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Probability of backflashover in transmission lines due to lightning strokes using Monte-Carlo simulation

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Abstract

A method, which estimates the lightning performance of high voltage transmission lines based on the Monte-Carlo simulation technique, is described in this paper. The average number of faults which occur in a transmission line, dividing them in single-phase and three-phase faults, as well as the average grounding resistances of the transmission lines are calculated. The method is applied, on several operating Greek transmission lines, showing good correlation between predicted and field observation results. The proposed method can be used as a useful tool in the design of electric power systems, aiding in the right insulation dimensioning of a transmission line.

Keywords: Lightning stroke; Backflashover; Monte-Carlo simulation; Transmission lines; Power systems

1. Introduction

Lightning as an electrical phenomenon is dependent on several parameters such as: the peak value of current, the maximum rate of change of the surge current, the transferred charge $\int i(t)\mathrm{d}t$ and the integral of the current square $\int i^2(t)\mathrm{d}t$, quantity proportional to the energy which is emitting from the lightning stroke. Any of these parameters has got very disturbing and destroying consequences for human lives and electrical installations.

Analytically, the peak value of current has as a consequence of the flashover of insulators and the damage of the insulation materials, due to the potential increase at the point of the strike. The maximum rate of change of the lightning current determines the inductive voltages in loop circuits. These voltages could be extremely dangerous with dramatic consequences when applied to logic circuits or circuits which contain sensitive electronic components and are used for navigation and communication applications.

The transferred charge causes local melting and piercing of metallic surfaces having small thickness.

The integral of the current square is proportional to the emitting energy, which causes thermal phenomena such as: metal melting, ignition of flammable steams and gases.

Since the grounding wires have been placed suitably, any atmospheric discharge with current value above a certain limit strikes them. Lightning strokes of lower intensity could also strike the phase-conductors but the resulting overvoltage is not capable to create a fault in the line. Therefore, it is obvious that the calculation of the potential increase of a grounding wire, as well as the potential increase of the neighbouring towers are necessary, in order to determine the distances between grounding wires and phase conductors, and insulation between the neighbour towers and phase-conductors.

The potential increase of the tower can be maintained in low levels, if the earth resistance of the tower is low. According to this, there are two different methods in the design of a transmission line. The first method uses good grounding and relatively low line insulation while the second one uses average grounding but relatively high line insulation.

Basic parameters in the insulation design of a transmission line are: the air gap between the phase-conductors and the towers, the leakage distance of the insulators, the air gap between the phase-conductors and the grounding wires and finally the air gap between different phase-conductors.

It is well known that there are two cases in the formation of backflashover. In the first case lightning strikes a tower or a grounding wire directly, having an increase in the potential of the tower. In the second case a lightning strikes

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an overhead phase-conductor, destroying the insulation, increasing the potential of the tower, and giving the probability to appear a backflashover between the tower and a healthy, until to this moment, phase-conductor.

Certainly many parameters, which affect the backflashover phenomenon, are not clear enough. Such parameters are:

- The performance of the tower when impulse current is flowing through it.
- The current distribution to the tower and the struck grounding wire.
- The critical flashover voltage between a power frequency phase-conductor and the tower which flowed from an impulse current.

2. Estimating method of lightning performance

Any method of estimating the lightning performance of transmission lines must cope with a variety of statistical and non-linear effects, and it is pointless, to promote a method whose prediction accuracy exceeds the precision of knowledge of the constants and stimuli that enter the problem [1]. Several methods exist, which allow the yearly estimation of the faults of the line caused by backflashover, giving results very close to the real ones. Such methods have been based in analogue computers [2], geometrical models, travelling waves, field theory methods and Monte-Carlo simulation [3, 4]. A relatively simple estimating method is presented below taking into consideration the following acceptances:

(a) When lightning strikes a phase-conductor the discharge current is propagating in both directions from the point of the strike.
(b) The tower, which is flowed by impulse current, is acting as an inductance with value approximately equal to 0.4 μH [1]. Theoretical estimations give inductance values from 0.5 to 0.7 μH, while measurements give values below 0.3 μH [8].
(c) The grounding of the tower is consisting of an ohmic resistance and an inductance approximately equal to 5 μH.
(d) Backflashover appears in more than one phase-conductor. There is no relation between the peak value and the rate of change of the lightning current.
(e) For every area, the voltages U_1, U_2 and U_3 are calculated using the following equations

$$U_1 = 0.85U_a - L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{1}$$

$$U_2 = U_a - L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{2}$$

$$U_3 = 1.15U_a - L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{3}$$

where L is the total inductance of the system and U_a the dielectric strength of the transmission line against lightning overvoltages.

