Backflashovers of Transmission Lines Due to Subsequent Lightning Strokes

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***Abstract*—Lightning overvoltages across insulator strings of existing 138- and 69-kV transmission lines were simulated using the hybrid electromagnetic model. It was found that, though the reduction of tower-footing grounding resistance is very effective to decrease lightning overvoltages caused by first strokes, this reduction is saturated around 750–600 kV for typical currents of subsequent strokes. The lightning performance of these lines was estimated and subsequent strokes were found to be relevant cause of backflashovers in 69-kV lines.**

***Index Terms*—Lightning parameters for engineering application, lightning overvoltage, lightning performance of transmission lines, subsequent strokes.**

I. Introduction

DIRECT lightning strikes are a common cause of transmission line outages. Three mechanisms are responsible for such outages, namely the flashover across insulator strings, the backflashover, and the midspan flashover. The first mechanism occurs when lightning strikes a phase conductor either due to the absence of shield wires or due to a shielding failure. In particular, lines presenting very long spans, whose shield wires are stricken at midspan, might experience flashover connecting the shield wires and phase conductors through the air [1]. Backflashover mechanism largely prevails as the main cause of outages for lines of voltages below 500 kV installed in regions of unfavorable soil-resistivity conditions. This makes this mechanism the main focus of techniques intended to improve the lightning performance of such lines [1]–[5].

Basically, backflashover occurs when the amplitude of the lightning overvoltage experienced by insulator strings in response to direct strikes to a tower or to the shield wires at tower vicinities exceeds the insulation withstand of the line. According to the integration method (DE), this condition corresponds to achieving a base destructive effect (DE_B), defined for each insulation configuration for standard voltage waves [6]–[8]. Considering nonstandard waves, such as those overvoltages yielded by real lightning currents, the result of the DE method is given for each specific voltage waveform in terms of the peak voltage required to achieve this condition. Thus, measures able to decrease the lightning overvoltage to values lower than this minimum peak voltage work to diminish the backflashover frequency and outage rates as well.

The main lightning parameters that influence the overvoltage amplitude are the peak, the front time, and the waveform of the current. The developed peak voltage is approximately proportional to the peak current. Although less influent, front time can also contribute to increase the peak voltage across insulators, in particular, the very short front times. Some line parameters affect this amplitude as well. Notably, the value of tower-footing grounding impedance is the major influent parameter. Low impedance values are able to decrease lightning overvoltages [1], [9].

All the factors aforementioned concur to determine the amplitude of the lightning overvoltage that opposes to the line insulation withstand, which is mainly defined by its voltage level to determine the occurrence (or not) of backflashover.

The reduction of grounding impedance is the most effective and common conventional practice to decrease overvoltages experienced by insulators to diminish the rate of backflashovers and, therefore, to improve the lightning performance of lines provided with shield wires [3].

Only first-stroke currents are considered as potential source of backflashover in regular evaluations of the lightning performance of high-voltage transmission lines [5]. It is generally believed that subsequent strokes are not likely to cause backflashovers since the value of the median peak current of subsequent strokes is typically around three times lower than that of first strokes [10], [11]. Quoting G.W. Brown, in his traditional work [12]: "Second components of lightning events, characterized by lower magnitudes and higher rates of rise, are shown to have an insignificant effect on backflash performance."

Recently, the authors have evaluated the lightning performance of an existing 138-kV transmission line presenting an unexpected large outage rate for its typical low tower-footing grounding resistance, using computational simulation. Investigating the developed overvoltages as a function of the grounding resistance, the authors found some interesting results that somehow conflict with the assumptions of the previous paragraph. In summary, the results showed that, though decreasing the grounding resistance was very effective to diminish continuously the lightning overvoltage yielded across insulator strings due to direct strikes of first strokes, this practice was not able to decrease the overvoltage of subsequent strokes below a certain threshold. This finding motivated a specific investigation on the risk of backflashovers due to subsequent strokes, whose results are presented herein.

