2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Influence of lightning strikes along the span on backflashover occurrence of transmission lines: A contribution on the span factor based on an advanced calculation procedure

Rafael Maia Gomes Fernando H. Silveira Silverio Visacro
LRC – Lightning Research Center
Graduate Program in Electrical Engineering - Universidade Federal de Minas Gerais
Av. Antônio Carlos 6627, 31270-901, Belo Horizonte, MG, Brazil
rafaelmaiagomes@gmail.com

***Abstract*— The effect of lightning strikes distribution along line span on the lightning performance of transmission lines is assessed following an advanced methodology based on the Hybrid Electromagnetic model to calculate overvoltages across line insulator strings, the Disruptive Effect method to assess flashover occurrence and a Monte Carlo procedure to determine lightning incidence distribution along the line. Systematic simulations considering a typical 138-kV line configuration as reference were performed for distinct conditions of tower-footing grounding impedance (Zp), span length, and lightning return stroke current waveform. The striking distance expressions proposed by Love and Eriksson were assumed. The results indicated span factors larger than the traditional 0.6-factor for all simulated scenarios. Especially when assuming a representative lightning return stroke current waveform, span factors about 35% to 56% larger were obtained, indicating the use of the 0.6-factor would lead to underestimations of calculated backflashover rates.**

Keywords— attractive radius; backflashover; lightning performance of transmission lines; Monte Carlo; span factor.

I. INTRODUCTION

The lightning performance of transmission lines (TL) is a relevant issue for power quality studies since such performance directly influences the power delivered to industrial and residential consumers. Transmission line outage rates higher than acceptable levels lead power utilities to investigate protection measures to improve such performance. In this context, special attention should be given to the calculation procedures applied to assess TL lightning performance.

The general procedure involved on the estimation of the lightning performance of transmission lines in terms of backflashover is well defined and consists of calculating the insulators overvoltage due to lightning incidences on tower top and then, by means of a flashover criterion, determine the critical current that leads line insulators to flashover. Following, assuming a peak current distribution for first strokes, the probability of lightning events to lead the insulator to flashover is estimated [1-4].

Generally, the expeditious determination of the backflashover rate (BFOR) of a transmission line follows the analytical procedures proposed a long time ago by traditional CIGRE and IEEE documents [1-3]. In the BFOR assessment, such procedures assume the application of a *span factor* to take into account lightning incidences that occur along line span. A 0.6-span factor is suggested in [3] but few details about the proceedings that lead to its value is provided.

Since CIGRE and IEEE analytical procedures as well as the 0.6-span were developed, significant advances on both the scientific knowledge on lightning and the modeling of transmission line components have been presented in literature. Also, computational tools based on circuit-parameter and electromagnetic approaches have been widely applied for estimations of the lightning performance of transmission lines, refining the determination of the resulting overvoltage across insulators. Also, an increase in the use of Monte Carlo method [5] in such kind of estimation allow developing sensitivity analyses considering the variation of important parameters of the problem, such as the lightning incidence distribution. In this scenario, it is urgent the review of the traditional procedure that takes into account the distribution of lightning strikes along line spans on evaluations of the backflashover rate by means of a single 0.6-factor.

The purpose of this work is to develop an investigation of the influence of lightning strikes distributed along the span on the assessment of backflashover occurrence of transmission lines, giving elements to establish a span factor more adjusted to advanced calculation procedures. Computational simulations were performed based on a procedure constituted by the Hybrid Electromagnetic model (HEM) [6], the Disruptive Effect method (DE) [3,7] and Monte Carlo method taken as reference a typical single-circuit 138-kV transmission line under several conditions of tower-footing grounding impedance (Zp), span length, lightning return stroke current waveform and lightning striking distance expressions.

II. ON THE REPRESENTATION OF LIGHTNING INCIDENCE DISTRIBUTION ALONG LINE SPAN FOR BFOR EVALUATIONS

Lightning strike incidence on transmission lines are naturally distributed along the tower, shield wires and phase conductors. When considering backflashover evaluations, the focus remains on lightning strikes to tower and shield wire.

