Novel Indicator of Transmission Line Towers Backflashover Performance

P. Sarajcev, D. Jakus and J. Vasilj

***Abstract*—Transmission line (TL) backflashover (BF) performance is traditionally ascertained using a single number, the backflashover rate (BFR), which is measured in number of BF events per 100 km-years. This paper aims at presenting a novel indicator for measuring performance of high-voltage TL tower's ability to tolerate direct lightning strikes without provoking a BF event. This indicator is also a single number, which can be computed for any TL tower (by means of EMTP simulations) and measures, in a novel way, its tolerance against BF events. It is given in terms of the risk of the BF occurrence, which means it is statistical in nature and depends on the total sum of conditions governing the BF events. The BF risk, as an indicator, is obtained from the probability density function of the shield wire(s) incident lightning currents and the cumulative distribution function of the BF currents statistical distribution. Hence, it merges complete probabilities of obtaining lightning currents striking a tower with probabilities of those currents provoking a BF events on that tower. This novel risk-based indicator can be related to the price of that risk and the associated investment costs, enabling the cost-effective optimisation solutions to the problems of TL arrester applications and station insulation coordination design.**

***Keywords*—Backflashover, EGM, EMTP, Gaussian Copula, Lightning, Risk, Transmission line**

I. Introduction

TRANSMISSION line (TL) performance in relation to direct lightning strikes is of paramount importance, for several different reasons [1]–[3]: (i) determining the line's yearly outage rate, (ii) line insulation coordination (including possible surge arresters application), and (iii) incident (transformer) station's insulation coordination design. In that regard, of particular importance is the TL backflashover (BF) performance, emanating from the direct lightning strikes to the tower tops and shield wire(s), [4], [5]. Transmission line BF performance is traditionally ascertained using the backflashover rate (BFR), which is a single number representing an entire line, expressed as the number of expected BF events per 100 km–years, [6]. The backflashover probability, as a feature of the BFR, is usually obtained from the repeated numerical simulations (i.e. Monte–Carlo method) [7], [8], using the ElectroMagnetic Transients Program (EMTP), [9], [10], or by other means (i.e. analytical treatment with many assumptions and simplifications), [6]. When this probability is combined with the number of expected BF events, traditionally determined from the application of the electrogeometric model (EGM) of lightning attachment to TLs, it yields a backflashover rate.

P. Sarajcev and D. Jakus are with the Department of Power Engineering, FESB, University of Split, R. Boskovica 32, HR-21000, Split, Croatia.

J. Vasilj is with the Chalmers University of Technology, Signals and Systems Department, Maskingrand 2, 412, Gothenburg, Sweden.

Corresponding author (P. Sarajcev): e-mail: petar.sarajcev@fesb.hr

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This paper aims at presenting a novel indicator for measuring performance of high-voltage (HV) transmission line tower's ability to tolerate direct lightning strikes without provoking a BF event. It can be determined for any single tower or given for the entire line (using a "representative" tower). This indicator is also a single number, which leverages powerful EMTP simulations in its computation, and measures, in a novel way, tower's tolerance against BF events. It is given in terms of the risk of the BF occurrence, which means it is statistical in nature and depends on the total sum of conditions governing the BF events [8]: local keraunic level, statistical depiction of lightning-current parameters (including statistical correlation between the parameters), EGM of lightning attachment, frequency dependence of TL parameters and electromagnetic coupling effects, TL span length, statistical distribution of lightning strokes along the TL span, tower geometry and surge impedance, tower grounding impulse impedance (with soil ionization if present), lightning-surge reflections from adjacent towers, non-linear behavior of the insulator strings flashover characteristic, and power frequency voltage. Proposed BF indicator, in addition, utilizes the so-called curve of limiting parameters (CLP), derived from systematic EMTP simulations [11]. The CLP itself brings into relationship shield wire(s) incident lightning currents with the "critical" currents for the BF occurrence. It minimizes the number of EMTP runs, due to the systematic simulations approach, and is considerably faster then the traditional Monte–Carlo method application.