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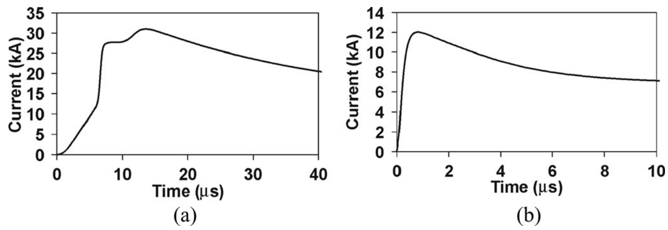


Fig. 1. Representation of typical waveforms of (a) first-stroke and (b) subsequent-stroke currents with median parameters of currents measured at MSS. The waveforms were reproduced using Heidler functions [15], according to the procedures described in [16] and [17] for first and subsequent strokes, respectively.

TABLE I
PARAMETERS OF LIGHTNING CURRENTS MEASURED AT MSS STATION

Event	Ip1 (kA)	Ip2 (kA)	T10 (µs)	T30 (µs)	T50 (µs)	dI/dt max (kA/µs)
FST	27.7	31.1	4.5	2.3	75.0	24.3
SUB	11.8	-	0.6	0.4	32.0	39.9

[a] I_{p1} and I_{p2} refer to the first and second return-stroke current peak values, T10 and T30 correspond respectively to the time between 0.1 I_{p1} and 0.9 I_{p1} and between 0.3 I_{p1} and 0.9 I_{p1}, T50 is the period of time necessary for the current amplitude to decay to 0.5 I_{p2}, and dI/dt max is the maximum time derivative.

II. PARAMETERS OF LIGHTNING CURRENTS OF FIRST AND SUBSEQUENT STROKES

Evaluations of the lightning performance of transmission lines are based on negative downward currents due to their larger frequency of occurrence, around 90% according to [13].

The patterns of the waveforms of natural first- and subsequent-stroke currents are quite different. As discussed in [14], waveforms of first-stroke currents include an initial concavity followed by an abrupt rise around the half-peak value and several subsidiary peaks, being the second peak usually the highest one. On the other hand, the waveform of most subsequent-stroke currents presents a single peak and a relatively smooth shape. Fig. 1 shows the representation of typical first- and subsequent-stroke current waveforms, considering the median current parameters measured at Mount San Salvatore (MSS), indicated in Table I [10].

III. DEVELOPMENTS

Basically, the developments of this study consisted in determining the overvoltage experienced across the insulators of transmission lines by means of computational simulation for different conditions of the tower-footing grounding resistance, in order to speculate on the probability of such overvoltage leading to backflashover. The performed simulations did not consider the effect of adjacent towers on the resulting overvoltage across the insulator strings. Such effect may be significant to decrease the resulting overvoltage at the central tower for first strokes, depending on the span length. However, it practically does not affect the overvoltage developed by subsequent strokes. Systematic simulations were developed using the hybrid electromagnetic model (HEM). This model, described in [18], has been widely employed to determine voltage and current distributions in lightning-related problems [19]–[22]. In particular, the application of HEM to calculate lightning overvoltages due to direct strikes to transmission lines is considered in [19] to denote the very good agreement of the calculated and measured voltages.

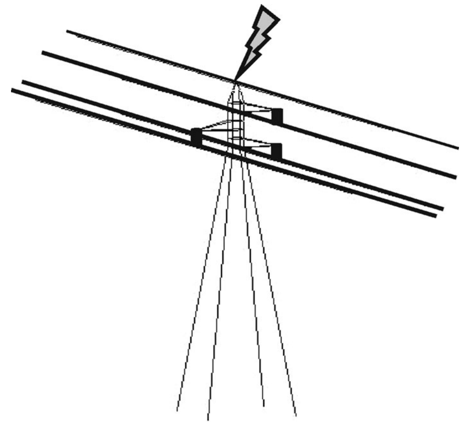


Fig. 2. Simulated condition: direct strike to the tower.