This work has been supported by the Brazilian agency CAPES. Rafael M. Gomes would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 for the finantial support. Fernando H. Silveira would like to thank the National Council for Scientific and Technological Development – CNPq and The State of Minas Gerais Research Foundation FAPEMIG for grants 308351/2018-5 and TEC-PPM-00491-16, respectively. Silverio Visacro would like to thank CNPq for grants 310564/2016-6.

In general, lightning incidence on tower top results in higher insulator overvoltages when compared to those related to incidences along shield wire span, since the parcel of the current that flows along tower grounding for the former event is larger. In this context, lightning strikes along the span would lead to a lower probability of BFOR at the tower, comparing the same lightning event occurring at the tower or the span.

The application of a span factor in BFOR evaluations was first presented in [8] to "establish effective tower flashes per 100 km per year", as originally quoted. In [9], it is suggested the span factor defined by the associated probability of critical currents at tower top $P(I_{tower})$ and line midspan $P(I_{midspan})$ as $(P(I_{tower})+P(I_{midspan}))/(2\ P(I_{Tower}))$.

The traditional procedure applied to determine BFOR of transmission lines assumes lightning strikes only at tower top and the application of a "0.6" multiplying factor in the resulting probability to consider those incidences along line span [1-3].

This rate is promptly determined from the expected number of strikes to the line (NL) and the estimated percentage P of lightning currents exceeding the critical current (Ic) that corresponds to the minimum peak current leading the insulator to flashover and the 0.6-span factor, as presented in (1).

$$\mathrm{BFOR} = 0.6 \times \mathrm{N_L} \times \mathrm{P}(\mathrm{I} \geq \mathrm{I_c}) \qquad (1)$$

This procedure was developed a long ago, pursuing obtaining an approach to be incorporated in a set of easily implementable analytical procedures. Several simplifications were assumed such as the modeling of transmission line components and the assumed flashover criteria only based on overvoltage peaks. One aspect that it is not commented in [3] concerns the striking distance expression (if any) adopted to consider lightning incidence distribution along the line. There is a trend of higher density of strikes to the tower and to its immediate vicinity and such aspect along with the assumed span length should influence the determination of a span factor.

These aspects will be addressed as follows.

III. Developments

The evaluations of this work considered an advanced calculation procedure to estimate line BFOR of a typical Brazilian 138-kV transmission lines as a case study.

Simulations considered the application of the Hybrid Electromagnetic Model (HEM) [6] to calculate the overvoltages across line insulator strings due to lightning strikes at tower top and along the span and the Disruptive Effect model (DE) to estimate the backflashover occurrence across line insulators [3,7]. Based on the Monte Carlo procedure and striking distance expressions [10,11], lightning incidence distribution along the line is determined.

A sketch of the simulated towers depicted in Fig. 1.

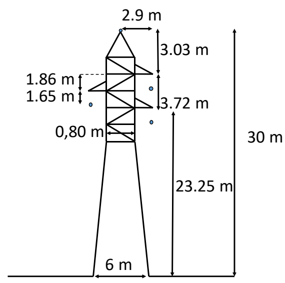

Fig. 1- Rough view of the simulated 138-kV and 30-m-high tower.

Three span lengths were simulated: 300 m, 400 m and 600 m. Tower-footing electrodes were modeled by its grounding impulse impedance Zp as recommended in [12]. This concise representation provides practically the same lightning performance related to the use of physical electrodes buried in the soil. Tower-footing impedance of the evaluated tower was varied in the 10-to-40 Ω range, whereas adjacent tower groundings were maintained as 20 Ω .

Double peaked and triangular current waveform representations with median parameter measured at Mount San Salvatore were assumed [13,14]. The former consists of a representative waveform of lightning first stroke currents measured in instrumented towers [15,16]. On the other hand, the latter is commonly adopted in expedite evaluations of the lightning performance of transmission lines.