Furthermore, pseudo-random shield wire(s) incident lightning currents, necessary for the statistical treatment of the phenomenon, are generated from the appropriate bivariate statistical probability distribution, by means of the Gaussian Copula approach [12], [13]. The Copula approach, when combined with the CLP method, provides for an extremely efficient way of obtaining pseudo-random BF currents, unlike the more traditional way of using the Monte–Carlo method (which is known to be very time consuming), [7]. These BF currents are in-turn used to derive a probability density function (PDF) of their statistical distribution, by means of the kernel density estimation (KDE) procedure [14]. The KDE employs Gaussian kernels, with bandwidths determined using the grid search and cross-validation of the estimator performance.

The BF risk, as an indicator, is finally computed from the PDF of the shield wire(s) incident lightning currents and the cumulative distribution function (CDF) of the BF currents statistical distribution. Hence, it merges complete probabilities (instead of working with their point estimates) of obtaining lightning currents striking a tower with probabilities of those currents provoking BF events on that tower (while accounting for any tower peculiarities as such).

II. Incident lightning currents

Transmission line tower's incident lightning currents need to be drawn from the appropriate bivariate statistical probability distribution, which accounts for the geometry of the TL tower (in accordance with the EGM) and statistics of lightning-current parameters (including correlation). This is achieved by, first, generating a pseudo-random sample (u, v) from the bivariate Gaussian Copula, which holds a desirable correlation structure, where a bivariate Gaussian Copula probability density function is given by:

$$c(u,v) = \frac{1}{\sqrt{1-\rho^2}} \exp\left(\frac{2\rho\xi(u,v) - \rho^2\zeta(u,v)}{2(1-\rho^2)}\right) \quad (1)$$

with:

$$\xi(u,v) = \Phi^{-1}(u)\Phi^{-1}(v) \quad (2)$$

$$\zeta(u,v) = \Phi^{-1}(u)^2 + \Phi^{-1}(v)^2 \quad (3)$$

where Φ^{-1} is the inverse cumulative distribution function of the univariate standard normal distribution, while ρ is the (linear) correlation coefficient between the statistical variates. Then, using the inverse CDFs of the independent marginal distributions (F_1, F_2), the random sample from the appropriate bivariate probability distribution is obtained as follows [12]:

$$(x,y) = \left(F_1^{-1}(u), F_2^{-1}(v)\right) \quad (4)$$

In this way, marginal distributions are independent and completely separated from the correlation structure of the final bivariate probability distribution, but the correlation is preserved nonetheless. In case of TL tower's incident lightning currents described here, one of the marginal distributions in (4) is the Log–Normal distribution of lightning wave-front times [15], while the other one is the distribution of incident lightning-current amplitudes, obtained from the application of the EGM of lightning attachment to the transmission lines. Namely, according to [16], PDF of shield wire(s) incident lightning-current amplitudes can be obtained as follows:

$$f_{gw}(I) = \begin{cases} \frac{(2D_g(I)+S_g)}{DEN} \cdot f(I)\ ;\ I \leq I_m \\ \frac{(2D_g^{'}(I)+S_g)}{DEN} \cdot f(I)\ ;\ I \geq I_m \end{cases} \quad (5)$$

with

$$DEN = 2\int_0^{I_m} D_g(I) f(I)\, dI + + 2\int_{I_m}^{\infty} D_g^{'}(I) f(I)\, dI + S_g \quad (6)$$

where $D_g(I)$ and $D_g^{'}(I)$ are exposure distances for the shield wire(s), while I_m is the maximum shielding failure current, all of which depend on the tower geometry in accordance with the EGM theory; e.g. see [16, Ch. 7] for more information. Furthermore, CDF of lightning-current amplitudes incident to shield wire(s), which is a second marginal distribution used in (4), can be given by the following expression [16, Ch. 7]:

$$F_{gw}(I) = \begin{cases} \frac{\int_0^I (2D_g+S_g) f(u) du}{DEN}\ ;\ I \leq I_m \\ \frac{\int_0^I (2D_g^{'}+S_g) f(u) du + \int_I^{\infty} 2D_g^{'} f(u) du}{DEN}\ ;\ I \geq I_m \end{cases} \quad (7)$$

Also, according to the EGM theory, following expression for estimating the number of direct lightning strikes to shield wire(s) can be obtained [16]:

$$N_{gw} = 2LN_g \cdot \int_0^{I_m} D_g(I) f(I)\, dI + + 2LN_g \cdot \int_{I_m}^{\infty} D_g^{'}(I) f(I)\, dI + LN_g S_g \quad (8)$$

where: N_g is the annual average ground flash density, L is the line length and S_g is the distance between the shield wires. Above expression should be multiplied by 0.6 in order to account for the non-uniform distribution of lightning strikes along the span length [16]. The $f(I)$ in the above expressions stands for the PDF of the (general downward negative) lightning current amplitudes statistical distribution, which follows a Log–Normal distribution [15].

