A STATISTICAL METHOD FOR THE ESTIMATION OF INDUCED-VOLTAGE FLASHOVER RATE OF UNSHIELDED OVERHEAD DISTRIBUTION LINES

P. N. Mikropoulos* and T. E. Tsovilis
High Voltage Laboratory, School of Electrical & Computer Engineering,
Faculty of Engineering, Aristotle University of Thessaloniki,
*Email: <pnm@eng.auth.gr>

Abstract: Lightning is a major cause of distribution line outages affecting reliability of power supply thus, consequently, resulting in economic losses. Line insulation flashover in overhead distribution lines may be caused by overvoltages associated with direct or nearby lightning strokes. In this paper a statistical method for the estimation of the induced-voltage flashover rate of unshielded overhead distribution lines due to nearby strokes is introduced. The proposed method yields a range for the expected induced-voltage flashover rate of the line, by considering, besides line parameters and lightning crest current distribution, the lightning interception probability distribution of the line phase conductors. Results of the statistical method are compared with those yielded by the methods suggested in IEEE Std. 1410:2004 and its recent revision IEEE Std. 1410:2011; a satisfactory agreement is shown to exist. An application of the statistical method to a typical 20 kV unshielded line of the Hellenic distribution system is made.

1 INTRODUCTION

Lightning is a major cause of power interruptions in distribution systems affecting reliability of power supply thus, consequently, resulting in economic losses. Lightning-related line insulation flashover in overhead unshielded distribution lines may be caused by overvoltages either arising at the phase conductors due to direct strokes or induced owing to nearby strokes. Direct strokes to phase conductors occur when the latter intercept a descending lightning leader through a connecting upward discharge from a distance called striking distance within an interception radius commonly called attractive radius. Descending lightning leaders which are not intercepted by the phase conductors striking nearby the line cause induced voltages in the line.

The estimation of the expected induced-voltage flashover rate of distributions lines due to nearby lightning strokes, requires knowledge of the lightning activity in the region along the line and implementation of a lightning attachment model for estimating the line conductors interception radius and of a coupling model for the calculation of the lateral distance from the line within which nearby lightning strokes cause flashover of line insulation. According to common practice, the interception radius of line phase conductors is estimated by employing an electrogeometric model [1, 2]. However, it has been recently shown that, owing to the stochastic nature of lightning interception phenomenon, interception radius should be treated as a statistical quantity, depending on, besides lightning crest current and line height, lightning interception probability [3-5].

The present paper introduces a statistical method for the estimation of the flashover rate of unshielded overhead distribution lines due to lightning induced-voltages. The proposed method employs the statistical lightning attachment model [3, 4] for estimating the distribution of the interception radius of line phase conductors. It also employs a modified Rusck model [6] according to IEEE Std. 1410:2011 [2] for the estimation of lateral distance from the line within which nearby lightning strokes cause flashover of line insulation.

The proposed statistical method yields, instead of a specific value, a range for the expected induced-voltage flashover rate, associated with lightning interception probability distribution. Results are compared with those yielded by the methods suggested in IEEE Std. 1410:2004 [1] and its recent revision IEEE Std. 1410:2011 [2]. Finally, an application to a typical 20 kV unshielded line of the Hellenic distribution system is made.

2 INDUCED-VOLTAGE FLASHOVER RATE METHODOLOGY

The annual number of line insulation flashover due to induced voltages caused by nearby lightning strokes per 100 km of an overhead unshielded distribution line, F_p, is given as:

$$F_p = 0.2N_g \int_{I_{min}}^{\infty} W_I(I)f(I)dI \qquad (1)$$

where

- N_g (strikes/km^2/yr) is the ground flash density,
- f(I) is the probability density function of the lightning crest current distribution given as [7]:

$$f(I)=\frac{1}{\sqrt{2\pi}\sigma_{\ln}I}\exp\left[-\frac{\left(\ln I-\ln \bar{I}\right)^2}{2\sigma_{\ln}^2}\right] \quad (2)$$

where $\bar{I}$ and σ_{ln} are the median value and the standard deviation of the natural logarithm of the lightning crest current, respectively, taking values $\bar{I}$ = 30.1 kA and σ_{ln} = 0.76 [7].