A single-phase fault appears in a transmission line with grounding wire, for any lightning current I, if

$$U_3 > R\frac{I}{2} \geq U_1 \tag{4}$$

A multiphase fault appears, if

$$R\frac{I}{2} \geq U_3 \tag{5}$$

In case that the transmission line does not have a grounding wire, then two cases are observed:

(a) Stroke to a tower. In this case, a single-phase fault exists if

$$U_3 > RI \geq U_1 \tag{6}$$

and a multiphase fault exists if

$$RI \geq U_3 \tag{7}$$

(b) Stroke to a phase-conductor. A backflashover exists to one of the healthy phases, immediately after the initial single-phase fault, in case that

$$RI \geq U_2 \tag{8}$$

The lightning level is the average number of days per year on which thunder is heard. An approximation for the number of flashes to any line is provided by the following equation [1]

$$N_\mathrm{L} = 0.004T^{1.35}(b + 4h^{1.09}) \tag{9}$$

where T is the lightning level in the vicinity of the lines (thunderstorm days/year); N_L the number of lightning flashes to a line per 100 km per year; h the average height, in metres, of the shield wires; and b is the horizontal spacing, in metres, between the shield wires.

Finally, it must be mentioned that the yearly average number of failures is given from the following equation:

$$\mathrm{AFN} = N_\mathrm{L} \times \mathrm{FP} \tag{10}$$

where FP is the percentage fault probability.

3. Monte-Carlo simulation

The design of transmission lines for a predetermined lightning performance requires a method of predicting failure rates of the lines over a prescribed period of time. Generally, the prediction methods are based on Monte-Carlo simulation [4].

Any approach using Monte-Carlo simulation requires the creation of a set of random numbers, uniformly distributed, in the interval (0,1), i.e. the numbers can take any value between 0 and 1 with equal likelihood [5].

The most effective algorithms for creating random numbers are the congruential generators from which a new number X_i in a sequence is calculated from the previous value X_{i-1} using the expression [5]

$$X_i = (pX_{i-1} + b)(\text{mod } m) \quad (11)$$

where p (the multiplier), m (the modulus) and b (the increment) are all non-negative integers. The process is started by choosing the value X_0 known as the seed. The sequence is then produced automatically.

After deducing the sequence of random numbers X_i, a uniform random number u_i in the range (0,1) can be found [5]:

$$u_i = X_i/m \quad (12)$$

When a generator of random numbers is used, the constant value p, the initial value X_0, the increment b and modulus m must be given. In this paper the following values were randomly selected [6]: $m = 714\,025$, $p = 1366$, $b = 150\,889$, $X_0 = 2345$ for the generation of the maximum lightning current, $X_0 = 4567$ for the generation of the slope of the lightning current and $X_0 = 6789$ for the generation of the nature and kind of the lightning.

In Monte-Carlo simulation the most important aspect is not only the generation of uniformly distributed random numbers, but also the conversion of them into other non-uniform distributions before the simulation process can begin [5].

In this paper the generated numbers were chosen to follow the normal distribution with average value μ and standard deviation σ. In order to obtain this, the following transformation was used

$$X_1 = \mu + \sigma\sqrt{-2 \ln u_i}\cos(2\pi u_2) \quad (13)$$

$$X_2 = \mu + \sigma\sqrt{-2 \ln u_i}\sin(2\pi u_2) \quad (14)$$

where X_1, X_2 is a pair of random numbers which is following the normal distribution $N(\mu, \sigma)$.

4. Procedure and simulation results

The probability of existence of backflashover in a high voltage transmission line, due to lightning strokes was studied. A transmission line having a grounding wire was considered, thus: for backflashover equations (Eqs. (1)–(8)) were used, while for the generation of random numbers uniformly distributed in the interval 0–1 Eqs. (11) and (12) were used using the already mentioned values. Finally the lightning strokes has been considered, the peak value of the lightning current and the rate of change of the lightning current follow the normal distribution and there is no relation between them. The values, which were used in the simulation, were given by Eq. (13). Eighty percent of the lightnings are negatively charged and 20% of them are positively charged with the average value μ and the standard deviation σ to be shown in Table 1.