III. Backflashover currents

Backflashover lightning currents probability distribution is derived by utilizing the so-called curve of limiting parameters (CLP); see Ref. [11] for more information. The CLP brings into relationship incident lightning currents with the "critical" currents for the BF occurrence and can be constructed in the coordinate space of lightning-current amplitudes and wave-front times using the systematic EMTP simulations approach. Namely, for each wave-front time there is a single value of the lightning-current amplitude (i.e. critical current) that causes a backflashover (based on the analysis using the EMTP program). Any amplitude above this critical level, for that particular wave-front time, will certainly cause a BF event (due to the determinism of the EMTP computational framework); any amplitude below this threshold will not.

The CLP, furthermore, depends on the transmission line itself, featuring all main aspects of the BF phenomenon, from the insulator strings flashover characteristic to the tower footing impulse impedance [11]. Hence, by superimposing the appropriate CLP (obtained from the EMTP simulations of BF events on the particular tower) on the shield wire(s) incident lightning (generated from the appropriate bivariate probability distribution), a statistical distribution of the BF current amplitudes directly follows. In a sense, the CLP curve can be seen as a filter, which passes through only the BF current amplitudes, from the total pseudo-random population of shield wire(s) incident lightning currents. This "filter" also preserves the correlation structure between the lightning current parameters (wave-front times and amplitudes), which has been incorporated from the beginning (see Section II).

The obtained BF current amplitudes can then be fitted by a probability distribution function—by means of the kernel density estimation (KDE) procedure, as follows [14]:

$$\hat{f}(x) = \frac{1}{Nh} \cdot \sum_{i=1}^{N} K\left(\frac{x - x_i}{h}\right) \quad (9)$$

where $\hat{f}(x)$ is the estimated PDF, with $K(\bullet)$ being the kernel (Tophat, Cosine, Gaussian, Epanechnikov, etc.) and $h > 0$ is the bandwidth. Gaussian kernels are used here. The problem of bandwidth selection is tackled numerically, by means of implementing the grid search and cross-validation procedures for evaluating estimator performance, [14]. This PDF forms the basis for obtaining (numerically) the associated CDF, as follows:

$$\hat{F}_{BF}(x) = \int_{-\infty}^{x} \hat{f}(t)dt \quad (10)$$

The backflashover event as a stochastic phenomenon, which is governed by the (i) probability of lightning (wave-front and amplitude combination) striking the tower and (ii) probability of that same lightning subsequently evoking a BF on that tower, is now statistically fully described.

IV. Backflashover risk indicator

By using the PDF of the shield wire(s) incident lightning current amplitudes statistical distribution (f_{gw}) and the CDF of the backflashover amplitudes statistical distribution ($\hat{F}_{BF}$), one can establish the risk of the TL backflashover, obtained from:

$$R_{BF} = \int_{0}^{\infty} f_{gw}(I)\hat{F}_{BF}(I)dI \quad (11)$$

as the area underneath the bell-shaped curve formed by the product of distributions $f_{gw}(I)$ and $\hat{F}_{BF}(I)$.

Furthermore, by bringing into the relationship the risk of backflashover with the yearly expected number of direct lightning strikes to TL tower (i.e. number of dangerous events per year), enables one to arrive at the mean time between backflashovers (MTBBF) as a measure of the tower's tolerance to BF events. The expected number of direct lightning strikes to the tower is obtained from the EGM application to the tower geometry (including keraunic level, span length, conductor sag, statistical distribution of lightning strikes along the span length, etc.), in accordance with (8). Hence, the mean time between backflashovers can be obtained as follows:

$$\text{MTBBF} = \frac{1}{R_{BF} \cdot N_{gw}} \text{ (years)} \quad (12)$$

This measure, which is a single number, can be used to create a rang list of towers and identify those "rogue" towers with excessive BF risk (having, statistically speaking, a small value of MTBBF years). A similar notion of the mean time between failures (MTBF) is well established in the field of station insulation coordination, e.g., see IEC 60071-2 for more information [2].