- W_I (m) is the induced-voltage flashover width, which can be estimated by using the following equation based on Figure 1:

$$W_I(I)=R_I-R \quad (3)$$

where R_I is the induced-voltage flashover radius, that is, the lateral distance of a nearby lightning stroke from the line within which the induced voltage in the line causes flashover of insulation; R is the interception radius, that is, the lateral distance from the line within which the phase conductor intercepts the descending lightning leader.

- $I_{\min}$ (kA) is the minimum induced-voltage flashover current, that is, the lightning crest current of all possible nearby lightning stroke currents corresponding to $R_I = R$ [$W_I(I_{\min}) = 0$].

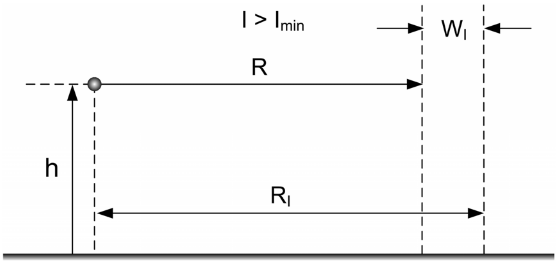

Figure 1: Determination of the induced-voltage flashover width W_I; R_I induced-voltage flashover radius, R interception radius of phase conductor, h phase conductor height.

From (1) it is obvious that the estimation of the induced-voltage flashover rate of an overhead unshielded distribution line requires the formulation of the induced-voltage flashover width, W_I, and the estimation of the minimum induced-voltage flashover current $I_{\min}$. These tasks can be accomplished by employing a lightning attachment and a coupling model for the determination of R and R_I in (3) respectively, as follows.

2.1 Statistical lightning attachment model

Based on the statistical lightning attachment model [3, 4], the interception radius, R, varies with lightning interception probability, following a normal distribution with a mean value, R_{ci}, called critical interception radius, and a standard deviation, σ.
R_{ci} (m) is given as:

$$\frac{R_{ci}}{h}=c_2\left(\frac{h}{D}\right)^{-k} \text{ [4]} \quad (4)$$

where h (m) is the conductor height, D (m) is the striking distance to earth surface and values for the coefficients c_2, k and σ, in formula form, are given in Table 1 [4].

Table 1: Coefficients and σ to be used in (4)

Positive Lightning			Negative Lightning		
c_2	k	$\sigma\%$	c_2	k	$\sigma\%$
0.90	0.6	$1.9\left(h/D\right)^{-0.75}$	1.24	0.7	$5.0\left(h/D\right)^{-0.43}$

In (4), a known relationship between striking distance to earth surface, D, and lightning crest current, I, commonly of the form $D = AI^B$, can be adopted. For negative lightning, a widely used expression in literature for D is:

$$D=10I^{0.65} \text{ [8]} \quad (5)$$

with D in meters and I is the lightning crest current in kA. Thus, from (4), (5) and Table 1 the interception radius of the line phase conductor at different interception probabilities can be calculated for negative lightning with the aid of the following expressions:

$$R_{ci}=6.2h^{0.3}I^{0.455} \quad (6a)$$

$$\sigma(\%)=13.5h^{-0.43}I^{0.28}. \quad (6b)$$

2.2 IEEE Std 1410:2011 simplified coupling model

According to IEEE Std 1410:2011 [2], for an overhead distribution line above ideal ground, without ground or neutral wires, the induced-voltage flashover radius, R_I (m), based on the simplified Rusck model [6], can be estimated as:

$$R_I=\frac{28Ih}{V_{CFO}} \quad (7a)$$

where I (kA) is the lightning crest current, h (m) is the line height and V_{CFO} (kV) is the critical flashover voltage of line insulation. By assuming that the latter equals 1.5 times the critical flashover voltage of line insulation under standard lightning impulses (CFO) [2], (7a) becomes:

$$R_I=\frac{28Ih}{1.5\text{CFO}}. \quad (7b)$$

2.3 Induced-voltage flashover width and minimum current formulation

As interception radius, R, varies with lightning interception probability according to (6), from (3) it can be deduced that the induced-voltage flashover width, W_I, can be treated as a statistical quantity; this is illustrated in Figure 2. Consequently, the minimum induced-voltage flashover current $I_{\min}$ which corresponds to W_I = 0 varies also with lightning interception probability. The minimum induced-voltage flashover current at 50% lightning interception probability, $I_{\min_{ci}}$, corresponding to $R_I = R_{ci}$ can be derived from (6a) and (7b) as:

$$I_{\min_{ci}} = \left[\frac{CFO}{3h^{0.7}}\right]^{\frac{1}{0.545}} \qquad (8a)$$

where CFO (kV) is the critical flashover voltage of line insulation under standard lightning impulses and h (m) is the line height. The minimum induced-voltage flashover currents at 97.5% and 2.5% interception probability, designated $I_{\min_a}$ and $I_{\min_f}$ respectively, can be estimated by the following approximate formula, obtained with the aid of mathematical software for lines up to 15 m:

$$\frac{I_{\min_{ci}}}{I_{\min_a}} = \frac{I_{\min_f}}{I_{\min_{ci}}} = 67 \cdot 10^{-3} h^{-1.28} CFO + \Sigma \qquad (8b)$$

where $\Sigma = 1.67h^{-0.12}$; Σ is approximately 1.27 for a 10 m overhead distribution line.

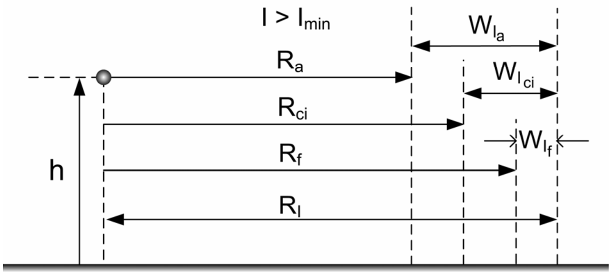

Figure 2: Induced-voltage flashover width W_I at different lightning interception probabilities; R_I induced-voltage flashover radius, R interception radius of line phase conductor, h phase conductor height, subscripts a, ci, and f refer to 97.5%, 50% and 2.5% lightning interception probability, respectively.

3 APPLICATION TO DISTRIBUTION LINES

3.1 Induced-voltage flashover width and minimum current

Figure 3 shows for a 10 m overhead distribution line the variation of the interception radius of phase conductors R with negative lightning crest current at different interception probabilities according to (6). It also shows the variation of the induced-voltage flashover radius R_I according to (7b) for CFO = 150 kV. From this figure the induced-voltage flashover width W_I at a fixed lightning crest current can be obtained as the difference between R_I and R. Also, the intersection points of the curves of R_I and R denote the minimum induced-voltage flashover current $I_{\min}$ above which nearby lightning strokes may cause induced-voltage flashover of line insulation.

As a result of the statistical variation of the line

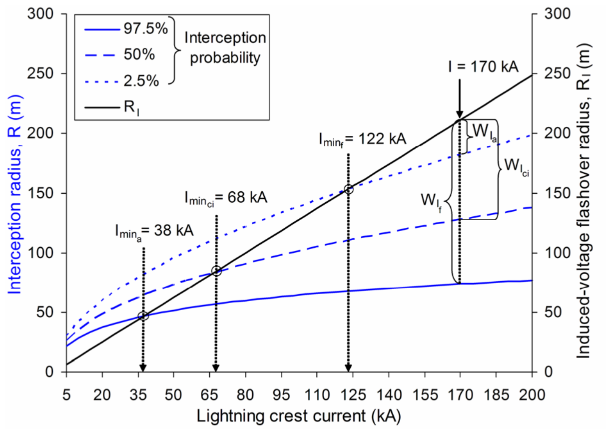

Figure 3: Interception radius of phase conductor R and induced-voltage flashover radius R_I as a function of lightning crest current; h = 10 m, CFO = 150 kV.

phase conductor interception radius, W_I, thus consequently $I_{\min}$, varies significantly with lightning interception probability (Figure 3). This is also shown in Figure 4 where W_I is plotted as a function of lightning crest current at different lightning interception probabilities. W_I, increasing with lightning crest current, is wider at higher interception probabilities. In Figure 4 the intersection of W_I curves with X-axis denotes the minimum induced-voltage flashover current, $I_{\min}$; thus, the latter takes higher values at lower lightning interception probabilities. This is better demonstrated in Figure 5 where $I_{\min}$ is plotted as a function of the CFO of line insulation. Furthermore, as expected, $I_{\min}$ increases with line insulation level and, as can be deduced from (8), decreases significantly with line height.