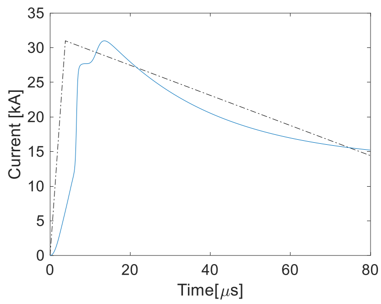

Fig. 2-Negative first stroke current waveform. Median currents, front time and time to half-value: Ip=31.1 kA, t_f=3.8 μs t_h=75 μs.

The resulting overvoltages across line insulator string and the associated critical current were calculated by means of HEM-DE methodology, considering lightning striking point at tower top and at several points along the shield wire span that was segmented in 50-m long sections from the tower to midspan. Based on the first peak current cumulative distribution proposed by IEEE [2], the backflashover expectation for each event was determined.

A Monte Carlo procedure was implemented to simulate the distribution of lightning strikes along line span according with striking distances expressions proposed by Love [10] and Eriksson [11] as described as follows:

Love's expression:

$$S = 10 I^{0.65} \quad (m) \qquad (2)$$

where I is the lightning peak current in kA. Following the recommendation of [17-18], the striking distance for shield wire and ground was considered as 0.9×S when applying equation (2).

Eriksson's expression:

$$S_t = 0.84 h_t^{0.6} I^{0.74} \quad (3)$$

$$S_l = 0.67 h_l^{0.6} I^{0.74} \quad (4)$$

where S_t and S_l stand for the striking distance for the tower and for the line, respectively. h_t and h_l are tower and line heights, respectively.

IV. Results and analysis

A. Introduction

The analyses of the work are divided into two groups. First, the analysis is focused on the backflashover expectation of the tower as function of the span length for lightning incidence at tower top and at line midspan. Following, the analysis is dedicated to evaluation of the backflashover expectation of the line and the estimation of the resulting span factor as function of the span length, striking distance model and current waveform.

B. Backflashover expectation of the tower

Fig. 3 presents the resulting overvoltages across the insulator string due to strikes at tower top and at line midspan, assuming a 400-m span line and a double-peaked current waveform. As expected, a lower overvoltage due to lightning incidence at midspan is shown. This behavior corroborates the adoption of span factors lower than 1 to take into account the effect of lightning incidence along line span.

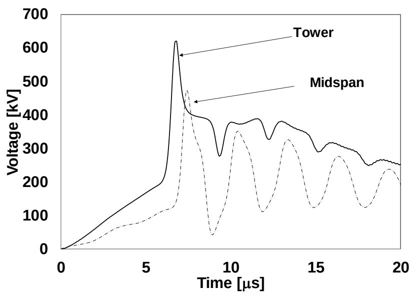

Fig. 3- Overvoltage waves across the lower insulator string of the 138-kV and 400-m span line, assuming tower-footing grounding impedance Zp of 20 Ω. Double-peaked current assumed.

The backflashover expectation of the tower for lightning incidences at tower top and at line midspan are denoted in Table I, as function of tower-footing grounding impedance (Zp) and span length, assuming Love's attractive radius. The BFOR ratio, defined as the ratio between BFOR (%) due to incidence at midspan and tower is also indicated.

The results indicate the lower expectation of backflashover occurrence for lightning strikes at midspan. BFOR ratios in the 0.5-to-0.6 range for Zp of 20 Ω and 40 Ω are noted. Considering the 10 Ω tower-footing grounding impedance case, such range is larger, from 0.6 to 0.85.

C. Backflashover expectation of the line

Considering the application of the Monte Carlo method to determine the lightning incidence distribution along the line and the backflashover probability at the tower due to several strike points along the line, the backflashover expectation of the line was determined and compared to the case that assumes lightning incidence only at tower top. The results are described as follows as function of the span length, striking distance expressions and current waveform. The resulting span factor for each case is also presented for the sake of the analyses.