In addition, in the case of transmission line arrester (TLA) applications, following iterative procedure can be followed: (i) preselect the surge-protective measures; (ii) estimate the BF risk with the preselected design; (iii) calculate the price (C_f) associated with the total risk (which includes repair costs, lost revenue due to outage time, and any additional surcharges), and determine if

$$R_{BF} \cdot C_f > C_p \quad (13)$$

where C_p is the cost of the TLA design (sum of expenditures for surge-protective measures), and return to (i) as necessary.

The proposed approach has been implemented using the combination of EMTP–ATP software and a Python language, leveraging many of its libraries, such as: `statsmodels`, `scikit-learn` and `seaborn` for bivariate statistical distributions, `matplotlib` for figures, `numpy` and `scipy` for different numerical tasks, including optimization, numerical integration, signal processing, statistics, and more.

V. Computational example

Heretofore presented method will be applied to the typical single-circuit 110 kV transmission line with vertical conductor configuration and steel-lattice towers [8], [11]. Tower geometry is typical for wind pressures between $750 - 1500\ N/m^2$, with individual spans of 350 m, typical for $750\ N/m^2$ wind pressure and $65 N/m^2$ of maximum allowed conductors tensile strength. Tower height is 27 m; distance from the top console to the tower top equals 3 m; span between tower consoles (arms) is 2 m; top console length 2.5 m, middle console length is 3 m and bottom console length is 3.5 m. Phase conductor DC resistance is 0.114 (Ω/km) with a 10.95 mm diameter, and that of the shield wire is 0.304 (Ω/km) with an 8 mm diameter. Insulator string length equals 0.9 m.

Transmission line is modeled in EMTP–ATP using the frequency-dependent JMarti model, including span length, conductor sag and tower geometry. Several spans on each side of the tower are modeled to account for the reflections of traveling waves from the adjacent towers. Surge propagation along the towers is taken into account. Influence of corona is neglected. Insulator flashover is modeled using the leader-progression model. Tower grounding system is modeled using the so-called Weck's model, which accounts for the soil ionization if present, [6], [17]. Pre-strike phase voltages are kept fixed, as recommended in [17]. The complete EMTP–ATP model of the TL tower employed in the analysis is graphically depicted in Ref. [8], along with additional modeling details.

Fig. 1 graphically presents the bivariate Gaussian Copula probability distribution (scatter and density plot), which holds the desired correlation structure. The associated marginal distributions are the uniform distributions, as expected.

Next, Fig. 2 depicts the bivariate (i.e. joint) PDF of lightning-currents incident to the TL shield wire, obtained with the EGM according to Brown and Whitehead for the assumed ground flash density. This bivariate PDF has been obtained from the application of the Gaussian Copula, with the marginal distributions defined in the Section II. As can be seen, Fig. 2 presents a scatter plot of lightning data with superimposed bivariate PDF, marginal distributions of the amplitudes (right-hand part) and wave-front times (top part), along with the

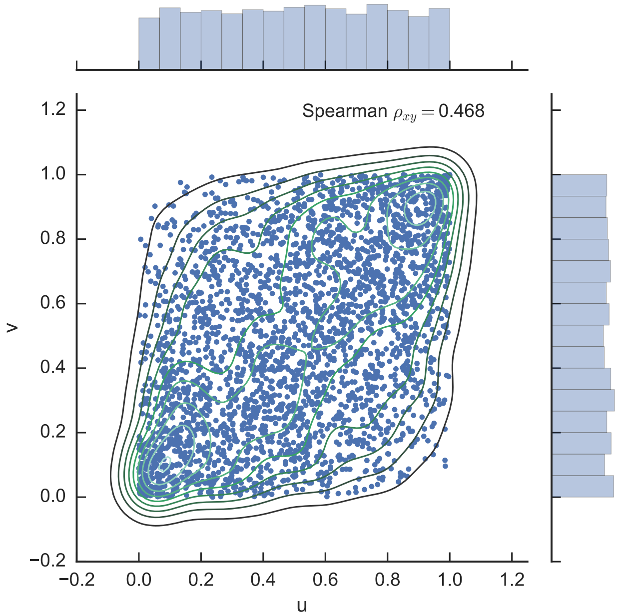

Fig. 1. Bivariate Gaussian Copula probability distribution.

original underlying Gaussian Copula (in the top right-hand part of the figure). Not all of these lightning-currents incident to TL shield wire will cause a BF event; only a certain portion of them will, in accordance with the curve of limiting parameters of a particular tower.