The model was applied to determine the overvoltages experienced across insulator strings of existing lines in response to lightning strikes to the tower top, as represented in Fig. 2, considering the current waveforms indicated in Fig. 1 to represent first- and subsequent-stroke currents. Values of tower-footing grounding resistance varying from 50 to 5 Ω were considered. It is worth mentioning that, commonly, the response of tower-footing electrodes subjected to lightning currents is characterized by means of the impulsive grounding impedance, which can be quite different from the low-frequency grounding resistance, as explained in [23]. Since the measurement of this impedance is not feasible in field conditions, the measured low-frequency resistance is still used to qualify the grounding response to lightning currents [23]. In this study, for the sake of simplicity, impedances were represented by equivalent lumped resistances.

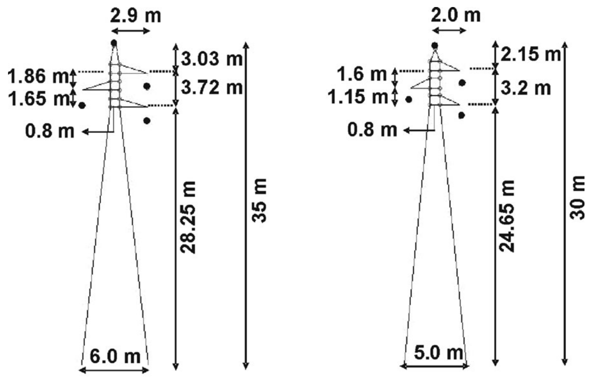
The configurations of two existing 138- and 69-kV-transmission lines illustrated in Fig. 3 were used in the tests of this study, both comprising self-sustained towers supporting four aerial cables (one ground wire and three phase conductors) that have their impedances matched at the extremities (30 m away from tower, at each side) to eliminate wave reflections. The procedure to match impedances includes the matching of self- and mutual impedance and, therefore, preserves the electromagnetic coupling between phase conductors and ground wire. Due to this aspect, the 30-m wire length is considered an appropriate distance for this impedance matching that, in addition, allows for saving time of simulations.

The average tower heights (35 m and 30 m) and tower bases (6 m and 5 m) of the existing lines were used in simulations, respectively, for the 138- and 69-kV lines.

IV. RESULTS AND ANALYSIS

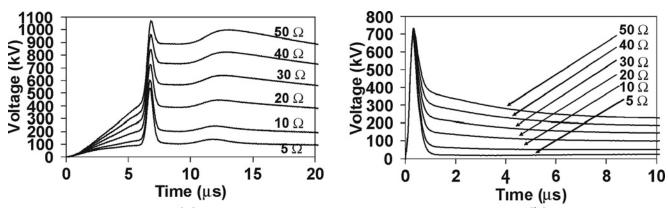
A. First Results: 138-kV Transmission Line

The first results, in terms of overvoltages developed across the upper insulator string of the 138-kV line in response to a



(a) (b)

Fig. 3. Dimensions and configurations of the (a) 138-kV- and (b) 69-kV-transmission-line towers.



(a) (b)

Fig. 4. Overvoltage waves across the upper insulator string of the 138-kV transmission line for different grounding-resistance values considering the strike of (a) first and (b) subsequent strokes at the tower top. ($H = 35$ m).

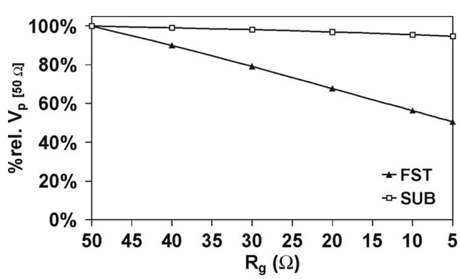


Fig. 5. Reduction of overvoltage across the upper insulator string obtained for different values of grounding resistance according to Fig. 4.

direct strike to the tower top, are presented in Fig. 4, assuming the incident lightning currents of Fig. 1.