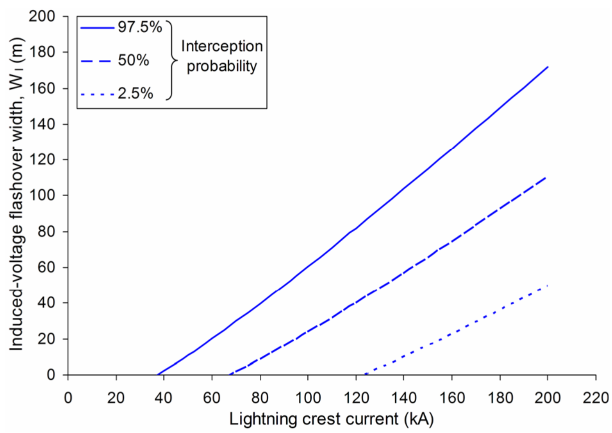

Figure 4: Induced-voltage flashover width of as a function of lightning crest current; h = 10 m, CFO = 150 kV.

3.2 Induced-voltage flashover rate

Figure 6 shows the induced-voltage flashover rate, F_p, of a 10 m overhead distribution line as a function of CFO according to the proposed statistical method, by using in (1) the lightning crest current distribution suggested in [7] and an upper integration limit of 200 kA. For comparison

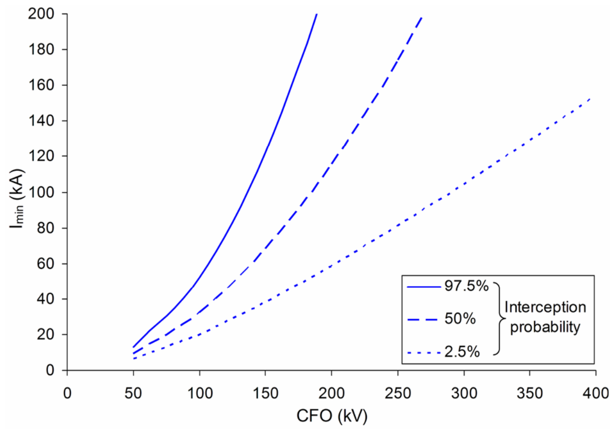

Figure 5: Minimum induced-voltage flashover current as a function of CFO of the line; h = 10 m.

purposes, Figure 6 also shows the F_p yielded by the methods suggested in IEEE Std 1410:2004 [1] and its recent revision IEEE Std 1410:2011 [2]; the latter has adopted for the estimation of F_p the method suggested by Borghetti et al. [9], which combines Monte Carlo simulation and lightning induced overvoltage computer code (LIOV [10]).

It is important to note that for a fixed CFO the statistical method yields, instead of a specific value, a range of F_p associated with lightning interception probability distribution; this, being more realistic when considering the stochastic nature of lightning interception phenomenon, is not the case of the IEEE Std methods [1, 2]. According to the statistical method, F_p is bigger at higher interception probabilities and decreases with CFO with a rate that depends on lightning interception probability (Figure 6).