Hence, Fig. 3 presents curves of limiting parameters ob-

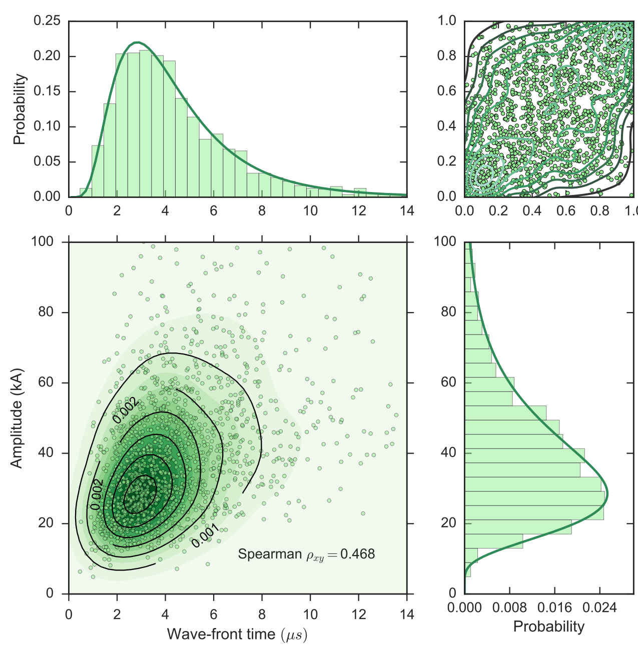

Fig. 2. Bivariate probability distribution of lightning-currents incident to TL shield wire(s) obtained with EGM according to Brown and Whitehead.

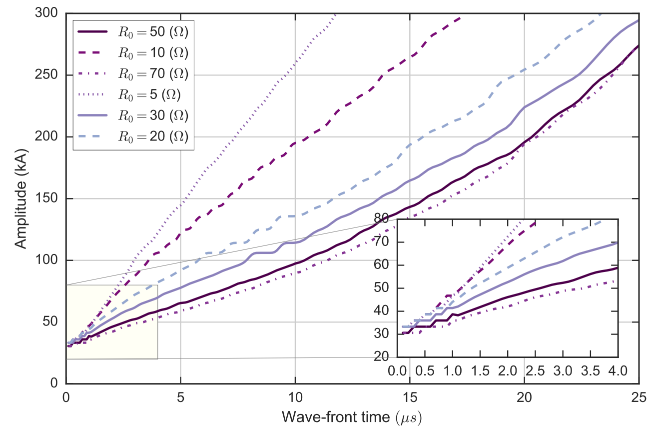

Fig. 3. Curves of limiting parameters for several different values of TL tower footing impedance.

tained for several different values of TL tower footing impedance; see Ref. [11] for more information. A Blackman filter has been applied to the CLPs here in order to smooth the curves and reduce the influence of unequal wave-front time increments and determinism of the EMTP computational framework. It can be nicely seen from this figure that the critical current amplitudes increase with the lowering of the tower footing impedance, which is a known phenomenon and a reason for reducing the tower footing (impulse) impedance. It is also clear that the critical currents increase as the wave-front duration is increased, which is also expected. In fact, for very long wave-front times the associated amplitudes attain very high values, meaning that the flashover is extremely improbable, regardless of the tower footing impedance. Resistance values in Fig. 3 represent tower grounding resistance values at low-frequency and low-current magnitude, while their impulse behavior is determined during the EMTP simulation, in accordance with the Weck's model [17].

By combining Figs. 2 and 3 one can now easily extract only BF currents. This is illustrated in Fig. 4 for the case of 50 Ω tower footing resistance, in terms of the scatter plot with superimposed histograms for each of the marginal distributions. In this figure, grey shaded marginal PDFs represent shield wire currents probability distributions, while orange shaded PDFs represent BF currents probability distributions. It ought to be emphasized once more that the BF currents obtained by this process account for the lightning statistics (including correlation), TL geometry, EGM according to Brown and Whitehead, and EMTP transmission line model specificity (such as the insulator flashover model and the model of the tower grounding impulse behavior).