A first and very impressive result concerns the fact that, in spite of the great effectiveness of the practice of reducing the grounding resistance to decrease the peak overvoltage developed in response to first-stroke current [see Fig. 4(a)], apparently this practice does not work to reduce the overvoltage yielded by subsequent-stroke currents [see Fig. 4(b)].

This behavior is depicted in the curves of Fig. 5. The results for the subsequent stroke show clearly the saturation of the overvoltage reduction with decreasing tower-footing grounding resistance around a voltage peak of 700 kV.

Similar results were obtained for overvoltages experienced by the lower and medium insulator strings. All peak values are presented in Tables II–IV.

TABLE II
PEAK VALUES OF OVERVOLTAGES ACROSS THE UPPER INSULATOR STRING OF THE 138-kV TRANSMISSION LINE ($H = 35$ m)

	FST		SUB	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	1006.95	-	725.65	-
40	959.60	10.06	719.36	0.87
30	844.68	20.83	712.05	1.87
20	721.95	32.34	703.64	3.03
10	600.71	43.70	693.65	4.41
5	539.52	49.43	688.05	5.18

TABLE III
PEAK VALUES OF OVERVOLTAGES ACROSS THE MEDIUM INSULATOR STRING OF THE 138-kV TRANSMISSION LINE ($H = 35$ m)

	FST		SUB	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	1079.04	-	713.70	-
40	966.60	10.42	706.09	1.07
30	846.75	21.53	697.48	2.27
20	718.48	33.42	687.49	3.67
10	588.09	45.50	675.80	5.31
5	524.16	51.42	669.25	6.23

TABLE IV
PEAK VALUES OF OVERVOLTAGES ACROSS THE LOWER INSULATOR STRING OF THE 138-kV TRANSMISSION LINE ($H = 35$ m)

	FST		SUB	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	1084.96	-	696.11	-
40	968.27	10.76	687.36	1.26
30	843.59	22.25	677.30	2.70
20	710.18	34.54	665.75	4.36
10	570.44	47.42	652.31	6.29
5	503.93	53.55	644.79	7.37

Table II shows a reduction around 50% of first-stroke peak voltage (1007 to 540 kV) for a decrease of the grounding resistance from 50 to 5 Ω. A similar behavior is experienced by the medium and lower insulator strings. On the other hand, the resulting decrease of the overvoltage amplitudes associated with subsequent stroke is not significant, only about 5–7%, considering all the insulator strings.

Another relevant result concerns the level of developed overvoltages around and below 700 kV for grounding resistances lower than 20 Ω. Considering the line critical flashover voltage (CFO), this implies it is unlikely that the currents of both first and subsequent strokes would lead to backflashover in 138-kV lines in this resistance range.

B. Understanding the Reasons for the Saturation of the Overvoltage Reduction Yielded by Subsequent Strokes

The set of results presented earlier shows that, while for first-stroke currents the decrease of grounding resistance is able to reduce continuously the peak overvoltage, for subsequent strokes the peak overvoltages remain practically the same or are only slightly reduced, achieving a saturate level around 700 kV for the upper insulator.

Furthermore, additional results developed for the 138-kV line, shown in Table V, denote that, though the trend to saturate the decrease of subsequent-stroke overvoltage with decreasing

TABLE V
PEAK VALUES OF OVERVOLTAGES ACROSS THE UPPER INSULATOR STRING OF 138-kV TRANSMISSION LINES FOR SUBSEQUENT STROKES

	H = 40 m		H = 35 m		H = 30 m	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	771.82	-	725.65	-	658.87	-
40	769.72	0.27	719.36	0.87	646.14	1.93
30	767.10	0.61	712.05	1.87	631.75	4.12
20	763.96	1.02	703.64	3.03	615.41	6.60
10	760.20	1.51	693.65	4.41	596.65	9.44
5	758.02	1.79	688.05	5.18	586.32	11.01