Table 1
Lightning parameters [7]

		μ	σ
Positive lightning	I_{max} (kA)	35	15
Positive lightning	di/dt (kA/μs)	2.4	1.1
Negative lightning	I_{max} (kA)	30	7.5
Negative lightning	di/dt (kA/μs)	40	14

Several tests were carried out varying the resistance from 10 to 35 Ω and the basic insulation level (BIL) from 750 to 1300 kV. It must be mentioned that all the input values were taken from the data from the real networks of Greek Public Power Corporation. For the tests presented in this paper convergence was achieved after a few thousand repetitions. The backflashover probability for different values of protective insulation and grounding resistance is shown in Fig. 1. The percentage probability of having multiphase fault for various grounding resistances is shown in Fig. 2.

In order to illustrate the proposed method three different 150 kV transmission lines running in the Greek territory are considered. The lines have been selected due to their high failure rates during lightning thunderstorms.

The line Tavropos–Lamia having length of 75.384 km, runs through a mountainous region and comprises of a three-phase double circuit, 219 towers with average span of 350 m, 750 kV BIL, phase-conductor dimensions ACSR 636 MCM, average height of grounding wires 19 m and horizontal spacing between the grounding wires 9 m. The average lightning level in the vicinity of the line for this area and the number of average failures occurred in this line from 1995 to 1999, were 22.2 and 6, respectively [8,9].

The line Kilkis–Serres having length of 58.068 km, runs through a plain region and comprises of a three-phase single circuit, 162 towers with average span of 360 m, 750 kV BIL, phase-conductor dimensions ACSR 336.4 MCM, average height of grounding wires 19 m and horizontal spacing between the grounding wires 6.5 m. The average lightning level in the vicinity of the line for this area and the yearly number of average failures occurred in this line from 1995 to 1999, were 27.2 and 3, respectively [8,9].

The line Igoumenitsa–Sagiada having length of 8.881 km, runs through the coastline and comprises of a three-phase single circuit, 41 towers with average span of 220 m, 750 kV BIL, phase-conductor dimensions ACSR 336.4 MCM, average height of grounding wires 19 m and horizontal spacing between the grounding wires 6.5 m. The average lightning level in the vicinity of the line for this area and the yearly number of average failures occurred in this line from 1995 to 1999, were 41.6 and 3, respectively [8,9].

The lightning performance for each one of the above

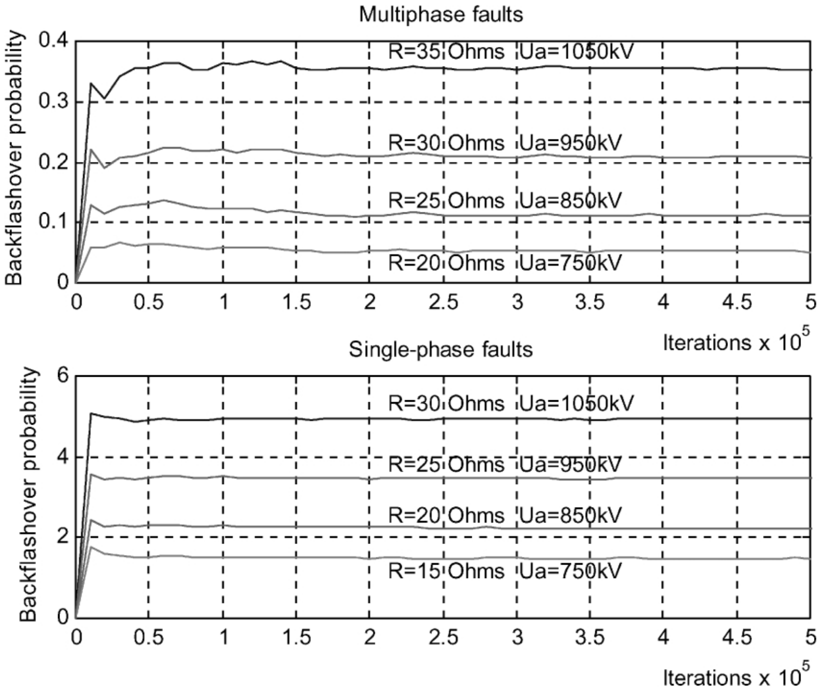

Fig. 1. Backflashover probability for different values of protective insulation and grounding resistance.

three lines was calculated, considering the characteristics of each line. Furthermore, the grounding resistance for each line was estimated, using Eq. (10).