At the same time, Fig. 5 presents only BF currents (for the case of 50 Ω tower footing resistance), once they have been filtered out from the total shield wires incident lightning currents. On the same figure are the marginal PDFs of the BF currents, along with superimposed CLP which have been used (red line) for the purpose of extracting the BF currents. In

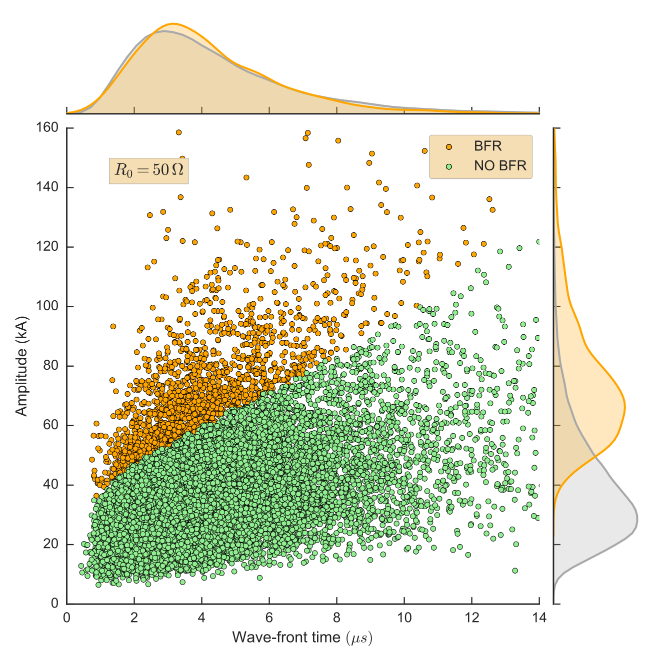

Fig. 4. Shield wire lightning currents and backflashover currents with superimposed histograms of their individual marginal distributions.

addition, CLPs for this transmission line, for several different values of tower footing resistances, have been provided in this figure (gray lines), for comparison. It should be mentioned that Figs. 4 and 5 hold some of the same information, presented somewhat differently for clarification and enhanced visual exposition of the computational procedure.

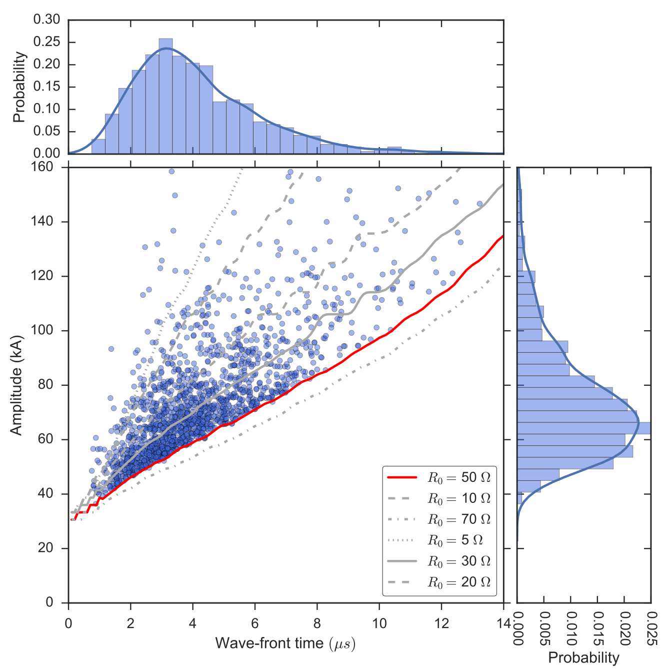

Fig. 5. Backflashover lightning currents with superimposed histograms of the marginal distributions.

This approach, depicted graphically in Figs. 4 and 5, can be easily repeated for any value of the tower footing resistance, using its appropriate CLP curve. It is straightforward and numerically very fast, even with a large initial population of shield wire incident lightning currents (e.g., a sample of 300,000 elements). Hence, Fig. 6 depicts the PDFs and the associated CDFs of the BF current amplitudes, for two different cases of tower footing resistances, which are the final products of this process (notice the usage of the two vertical (ordinate) axes in this figure).

