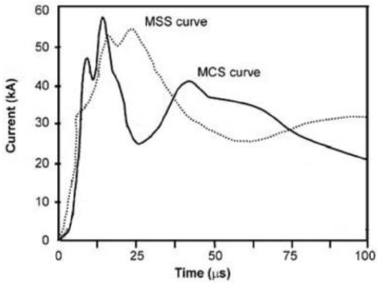


Figure 1. Measured first negative downward stroke current at Mount San Salvatore (MSS) and Morro do Cachimbo (MCS) stations. Adapted from [1].

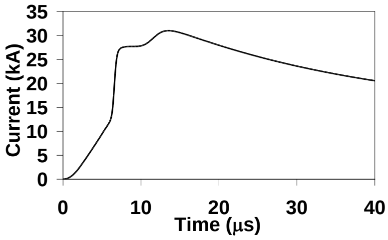


Figure 2. Double-peaked current waveform considering median current parameters measured at MSS station [7].

In spite of such suggestions, the lightning performance of transmission lines is generally calculated considering linearly rising current waveforms that follows a triangular or trapezoidal waveshape. Such kind of representation is commonly used since its reproduction in analytical procedures and computational simulations is simple. Nevertheless, such current representation is characterized by presenting a constant current time derivative at the wavefront that is quite distinct to the wavefront of real registers of lightning current waveforms. Figure 3 shows a linearly rising wavefront of a typical triangular current waveform with current peak and Td30 front time median parameters measured at MSS [9].

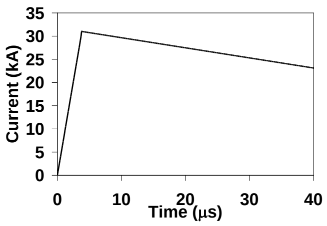
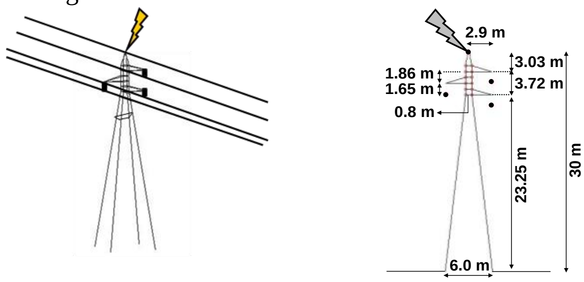


Figure 3. Triangular current waveform considering median current parameters measured at MSS station [9].

B. *Computational simulations*

The analyses developed in this work are based on systematic computational simulations using the Hybrid Electromagnetic Model (HEM) [10-11] to calculate overvoltages across the insulator strings of a 138-kV transmission line due to direct lightning strikes on tower top, as illustrated in Figure 4(a). The critical first stroke currents able to flashover the insulators were determined by means of the Disruptive Effect (DE) model [12]. The probability of backflashover occurrence of each simulated tower-footing grounding resistance (Rg: 10-to-30 Ω) was estimated by means of the calculated critical currents and the cumulative first-stroke peak current distribution proposed by IEEE standard [13].

Figure 4(b) shows the geometrical configuration of the 30-m-high simulated transmission line tower.



(a) (b)

Figure 4. Lightning striking tower top (a). Geometrical configuration of the 138-kV transmission line tower (b).

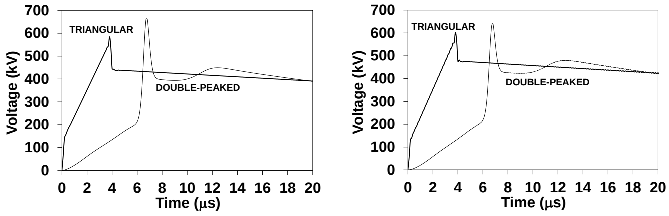
The presence of adjacent towers was not considered in simulations to avoid this kind of effect on the resulting overvoltage.

III. Results and Analysis

This section presents results in terms of overvoltages across insulators, critical currents and percentage of backflashover occurrence as function of the current waveform representation and current front time.

A. *The Effect of Current Waveform Representation*

Figure 5 shows the overvoltages developed across the upper and lower insulator string of the simulated transmission line for tower-footing grounding resistance of 20 Ω, assuming the injection of current waveforms illustrated in Figures 2 and 3 on the top of the simulated transmission line tower.



(a) (b)

Figure 5. Overvoltages across the upper (a) and lower (b) insulator strings for 20-Ω-tower-footing grounding resistance.

As can be noted, the application of the simulated current waveform representations resulted on quite distinct overvoltage profiles that somehow reflect the wavefront characteristic of the simulated current waveforms. Also, it is observed that the peak overvoltage related to the triangular waveform occurs in a much shorter time, about 4 μs against 7 μs of the double-peaked overvoltage.

The peak overvoltages related to the upper and lower insulator strings are summarized in Tables I and II, respectively, as function of the tower-footing grounding resistance.