TABLE I. Backflashover expectation of the tower as function of lightning striking point assuming Double-peaked current waveform.

Span (m)	Zp (Ω)	Striking point	BFOR (%)	BFOR ratio
300	10	Tower	6.3	-
		Midspan	4.2	0.67
	20	Tower	17.8	-
		Midspan	9.0	0.51
	40	Tower	38.9	-
		Midspan	19.2	0.49
400	10	Tower	7.2	-
		Midspan	4.4	0.61
	20	Tower	20.9	-
		Midspan	10.4	0.50
	40	Tower	45.6	-
		Midspan	23.6	0.52
600	10	Tower	7.9	-
		Midspan	6.7	0.85
	20	Tower	25.2	-
		Midspan	14.8	0.59
	40	Tower	54	-
		Midspan	32.3	0.60

1) Influence of span length

Table II presents the backflashover expectation and the span factor as function of the span length, considering the double-peaked current waveform and Love's striking distance expression.

TABLE II. Backflashover expectation of the line for span length varying from 300 m to 600 m, assuming Love's expression and double-peaked current waveform.

BFOR expectation (%) [300 m span]			
Zp (Ω)	**Tower incidence**	**Distributed incidence**	**Span fator**
10	10.1	8.9	0.88
20	26.0	21.7	0.83
40	49.9	42.1	0.84
BFOR expectation (%) [400 m span]			
Zp (Ω)	**Tower incidence**	**Distributed incidence**	**Span fator**
10	10.8	9.1	0.85
20	29.2	23.7	0.81
40	56.2	46.9	0.84
BFOR expectation (%) [600 m span]			
Zp (Ω)	**Tower incidence**	**Distributed incidence**	**Span fator**
10	11.8	11.0	0.94
20	33.8	28.3	0.84
40	64.1	55.1	0.86

As can be observed, in all simulated cases, span factors larger than 0.6 are obtained. In general, such values are about 40%-to-47% larger for the simulated span length, excepted for the 600-m span and 10 Ω tower-footing grounding impedance case that presented a span factor of 0.94. These results show the variation of span length did not alter significantly the obtained span factors.

2) Influence of striking distance model

Table III shows the resulting span factors considering Love [6] and Eriksson [7] striking distance expressions for 300 m, 400 m and 600-m line spans and the assumption of the double-peaked current waveform.

TABLE III. SPAN FACTOR ESTIMATION FOR DOUBLE-PEAKED WAVEFORM CONSIDERING LOVE'S AND ERIKSSON STRIKING DISTANCE EXPRESSIONS.

300-m span		
Z_P (Ω)	*Span factor*	
	Love	**Eriksson**
10	0.88	0.93
20	0.83	0.90
40	0.84	0.91
400-m span		
Z_P (Ω)	**Span factor**	
	Love	**Eriksson**
10	0.85	0.90
20	0.81	0.88
40	0.84	0.89
600-m span		
Z_P (Ω)	*Span factor*	
	Love	**Eriksson**
10	0.94	0.95
20	0.84	0.88
40	0.86	0.89

In all simulated cases, the use of Eriksson`s expression leaded to larger span factors, about 8.4%, 8.6%, and 4.8% higher for 300 m, 400 m and 600 m span, respectively, when a Z_p of 20 Ω is considered.

As illustrated in Fig. 4, the percentage of lightning incidence in the tower is affected by the assumed striking distance expression. The use of Eriksson expression results in higher tower incidence than the application of Love's one. The comparison among lightning incidences along the line shows similar values, being those related to Love's expression slightly larger. In spite of this features, the span factor variation is not so significant in relation to striking distance model adopted. An aspect that should be noted is that the tower influence does not plays an important role for longer spans, leading to similar span factors for Love and Eriksson expressions.