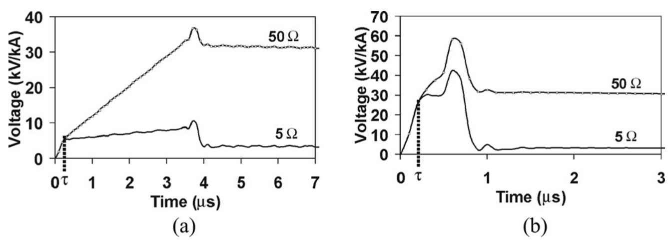


Fig. 6. Overvoltage waves across the upper insulator string of the 138-kV line ($H = 35$ m) for $R_g = 50$ and 5 Ω considering the occurrence of (a) first and (b) subsequent strokes represented by triangular waveforms with 1-kA current peak and Td_{30} medium front times measured at the MSS station.

grounding resistance is preserved, the value of the saturated peak voltage was very sensitivity to the tower height. The rise of tower height from 30 to 35 m and to 40 m resulted in an almost proportional increase of the saturated voltage from about 610 to 700 kV and to 760 kV (upper insulator). Furthermore, simulations also showed little sensitivity of the peak overvoltage of first stroke to the tower height.

The strong sensitivity of the saturated peak voltage to the tower height only for subsequent strokes suggested examining the overvoltage formation in the wavefront, in an attempt to understand the reasons for the observed saturation. This led to a specific simulation of the overvoltage experienced across the upper insulator string of the 138-kV line in Fig. 3(a), considering first- and subsequent-stroke currents represented by 1-kA current-peak triangular waveforms with the median Td_{30} of Berger's measurement, corresponding to front times of 3.8 and 0.7 μs, respectively [10]. The triangular waveform allows visualizing better the behavior of the overvoltage in the wavefront. The resulting overvoltages are illustrated in Fig. 6 for tower-footing resistances of 50 and 5 Ω.

There are different approaches to explain why the grounding resistance has less influence on the voltage developed across insulators due to subsequent strokes, such as the circuit-theory- and the transmission-line-theory approaches. The authors consider the latter to explain such behavior.

The overvoltage across insulators results basically from the superposing of the incident voltage wave (associated with the current traveling downward the tower) and the negative voltage wave reflected at the tower-footing, taking into account the time shift between such waves [24]. As tower-footing grounding resistance is decreased, the amplitude of the negative reflected wave is increased, resulting in larger potential to reduce overvoltages.

TABLE VI
PEAK VALUES OF OVERVOLTAGES ACROSS THE UPPER INSULATOR STRING OF THE 69-kV TRANSMISSION LINE ($H = 30$ m)

	FST		SUB	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	984.14	-	649.90	-
40	877.43	10.84	638.19	1.80
30	763.21	22.45	624.96	3.84
20	642.41	34.72	609.98	6.14
10	526.61	46.49	592.82	8.78
5	465.45	52.70	583.35	10.24

The curves in Fig. 6 show that for both events (first and subsequent strokes), the overvoltage formation comprises two phases, whose durations are delimited by the same instant of time "τ," around 0.23 μs. This τ corresponds to the time required for the voltage wave to travel downward the tower and to return to the tower top, after a negative reflection at the tower-footing ($\tau = 2(35\text{ m})/(300\text{ m}/\mu\text{s})$).

During the first phase, before the transit time, the reduction of tower-footing grounding resistance has no effect on the overvoltage, since the reflected wave has not reached the tower top yet. During the second phase, from the transit time to the peak-voltage time, the effect of the reflected negative wave works to diminish the voltage rise.

What is different in the formation of the overvoltages related to first and subsequent strokes is the period of influence of this negative reflected wave. Due to the long front time of first strokes, the first phase lasts less than 10% of the front time and voltage can reach only around 20% of the peak value. Thus, the reflect wave acts, during about 90% of the front time to reduce strongly the voltage rise (reduction of overvoltage peak around 75% for a resistance decrease from 50 to 5 Ω). On the other hand, due to the very short front time of subsequent strokes, the first phase lasts around 35% of the voltage-rise time, allowing the voltage to reach about its half peak in this phase, before the effect of the reflected wave begins to work. The time the reduction effect works do not allow reducing the voltage peak significantly (overall reduction about 25% for a resistance decrease from 50 to 5 Ω).