TABLE I. PEAK OVERVOLTAGES AT THE UPPER INSULATOR STRING AS FUNCTION OF THE TOWER-FOOTING GROUNDING RESISTANCE. (TD30 =3.8 μS)

Rg (Ω)	Vp (kV) Double-peaked	Vp (kV) Triangular	Variation (%)
30	790.5	772.8	-2.2
20	662.4	584.8	-11.7
10	540.2	383.8	-29.0

TABLE II. PEAK OVERVOLTAGES AT THE LOWER INSULATOR STRING AS FUNCTION OF THE TOWER-FOOTING GROUNDING RESISTANCE. (TD30 =3.8 μS)

Rg (Ω)	Vp (kV) Double-peaked	Vp (kV) Triangular	Variation (%)
30	781.5	805.0	+3
20	640.9	602.5	-6
10	499.1	386.0	-22.7

In general, the peak overvoltages promoted by the double-peaked current are larger, except for the lower insulator string and 30-Ω-tower-footing grounding resistance. In this specific case, the peak overvoltage related to the triangular current is just 3% larger. Furthermore, it is observed a decrease on the difference between the peak overvoltages related to the double-peaked and the triangular current representations with increasing values of tower-footing grounding resistance. Considering the upper insulator string, for 10-Ω grounding resistance the peak of the triangular overvoltage is about 30% lower than the peak of the double-peaked overvoltage. For 20-, and 30-Ω resistance, the difference decreases to 12% and 2%, respectively.

The effect of the current waveform representation on the resulting backflashover outage rate was evaluated considering the application of the DE model to determine the flashover condition in terms of the critical peak current, based on the resulting overvoltage waveforms across insulator strings. The backflashover frequency of occurrence per strike to the tower is equivalent to the percentage of currents that are expected to overcome the current peak required to flashover line insulators. In this work, such percentage was determined considering the cumulative distribution of first-stroke peak currents proposed by IEEE standards, that follows Berger's data [13].

Table III summarizes the backflashover frequency of occurrence as function of the grounding resistance, taking as reference the lower insulator string. Such string presented the lower critical currents.

The obtained results show the larger expectation of backflashover related to the triangular current representation, approximately 58%, 35%, and 10% for 30-, 20-, and 10-Ω tower-footing grounding resistance, respectively. Consequently, the use of linearly rising current wavefronts leads to conservative results in comparison to the application of realistic concave current wavefronts, though the results for both waveforms are not very different. As indicated, the backflashover rates provided by the triangular waveform are about 4-6% larger than the ones related to the use of the double-peaked current assuming the 30-to-10-Ω grounding resistance range.

TABLE III. PERCENTAGE OF CURRENTS ABLE TO FLASHOVER.

Rg (Ω)	%I>Ic Double-peaked	%I>Ic Triangular	Variation (%)
30	55.4	57.5	+3.8
20	32.7	34.5	+5.5
10	8.9	9.4	+5.6

The explanation for such behavior is related to the characteristics of the resulting overvoltage waves. The comparison between the overvoltage waveforms for the same value of peak current shows the triangular overvoltage with a larger area of the region close to the peak. Taking as reference the application of the DE model to check the flashover condition, such waveform characteristic results on lower values of critical currents related to the triangular waveform.

B. The Effect of Current Front Time

The analyses developed in the previous section considered the current front time fixed and equal to the median Td30 [9] for both the double-peaked and the triangular current waveform representations. For such simulation condition, the results indicated outage rates related to the triangular waveform up to 6% larger.

However, there is the expectation that larger current amplitudes are related to larger current front time values. Furthermore, larger current front times contribute to diminish the resulting peak overvoltage, decreasing, as consequence, the resulting backflashover occurrence. In this context, the approach of using a fixed value of current front time related to any value of current peak needs to be carefully analyzed.

Some references adopt current representations that reflects the correlation of the peak amplitude with some wavefront parameter, such as the front time or current rate of rise. It is also common the definition of the current front time as the relation of the peak current and the maximum current time derivative [4,14].

In order to give a contribution on this topic, this section presents a preliminary evaluation on the effect caused by the current front time on the calculated backflashover frequency of occurrence as a function of the tower-footing grounding resistance and the current waveform representation.

According to Berger's data, most of the first stroke currents has Td30 front time between 1.5 μs and 10 μs. Table IV indicate the 5%, 50% and 95% values of the cumulative probability of the Td30 current front time of Berger´s data.

In order to consider extreme simulation conditions, modifications were implemented on the original triangular and double-peaked current waveforms to have the aforementioned Td30 current waveform into account. The resulting overvoltages across insulator string were calculated for each tower-footing grounding resistance and the DE model was applied to determine the critical current able to flashover line insulators. Tables V and VI summarize the results obtained assuming a 10-μs current front time for both current waveform representations. For the sake of comparison, the results described in Section III.A for the 3.8-μs current front time were also included.