1) Influence of current waveform

Table IV presents the results as function of the simulated current waveshape (double-peaked or triangular current waveform representations) and Love's expression for assessing the structures striking distances.

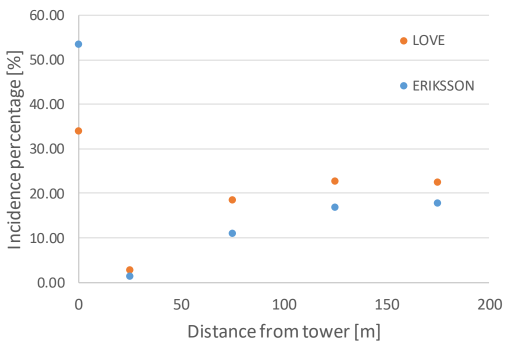

Fig.4 – Distribution of incidences in the 138-kV simulated transmission line.

TABLE IV. SPAN FACTOR ESTIMATION FOR DOUBLE-PEAKED AND TRIANGULAR WAVEFORMS CONSIDERING LOVE'S STRIKING DISTANCE MODEL.

BFOR expectation (%) [300 m span]			
Z_P (Ω)	**Tower incidence** *Double-peaked / Triangular*	**Distributed incidence** *Double-peaked / Triangular*	**Span Factor** *Double-peaked / Triangular*
10	10.1 / 10.1	8.9 / 7.2	0.88 / 0.72
20	26.0 / 27.7	21.7/ 20.9	0.83 / 0.76
40	49.9 / 49.9	42.1 / 42.1	0.84 / 0.84
BFOR expectation (%) [400 m span]			
Z_P (Ω)	**Tower incidence** *Double-peaked / Triangular*	**Distributed incidence** *Double-peaked / Triangular*	**Span Factor** *Double-peaked / Triangular*
10	10.8 / 10.7	9.1 / 7.4	0.85 / 0.69
20	29.2 / 30.5	23.7 / 22.2	0.81 / 0.73
40	56.2 / 60.5	46.9 / 48.0	0.84 / 0.79
BFOR expectation (%) [600 m span]			
Z_P (Ω)	**Tower incidence** *Double-peaked / Triangular*	**Distributed incidence** *Double-peaked / Triangular*	**Span Factor** *Double-peaked / Triangular*
10	11.8 / 12.0	11.0 / 9.6	0.94 / 0.80
20	33.8 / 34.9	28.3 / 26.0	0.84 / 0.74
40	64.1 / 67.4	55.1 / 54.2	0.86 / 0.80

The use of a triangular waveform exhibits lower span factors in relation to the use of more realistic waveform (double-peaked one). Such values are about 15% to 40% larger than the 0.6.

As presented in [12], for strikes to tower, the use of double-peaked and triangular current waveforms leads to very similar backflashover probability when considering the DE model. However, for those strikes along the span, the resulting probabilities due to such current waveform differ, being those related to the triangular waveform inferior. This behavior explains the lower span factor for such kind of waveform.

V. CONCLUSIONS

This work presented a dedicated contribution concerning the effect of lightning strikes distribution along line span on the lightning performance of transmission lines in terms of backflashover occurrence taking as reference a typical 138-kV line. Systematic simulations considering the HEM-DE methodology and the Monte Carlo procedure to distribute lightning incidence along line span were implemented. Span factors were obtained for several conditions of tower-footing grounding impedance, span length, and lightning return stroke current waveform, and compared with the traditional 0.6 factor recommended in the literature.

The obtained results indicated span factors significantly larger than the 0.6 factor in all simulated scenarios, about 35-to-56% larger when adopting representative lightning current waveform.

The sensitivity analyses also revealed that span length and striking distance expressions, for the conditions adopted in this work, did not impact the span factor as the choice of the lightning current waveform does. While the span length and striking distance expressions resulted in span factor variations up to 10% and up to 8%, respectively, the use of representative current waveform exhibited values up to 22% higher when compared to simplified triangular waveform. This result indicates that lightning current waveform is an important parameter of influence on span factor determination and, therefore, on BFOR probability for evaluations considering lightning strikes along the span.