The variation of F_p with CFO yielded by the IEEE Std methods [1, 2] is within the range of F_p values obtained by the statistical method. Actually, there is a close agreement between the F_p values yielded by the IEEE Std 1410:2011 [2] and those referring to 50% interception probability according to the statistical method (Figure 6); it must be mentioned that when evaluating the long term

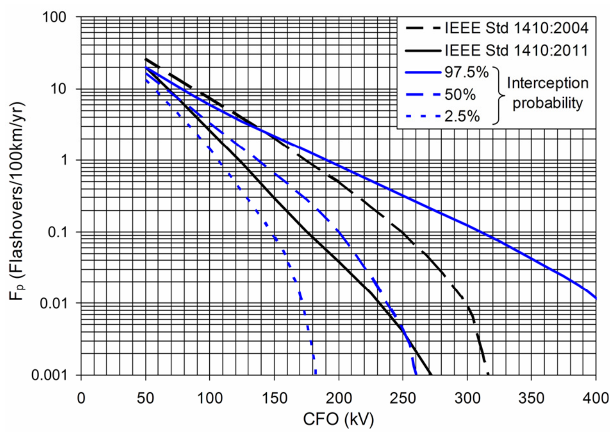

Figure 6: Induced-voltage flashover rate of a 10 m unshielded overhead distribution line; N_g =1 strike/km^2/yr, ideal ground.

performance of distribution lines the F_p at 50% lightning interception probability should be used.

The statistical method provides the means for a straightforward estimation of the induced-voltage flashover rate of unshielded distribution lines, yielding results, consistent with that obtained by IEEE Std method [2], however, without requiring extensive computing effort. It may also provide the range of induced-voltage flashover rate of a distribution line by considering the lightning interception probability distribution of phase conductors; this is shown in Table 2 where the expected induced-voltage flashover rate of a typical 20 kV unshielded overhead line of the Hellenic distribution system is estimated.

Table 2: F_p (flashovers/100km/yr) of a 20 kV unshielded overhead distribution line

	h = 8 m, CFO = 165 kV N_g = 4 strikes/km^2/yr		
Statistical method	6.29^a	1.26^{ci}	0^f

a, ci, f: 97.5%, 50%, 2.5% lightning interception probability

4 CONCLUSION

A statistical method for the estimation of the induced-voltage flashover rate of unshielded overhead distribution lines has been introduced. The method takes into account, besides line height and insulation level and lightning crest current distribution, the lightning interception probability distribution of the line phase conductors.

The proposed method yields, instead of a deterministic value, a range for the expected induced-voltage flashover rate of the distribution line, associated with the lightning interception probability distribution of the phase conductors; this seems more realistic when considering the stochastic nature of lightning interception phenomenon. The induced-voltage flashover rate results of the statistical method, obtained without requiring extensive computing effort, are consistent with those of the IEEE Std. 1410:2011.

5 REFERENCES

[1] IEEE Guide for improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE Std. 1410-2004, Jul. 2004.

[2] IEEE Guide for improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE Std. 1410-2011, Jan. 2011.

[3] P. N. Mikropoulos and T. E. Tsovilis: "Striking distance and interception probability", IEEE Trans. Power Delivery, Vol. 23, No. 3, pp. 1571-1580, Jul. 2008.

[4] P. N. Mikropoulos and T. E. Tsovilis: "Interception probability and shielding against lightning", IEEE Trans. Power Delivery, Vol. 24, No. 2, pp. 863-873, Apr. 2009.

[5] P. N. Mikropoulos and T. E. Tsovilis: "Estimation of lightning incidence to overhead transmission lines", IEEE Trans. Power Delivery, Vol. 25, No. 3, pp. 1855-1865, Jul. 2010.

[6] Rusck, S: "Protection of Distribution Lines", in Lightning, Vol. 2, R. H. Golde, ed., London: Academic Press, pp. 747-771, 1977.

[7] Lightning and Insulator Subcommittee of the T&D Committee: "Parameters of lightning strokes: A review", IEEE Trans. Power Delivery, Vol. 20, No. 1, pp. 346-358, Jan. 2005.

[8] E. R. Love: "Improvements in lightning stroke modeling and applications to design of EHV and UHV transmission lines", M.Sc. thesis, Univ. Colorado, Denver, CO, 1973.

[9] A. Borghetti, C. A. Nucci, and M. Paolone: "An improved procedure for the assessment of overhead line indirect lightning performance and its comparison with the IEEE Std. 1410 method", IEEE Trans. Power Delivery, Vol. 22, No. 1, pp. 684-692, Jan. 2007.

[10] LIOV Code, url: http://www.liov.ing.unibo.it/, last accessed: May 01, 2011.