Finally, by employing the PDF of the shield wire(s) incident lightning-current amplitudes statistical distribution (f_{gw}) with the CDF of the backflashover amplitudes statistical distribution ($\hat{F}_{BF}$), one can establish the risk of the TL backflashover. This has been carried-out here, for the case of two different TL tower footing impedance, and graphically presented in Fig. 7. This figure depicts, at the same time (using two vertical (ordinate) axes), the PDF of shield-wire incident lightning amplitudes and the CDFs of the BF currents (for two different treated tower footing resistances). It also graphically presents the product of these two distributions ($f_{gw} \cdot \hat{F}_{BF}$), the area below which represents the BF risk (see the inset figure), in accordance with (11). It can be seen that the BF risk increases with the increase in the tower footing impedance, when all other aspects of the transmission line are being held constant. This is expected. Risk can be seen as a measure of the tower's ability to tolerate direct lightning strikes without provoking a backflashover. The higher the risk is, the lower will be the tower's ability to tolerate direct lightning strikes without provoking a BF event, and *vice–versa*.

When the BF risk is associated with the yearly expected number of dangerous events, it yields the associated MTBBF, in accordance with (12). It ought to be mentioned that the BF risk, along with the MTBBF, depends on the applied EGM, and that a Brown and Whitehead model was used in this paper. The expected number of direct lightning strikes to the TL tower accounts for the applied EGM, tower geometry, span length,

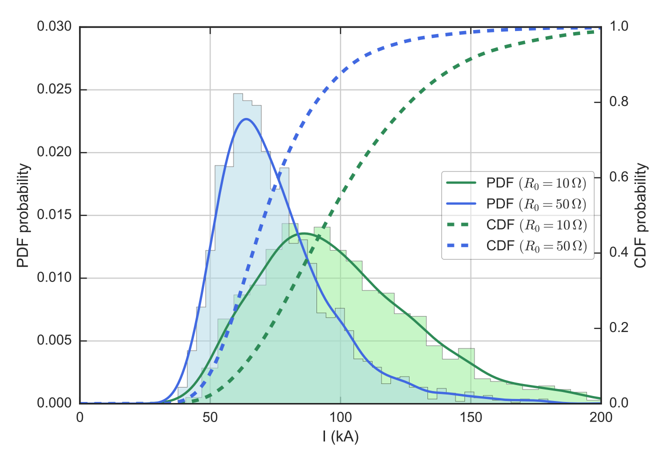

Fig. 6. PDFs and CDFs of the BF currents for two different cases of tower footing resistances.

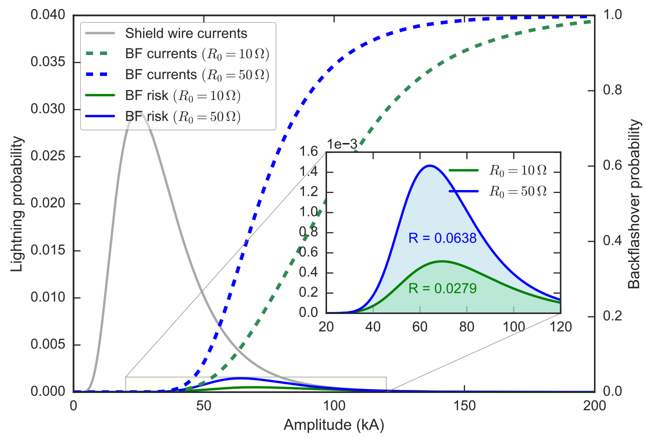

Fig. 7. Risk of backflashover computed from the shield wire incident lightning and BF lightning currents probability distributions.

distribution of strikes along the span, and ground flash density. Hence, Table I presents the BF risk and the MTBBF for the TL tower at hand, for several different values of the tower footing resistance and ground flash density.

TABLE I
THE BF RISK AND THE MTBBF WITH DIFFERENT TOWER FOOTING RESISTANCES AND GROUND FLASH DENSITIES.

		MTBBF (years)	
R_0 (Ω)	BF Risk	$1\,km^{-2}year^{-1}$	$4\,km^{-2}year^{-1}$
10	0.0279415	1080	274
30	0.0410483	774	195
50	0.0638129	503	123
70	0.0808628	393	96

It should be mention that the concrete values presented in Table I can change slightly between different runs, due to the statistical nature of the indicator. Also, further deviation is to be expected with applications of different possible EGMs. However, all these are rather small and do not influence the final conclusions. On the other hand, MTBBF will scale in the inverse proportion to the ground flash density (see Table I). At the same time, lightning current statistical parameters, including correlation, exert important influence on the BF risk, as noticed in [11]. The "tolerable level" of the MTBBF can be determined either by examining the BF influence on the substation insulation coordination [2], [3], [13], or by means of the full financial risk analysis.