The developments presented herein also suggest caution when adopting the traditional 0.6-factor for estimating the lightning performance of transmissions lines in terms of backflashover since its use results on underestimated BFOR rates when applied in advanced calculation procedures.

References

[1] CIGRE WG 33-01, Guide to procedures for estimating the lightning performance of transmission lines, Cigre Brochure 64, October 1991.

[2] IEEE, Guide for Improving the Lightning Performance of Transmission Lines, IEEE Std. 1243, 1997.

[3] A. Hileman, Insulation coordination for power systems. Boca Raton, FL: CRC, 1999.

[4] F. H. Silveira, S. Visacro, R. E. Souza, Lightning performance of transmission lines: Assessing the quality of traditional methodologies to determine backflashover rate of transmission lines taking as reference results provided by an advanced approach, Electric Power Systems, doi: j.epsr.2017.01.005,2017.

[5] J.G. Anderson, “Monte Carlo Computer Calculation of Transmission-Line Lightning Performance,” Trans. American Institute of Electrical Engineers. Part III: Power Apparatus and Systems, Vol.80, Issue: 3, p.414-419, Aug. 1961.

[6] S. Visacro, A. Soares Jr., HEM: a model for simulation of lightning-related engineering problems, IEEE Trans. Power Deliv. 20 (April (2)) (2005) 1026-1028.

[7] R.O. Caldwell and M. Darveniza, Experimental and analytical studies of the effect of non-standard waveshapes on the impulse strength of external insulation, IEEE Trans. Power App. Syst., vol. PAS-92, no. 4, pp. 1420-1428, Jul. 1973.

[8] J.G. Anderson, Lightning performance of transmission lines, in: Transmission Line Reference Book - 345 kV and Above, Electric Power Research Institute-EPRI, California, 1982, pp. 545-597.

[9] W. A. Chisholm and W. Janischewskyj, Lightning surge responde of ground electrodes, IEEE Trans. on Power Del., vol. 4, No. 2, p.1329-1337,April,1989

[10] E. R. Love, Improvements on lightning stroke modeling and applications to the design of EHV and UHV transmission lines, M.Sc., Univ. Colorado, Denver, CO, 1973.

[11] A. J. Eriksson, The incidence of lightning strikes to power lines, IEEE Trans. on Power Del., vol. PWRD-2, No. 3, July, 1987.

[12] S. Visacro, F.H. Silveira, Lightning Performance of Transmission Lines: Methodology to Design Grounding Electrodes to Ensure an Expected Outage Rate. IEEE Trans. Power Del., vol.30, p.237 - 245, 2015

[13] F.H. Silveira and S. Visacro, Lightning Performance of Transmission Lines: Impact of Current Waveform and Front Time on Backflashover Occurrence," in press, IEEE Trans. Power Del., doi: 10.1109/TPWRD.2019.2897892, 2019.

[14] R. B. Anderson and A. J. Eriksson, Lightning Parameters for enfineering application, Electra, Vol. 69, pp.65-102, 1980.

[15] S. Visacro, "A representative curve for lightning current waveshape of first negative stroke," Geophys. Res. Lett., vol. 31, L07112, Apr. 2004

[16] A. De Conti and S. Visacro, Analytical representation of single and double-peaked lightning current waveforms, IEEE Trans. Electromagn. Compat., Vol. 49, No. 2, pp. 448-451, May 2007.

[17] A. Mousa and K. Srivastava, Modelling of power lines in lightning performance of transmission lines, IEEE Trans., Vol. PAS-104, No. 4, pp. 919-932, 1985.

[18] A. Mousa and K. Srivastava, The distribution of lightning strokes to towers and along the span of shielded and unshielded power lines, Can. J. Elect. And Comp. Eng, vol. 15 No. 3. 1990.