The obtained results were very close to the actual ones, which implies that the proposed method has an acceptable accuracy.

5. Conclusions

The paper presents a method, which estimates the lightning performance of high voltage transmission lines using backflashover calculations and Monte-Carlo simulation. Satisfactory results for three different lines of the

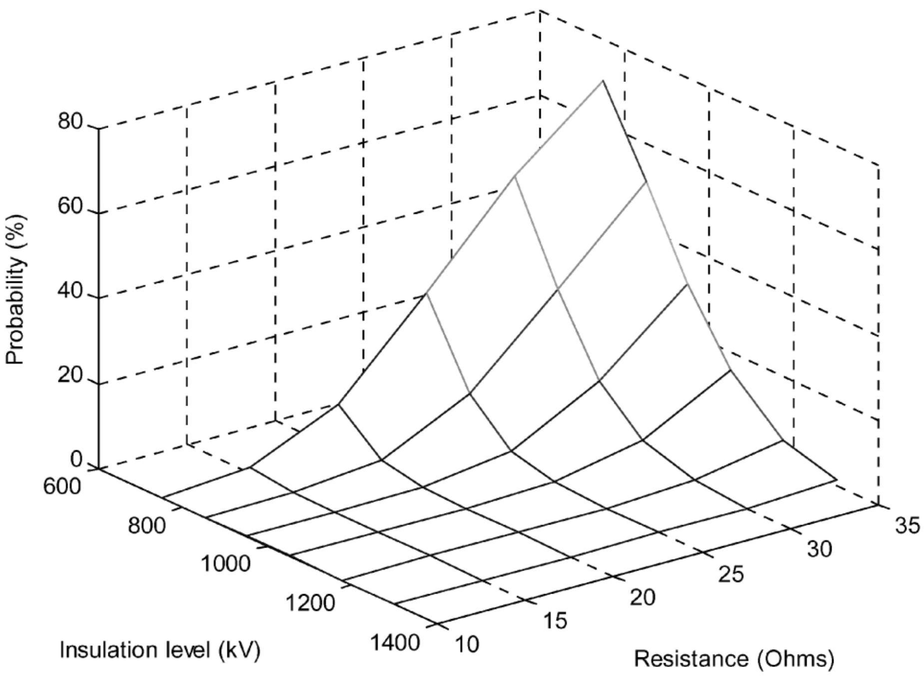

Fig. 2. The percentage probability of having fault.

Greek interconnected transmission system were presented, verifying the accuracy of the method.

Similar studies could be conducted for other transmission lines for sensitivity analysis.

The presented method as well as the obtained results can be used from electric power utilities in order to predict the lightning performance of any type of transmission and distribution line which means that it is an useful tool for the design of electric power systems.

References

[1] IEEE Working Group on Lightning Performance of Transmission Lines, A simplified method for estimating lightning performance of transmission lines. IEEE Trans Power Appar Syst 1985;104(4): 919–27.

[2] Clayton JM, Young FS. Estimating lightning performance of transmission lines. IEEE Trans Power Appar Syst 1964;83:1102–10.

[3] Anderson JG. Monte Carlo computer calculation of transmission-line lightning performance. AIEE Trans 1961;80:414–20.

[4] Torres CR. Lightning outages calculations for transmission lines. Proc 11th Int Symp High Voltage Engng 1999;5(467).

[5] Billinton R, Allan RN. Reliability evaluation of engineering systems, 2nd ed. New York: Plenum Press; 1994.

[6] Gonos IF. Probability of fault due to lightning current at the high voltage lines. Monography, Greece: National Technical University of Athens; 1997.

[7] Berger K, Anderson RB, Kroninger H. Parameters of lightning flashes. Electra 1975;41:23–37.

[8] PPC, Transmission lines characteristics. Athens: Public Power Corporation; 2000.

[9] Ekonomou L, Gonos IF, Stathopulos IA, Dialynas EN. A backflashover model for calculating the transmission lines' lightning performance. Proceedings of the 12th International Symposium on High-Voltage Engineering (ISH 2001), Bangalore, India; August 19–24, 2001.

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