VI. Conclusion

This paper proposed a novel indicator of transmission line tower's BF performance, which is risk based and utilizes entire probability distributions (of incident lightning strikes and generated BF currents) instead of working with point estimates. This indicator (being a single number) can be used to create a rang list of TL towers and identify certain towers with a high risk of BF occurrence. These would then become prime candidates for applying dedicated measures for decreasing their BF risk, such as lowering their impulse grounding impedance or installing surge arresters (i.e. TLA application). This could be of importance for the towers emanating from the substation, in relation to the substation lightning insulation coordination design. It can be of use for identifying so-called "rogue" towers and/or selecting appropriate tower candidates for the TLA installation. This novel risk-based BF indicator can be easily related to the price of that risk and the associated investment costs, enabling the cost-effective optimization solutions to the mentioned problems of insulation coordination design and TLA applications. Risk based indicator is deemed appropriate here, considering the fact that the investment in surge arresters and related protective measures is commonly perceived as buying insurance.

References

[1] IEC 60071-1, "Insulation co-ordination - Part 1: Definitions, principles and rules," IEC, Standard, 2006.
[2] IEC 60071-2, "Insulation co-ordination - Part 2: Application guide," IEC, Standard, 1996.
[3] IEC 60071-4, "Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modelling of electrical networks," IEC, Standard, 2004.
[4] Y. Han, L. Li, H. Chen, and Y. Lu, "Influence of modeling methods on the calculated lightning surge overvoltages at a UHVDC converter station due to backflashover," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1090–1095, 2012.
[5] M. S. Savic and A. S. Savic, "Substation lightning performance estimation due to strikes into connected overhead lines," *IEEE Transactions on Power Delivery*, vol. 30, no. 4, pp. 1752–1760, 2015.
[6] I. S. Grant, J. G. Anderson, A. R. Hileman, W. Janischewskyj, G. E. Lee, V. J. Longo, W. Chisholm, D. Parrish, N. K. Roukos, C. T. Main, E. Whitehead, and J. T. Whitehead, "A simplified method for estimating lightning performance of transmission lines," *IEEE Transactions on Power Apparatus and Systems*, vol. 104, no. 4, pp. 919–932, 1985.
[7] F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and A. Santarpia, "An ATP-EMTP Monte Carlo procedure for backflashover rate evaluation: A comparison with the CIGRE method," *Electric Power Systems Research*, vol. 113, pp. 134–140, 2014.
[8] P. Sarajcev, "Monte Carlo method for estimating backflashover rates on high voltage transmission lines," *Electric Power Systems Research*, vol. 119, pp. 247–257, 2015.
[9] H. W. Dommel, *EMTP Theory Book*, 2nd ed. Vancouver, British Columbia: Microtran Power System Analysis Corporation, 1992.
[10] EPRI, "Electromagnetic transients program (EMTP): Application guide," Electric Power Research Institute, Tech. Rep., 1988, EMTP development coordination group, EPRI EL-4650.
[11] P. Sarajcev, J. Vasilj, and D. Jakus, "Method for estimating backflashover rates on HV transmission lines based on EMTP-ATP and curve of limiting parameters," *International journal of electrical power and energy systems*, vol. 78, pp. 127–137, 2016.
[12] C. Scholzel and P. Friederichs, "Multivariate non-normally distributed random variables in climate research – Introduction to the copula approach," *Nonlinear Processes in Geophysics*, vol. 15, pp. 761–772, 2008.
[13] P. Sarajcev, J. Vasilj, and D. Jakus, "Application of Gaussian Copulas in describing station impinging lightning overvoltages," in *Proceedings of the 34th Electrical Insulation Conference (EIC)*. Montreal, Canada: IEEE, June, 19-22 2016, pp. 317–320.
[14] B. W. Silverman, *Density Estimation for Statistics and Data Analysis*. London, UK: Chapman and Hall, 1986.
[15] IEEE WG, "Parameters of lightning strokes: A review," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 346–358, 2005.
[16] A. R. Hileman, *Insulation Coordination for Power Systems*. Boca Raton, FL: CRC Press, 1999.
[17] IEEE WG, "Modeling guidelines for fast front transients," *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 493–506, 1996.