This explains the little influence of the tower height in the first-stroke overvoltage. The associated variation of the transit time only slightly affects the duration of the second phase of voltage rise. On the other hand, it affects significantly the duration of this phase for subsequent strokes.

C. Overvoltages Developed Across 69-kV Line Insulator Strings Due to Subsequent Strokes

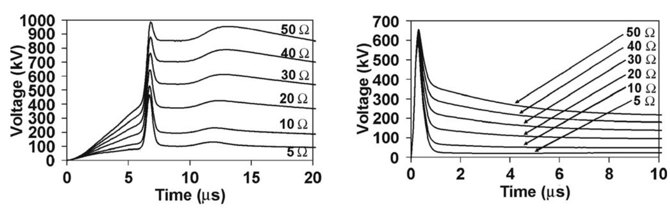
The saturation level around 700 kV motivated evaluating the occurrence of backflashover due to subsequent strokes in 69-kV transmission lines, whose insulation withstand is significantly lower, with a CFO around 450 kV. The same previous simulations were developed considering the tower configuration represented in Fig. 3(b) and the simulated results are presented in Tables VI–VIII, considering the currents of first and subsequent strokes of Fig. 1. The overvoltage waves experienced across the upper insulator strings are shown for both events in Fig. 7.

TABLE VII
PEAK VALUES OF OVERVOLTAGES ACROSS THE MEDIUM INSULATOR STRING OF THE 69-kV TRANSMISSION LINE ($H = 30$ m)

	FST		SUB	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	1009.46	-	647.88	-
40	896.92	11.15	634.68	2.04
30	776.35	23.09	619.80	4.33
20	647.38	35.87	603.00	6.93
10	522.82	48.21	583.80	9.89
5	458.41	54.59	573.24	11.52

TABLE VIII
PEAK VALUES OF OVERVOLTAGES ACROSS THE LOWER INSULATOR STRING OF THE 69-kV TRANSMISSION LINE ($H = 30$ m)

	FST		SUB	
Rg (Ω)	Vp (kV)	Red. (%)	Vp (kV)	Red. (%)
50	1041.23	-	637.64	-
40	906.43	12.95	622.96	2.30
30	780.85	25.01	606.52	4.88
20	646.05	37.95	587.91	7.80
10	512.31	50.80	566.77	11.11
5	445.00	57.26	555.14	12.94



(a) (b)

Fig. 7. Overvoltage waves across the upper insulator string of the 69-kV transmission line for different grounding-resistance values considering the strike of (a) first and (b) subsequent strokes at the tower top ($H = 30$ m).

The results show the same trends observed for the 138-kV line. Reductions in the range of 53–57% and 10–13% of the peak overvoltage are observed for first and subsequent strokes, respectively.

Also, it is important to note that in all the simulated cases, the overvoltages related to subsequent strokes are in the range of 555–650 kV (around 1.2–1.4 times the line CFO). This raises expectations of occurrence of backflashovers due to subsequent strokes that require further investigations.

V. DISCUSSIONS

A. Backflashovers Due to Subsequent Strokes in 69-kV Lines

In order to speculate on the potential of subsequent strokes to cause backflashover in 69-kV lines, some evaluations were developed using the voltage waveforms of Fig. 7.

The integration method [7], [8] was used with the coefficients provided by Hileman [25] to determine the peak voltage required to flash over, assuming a CFO of 450 kV. Other values suggested for such coefficients are indicated in [8], [26], and [27]. Based on the cumulative distribution of first and subsequent strokes of Berger's measurements [28], the percentages of currents expected to flash over due to lightning strikes to the towers are indicated in Table IX for different grounding resistance values, for first and subsequent strokes.