TABLE IV. PERCENT OF CASES THAT EXCEEDS THE TABULATED VALUES OF TD30 CURRENT FRONT TIME OF BERGER'S DATA.

95%	50%	5%
1.5 μs	3.8 μs	10 μs

TABLE V. PERCENTAGE OF CURRENTS ABLE TO FLASHOVER (DOUBLE-PEAKED CURRENT WITH TD30 = 10 μS.)

Rg (Ω)	%I > Ic (Td30=3.8 us)	%I > Ic (Td30=10 us)	Variation (%)
30	55.4	55.4	0
20	32.7	32.3	-1.3
10	8.9	8.5	-4.7

TABLE VI. PERCENTAGE OF CURRENTS ABLE TO FLASHOVER (TRIANGULAR CURRENT WITH TD30 = 10 μS.)

Rg (Ω)	%I > Ic (Td30=3.8 us)	%I > Ic (Td30=10 us)	Variation (%)
30	57.5	56.8	-1.2
20	34.5	33.6	-2.6
10	9.4	8.6	-8.4

As expected, the results indicated the trend of decreasing the resulting backflashover frequency of occurrence with the increase of current front time. However, the reduction effect depends on the grounding resistance and has a much lower impact when considering the double-peaked current representation.

The use of the 10-μs and Td30 concave wavefront representation did not impact the outage rate related to the 30-to-20-Ω tower-footing grounding resistance. For very low grounding resistance (10 Ω), the reduction was only 5% in relation to the adoption of the median Td30.

The impact of using this larger front time was more relevant for outage rates related to the linearly rising wavefront. Differences up to 9% (Zp=10 Ω) were noted.

Complementing the previous analyses, simulations were performed considering triangular and double-peaked current representations modified to present a 1.5-μs-Td30 front time. The results are indicated in Tables VII and VIII.

For 20-to-30 Ω-grounding resistance, the resulting outage rate is very close to the case assuming the median Td30 when considering double-peaked current representation (just 1% larger). For 10 Ω, the resulting outage rate is about 10% larger.

However, the use of such a lower current front time on the triangular current representation has a more relevant impact on the calculated outage rate. The resulting increase is about 3,7, and 28% in comparison to the use of the median Td30, for 30, 20, and 10 Ω-tower-footing grounding resistance, respectively.

These results show that, particularly for double-peaked current representation, the variation of current front time practically does not affect the resulting outage rate of transmission lines. Hence, the approach based on the use of a fixed Td30, since it is assumed as the medium Td30 and the double-peaked current representation, may be considered consistent for evaluations of the lightning performance of transmission lines.

TABLE VII. PERCENTAGE OF CURRENTS ABLE TO FLASHOVER (DOUBLE-PEAKED CURRENT WITH TD30 = 1.5 μS.)

Rg (Ω)	%I > Ic (Td30=3.8 us)	%I > Ic (Td30=1.5 us)	Variation (%)
30	55.4	56.1	+1.3
20	32.7	33.1	+1.2
10	8.9	9.8	+10.1

TABLE VIII. PERCENTAGE OF CURRENTS ABLE TO FLASHOVER (TRIANGULAR CURRENT WITH TD30 = 1.5 μS.)

Rg (Ω)	%I > Ic (Td30=3.8 us)	%I > Ic (Td30=1.5 us)	Variation (%)
30	57.5	59	+2.6
20	34.5	36.9	+7
10	9.4	12	+27.7

IV. CONCLUSIONS

This work presented results related to the effect of return stroke current representations on the calculated backflashover rate of transmission lines. The analyses considered linearly rising and concave wavefronts and typical front times of first return stroke currents.

The results obtained by computational simulations using the HEM model to calculate the overvoltages developed across insulator strings and the DE model to estimate the flashover occurrence of such insulators indicated larger outage rates calculated by the assumption of linearly rising wavefront representation (triangular waveform). In spite of the easiness of reproduction of this current waveform, it does not represent the pronounced initial concavity followed by the abrupt rise around the half peak and, the presence of subsidiary peaks, as the double-peaked current waveform does. Furthermore, the double-peaked current representation reproduces all median current parameters measured in instrumented towers.

Also, it was also shown that, when the double-peaked current representation is assumed, varying the current front time does not impact the resulting outage rate for 20-to-30 Ω grounding resistance and has a minor impact for 10-Ω grounding resistance. For simulations considering linearly rising current wavefronts, the current front time may have a relevant effect on the calculated outage rate, mainly for those lines with very low tower-footing grounding resistance. These behaviour is related to the use of DE model to estimate the flashover occurrence. Therefore, for the conditions adopted herein the use of double-peaked current representation with a fixed front time assumed as the median Td30 may be considered a consistent approach to be adopted on evaluations of the lightning performance of transmission lines.

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