TABLE IX
PERCENTAGE OF CURRENTS EXCEEDING THE PEAK REQUIRED TO FLASH OVER AS A FUNCTION OF TOWER-FOOTING GROUNDING RESISTANCE

Rg	FST		SUB	
(Ω)	I_P (kA)	A (%)	I_P (kA)	B (%)
50	14.26	88.3	17.76	25.8
40	17.36	81.9	20.88	18.3
30	22.32	70.1	25.20	11.9
20	31.93	48.1	30.36	7.5
10	57.35	16.8	33.48	5.9
5	80.91	7.6	34.92	5.3

A:percentage of first-stroke currents that would lead to backflashovers.
B:percentage of subsequent-stroke currents that would lead to backflashovers.

TABLE X
PERCENTAGE OF FLASHES LEADING TO BACKFLASHOVER AS A FUNCTION OF TOWER-FOOTING GROUNDING RESISTANCE

Rg	Single flash	Multiple flash			TOTAL
(Ω)	TOTAL X (%)	FST Y (%)	SUB W (%)	TOTAL K (%)	Z (%)
50	88.3	88.3	59.1	95.2	93.8
40	81.9	81.9	45.4	90.1	88.5
30	70.1	70.1	31.6	79.6	77.7
20	48.1	48.1	20.9	58.9	56.8
10	16.8	16.8	16.7	30.7	27.9
5	7.6	7.6	15.1	21.5	18.7

X: percentage of single flashes that would lead to backflashovers [X = A].
Y: percentage of first strokes in a multiple flash that would lead to backflashover [Y = A].
W: percentage of subsequent strokes in a multiple flash that would lead to backflashover for non-conditional events. [$W = 3B - 3B^2 + B^3$].
K: percentage of multiple flashes that would lead to backflashovers for non-conditional events. [K = Y+W-(YW)].
Z: total percentage of flashes that would flash over [Z = 0.2X +0.8K].

Furthermore, certain assumptions are adopted to roughly estimate the percentage of backflashovers the 69-kV line would experience for single- and multiple-stroke flashes. First, it is considered that about 80% of flashes have multiple strokes and only 20% are single-stroke flashes [13]. A number of three subsequent strokes are assumed for multiple-stroke flashes due to the typical multiplicity of such event, around 3 [13]. Finally, the same distribution of peak currents is assumed for first strokes in single- and multiple-stroke flashes.

With such assumptions, if the percentages of currents leading to flashovers of first and subsequent strokes are A and B, respectively (as noted in Table IX) and all events are considered nonconditional events, the percentages of flashes leading to backflashover are indicated in Table X, based on the probability expressions indicated below this table [29].

What the results of Table X show is that, even considering only first stroke as usually assumed in lightning performance evaluations of transmission lines, the probability of backflashover occurrence is very significant for grounding resistances above 10 Ω (see column X). This is the reason for the very common requirement of a value below 10 Ω for the tower-footing grounding resistances of 69-kV lines [1] or using surge arresters when it is not possible to achieve such a low resistance for specific towers due to local environmental conditions. Also in this grounding resistance range, considering only multiple flashes, the frequency of backflashovers due to subsequent strokes (column W) has the same order or is larger than that of first strokes (column Y)

TABLE XI
PERCENTAGE OF FIRST AND SUBSEQUENT STROKES LEADING TO BACKFLASHOVER FOR DIFFERENT DISTRIBUTION OF TOWER-FOOTING GROUNDING RESISTANCE

Hypotheses for the distribution of Rg				Percentage of strokes leading to backflashover (%)	
20 Ω (%)	10 Ω (%)	5 Ω (%)	below 3 Ω (%)	FST	SUB
100	0	0	0	49.0	51.0
0	100	0	0	29.6	70.4
0	0	100	0	17.4	82.6
0	0	0	100	0	100
0	40	40	20	29.4	70.6
0	20	60	20	20.1	79.9
0	10	70	20	16.5	83.5
0	0	80	20	13.4	86.6
0	0	40	60	7.4	92.6

for grounding resistances of 10 and 5 Ω, around 16.7% against 16.8% and 15.1% against 7.6%, respectively. This makes the overall expectation of backflashover per multiple flashes relatively high: around 31% ($R_g = 10\ \Omega$) and 22% ($R_g = 5\ \Omega$). The total expectation of a backflashover of the 69-kV line for such grounding resistances (comprising those due to single and multiple flashes) is high: 28% and 19% of flashes.

B. Speculating on the Impact of Subsequent Strokes in the Lightning Performance of 69-kV Lines

The authors feel it is instructive to develop a rehearsal of the impact of subsequent strokes on the performance of 69-kV lines, in terms of outage rates, even following a simplified approach, as described next.

Based on the data of Table X, the percentage of expected backflashover rates due to first and subsequent strokes are calculated and indicated in Table XI. The evaluations assumed a flash density (Ng) of 4 flashes/km^2/year and an average lightning collective zone around 70 m wide for the line with 30-m-high towers. Thus, about 28 flashes per 100 km/year are expected to strike the line.

Since real distributions of tower-footing grounding resistances can vary a lot, it was decided to exploit nine different hypotheses for such distributions. Four of them assume uniform distribution of grounding resistances: all towers (100%) presenting only one resistance value (20, or 10 or 5 Ω) or a value below 3 Ω. Five other hypotheses assume nonuniform distribution.

The expected outage rates due to backflashovers are calculated as follows.

1) The number of first and subsequent strokes of the expected 28 flashes per 100 km/year striking the line is determined, considering 20% single-stroke flashes and 80% multiple-stroke flashes. Multiple-stroke flashes were assumed to comprise 1 first stroke and 3 subsequent strokes [13].
2) The number of first strokes (on both single- and multiple-stroke flashes) and of subsequent strokes that would lead to backflashover as well as the total number of outages per flash are calculated, based on the percentages of Table X (columns X, Y, W, and K).
3) Finally, the percentage of first and subsequent strokes in relation to the total number of strokes leading to backflashover is determined for each hypothesis of grounding-resistance distribution.

The results in Table XI show that as the density of low-resistance values is increased in any distribution, the percentage of backflashover due to subsequent strokes increases.

The main conclusion of this evaluation is that, regardless of the distribution of grounding resistances, subsequent strokes have a very relevant contribution for the outage rates of 69-kV lines. This result is derived from the saturation on the decrease of subsequent-stroke overvoltage with decreasing tower-footing resistances discussed in Section IV.

In the performed evaluations, it was not considered the eventual contribution of residual ionized channels of first strokes to the process leading to backflashover of subsequent strokes.

The typical wavefront profile of the overvoltages yielded by subsequent strokes (and also by first stroke) suggests a future improvement on the application of the DE method, the experimental investigation of parameters to be used specifically with waveforms presenting short front and decay times.

VI. CONCLUSION

The results of this paper show that, though decreasing tower-footing grounding resistances yields continuous reduction of the overvoltage experienced across insulator strings in response to first-stroke current strikes, this practice is not effective to decrease overvoltages of subsequent strokes.

It was found that the reduction of subsequent-stroke overvoltage is saturated and a peak overvoltage is retained with a level of 750–600 kV, depending on the line parameters. In particular, the height of the stricken tower is very influent: the saturate peak voltage increases with increasing height.

The evaluations showed that, for the studied lines, it is unlikely to occur backflashovers due to subsequent strokes in transmission lines of 138 kV and above. However, a significant number of such events are expected for 69-kV lines.

The simplified estimates of lightning-related outages developed for 69-kV lines denoted that subsequent strokes have a relevant contribution for the outage rates of such lines, larger than the first-stroke contribution regardless of the tower-footing grounding resistance distribution along the line. The subsequent-stroke contribution increases as tower-footing grounding resistances are decreased. For those distributions with prevailing low grounding resistance values, subsequent strokes are responsible for almost all backflashovers.

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