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Lightning performance of a real distribution network with focus on transformer protection

Fabio Napolitano [a,*], Fabio Tossani [a], Alberto Borghetti [a], Carlo Alberto Nucci [a], Manuel L.B. Martinez [b], Gustavo P. Lopes [b], Gilnei J. G. Dos Santos [c], Donorvan R. Fagundes [c]

[a] University of Bologna, Bologna, Italy
[b] Federal University of Itajubá, Itajubá, Brazil
[c] AES Sul, São Leopoldo, Brazil

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ABSTRACT

The paper applies a Monte Carlo procedure to evaluate the lightning performance of a real medium-voltage distribution network, which includes a number of lines, transformer stations and surge protection devices. Such a procedure allows inferring the characteristics of the statistical distributions of lightning-originated voltages at any point and at any phase of the network. The analysis presented in this paper aims at assessing the expected mean time between failures of MV/LV transformers caused by both direct and indirect lightning strikes. A heuristic technique has been specifically developed to reduce the computational effort despite the non-linear response of the network equipped with surge arresters.

1. Introduction

The frequency of lightning-caused transformer failures in overhead distribution feeders may be of concern especially in areas characterized by a high keraunic level (e.g. [1,2]), thus justifying specific studies in order to reduce the outage rate below the requested threshold.

A joint research project between the Brazilian electric distribution utility AES Sul and two Universities, namely the Federal University of Itajubá and the University of Bologna, has focused on the assessment of the protection distance of surge arresters (SAs) in distribution networks with resonant grounding, in order the achieve the desired protection level of distribution transformers against lightning at affordable costs. The expected frequency of flashovers due to indirect strikes, i.e. lightning strikes hitting the ground nearby the lines, has been calculated for the case of medium voltage straight lines with different types of poles and the relevant results have been presented in [3,4]. The lightning induced voltage calculations is performed by using the LIOV-EMTP-RV code [5,6]; a Monte Carlo procedure adapted from the one presented in [7], also described in [8], is applied in order to calculate the expected mean time between failures (MTBF) of the MV/LV transformers.

This paper describes the development of such a procedure for the evaluation of the lightning performance of a real three-phase distribution medium voltage feeder located near Novo Hamburgo (Brazil). The feeder is characterized by a complex topology, with several multi-conductor lines, MV/LV transformers and surge protection devices.

In addition to the estimation of the indirect lightning performance (i.e. the lightning performance calculated only for the case of indirect strikes), in this paper the analysis has been extended to include the effects of direct strikes.

The developed model of the distribution network represents the specific features of the real network, such as the network topology, the multi-conductor line and pole configurations, the presence of surge protective devices. The coupling model between the lightning electromagnetic pulse (LEMP) and the overhead conductors takes into account the characteristics of the lightning current, the return stroke model, and the LEMP propagation above a lossy ground.

The Monte Carlo procedure adopted in this paper includes a heuristic technique, designed and implemented in order to reduce the computational effort required for the analysis of large networks. The heuristic technique is able to deal with the non-linear response of the network due to the presence of SAs.

* Corresponding author. Tel.: +390512093573.
E-mail address: fabio.napolitano@unibo.it (F. Napolitano).

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Section 2 presents and discusses the calculation procedure. Section 3 describes the Novo Hamburgo distribution feeder and presents the results obtained assuming different locations of the SAs. Section 4 concludes the paper.

2. Calculation method

The statistical procedure is based on the application of the Monte Carlo method and can be summarized as follows. A large number n_{tot} of lightning events is randomly generated. Each event is characterized by four parameters: lightning current amplitude I_p, time to peak t_f and stroke location with coordinates x and y.

The lightning current parameters are assumed to follow the Cigré log-normal probability distributions [9,10] for negative first strokes, with a correlation coefficient between t_f and I_p equal to 0.47. The effects of the presence of positive flashes and of subsequent strokes in negative flashes on the lightning performance of the feeder are assumed to be negligible.

The stroke locations are assumed to be uniformly distributed in a striking area, having a size large enough to contain the entire network and all the stroke locations of the indirect lightning events that could cause voltages larger than the minimum value of interest for the analysis.

In general (e.g. [8]), the lightning performance is expressed by means of a curve providing the expected annual numbers of lightning events F_p that cause voltages with amplitude larger than the insulation level reported in abscissa:

$$F_p = \frac{n}{n_{tot}} A N_g \quad (1)$$

where n is the number of events that cause voltages higher than the considered insulation level, A is the striking area and N_g is the annual ground flash density (assumed equal to 1 flash/km^2/yr in this paper).

If referred to a single straight line, the lightning performance is usually expressed in terms of number of events per year per unit length of line. However, the indirect lightning performance of a network with complex topology (e.g. a distribution feeder with several laterals) may significantly deviate by the one inferred from the results obtained for the case of a single straight line [11]. Therefore, since the project that motivates this paper is focused on the protection of MV/LV transformers, the MTBF values are calculated by applying (1) to each MV bus where a transformer is connected. Value n is obtained by comparing the lightning voltage with the relevant withstand voltage of the transformer insulation that is assumed to be constant and known. In order to take into account the withstand probability distribution of transformer insulation a more complex procedure would need to be applied [12].

2.1. Indirect lightning performance

From the total set of n_{tot} lightning events, the ones relevant to indirect lightning are selected by using a lightning incidence model for the line. In this paper we have adopted the electro-geometric model suggested in [8].

As already mentioned, the calculation of the induced voltages caused by indirect lightning strikes is performed by using the LIOV–EMTP-RV code. It allows for the evaluation of the voltages induced by lightning return strokes on multi-conductor overhead lines above lossy ground by using a finite-difference time-domain (FDTD) solution method of the Agrawal et al. field-to-line coupling model [13]. The LEMP is calculated by using the analytical formulation presented in [14] with the assumption that the lightning return stroke current propagates along a straight vertical channel according to the transmission line (TL) model. The assumed value for the return-stroke propagation speed is 1.5×10^8 m/s. The lightning current waveform at the channel base is approximated by a linear ramp up to the peak value I_p at time t_f, followed by a constant value. Two values of the ground conductivity σ_g are considered: 10^{-3} and 10^{-2} S/m. The lossy ground effect on the LEMP are accounted by means of the Cooray–Rubinstein formula [15–17]. The bus voltage at the utility frequency is taken into account by using the procedure described in [3].

In order to appraise the indirect lightning performance in a reasonably low computational time, a heuristic technique has been applied that avoids performing the time-domain simulation for events expected to be less harmful than previously calculated events that have not caused flashovers. The events that are believed to be not significant for the calculation of n without performing the corresponding time-domain simulations are those that are characterized by lower I_p, greater t_f and greater distance between the stroke location and the nearest SAs than a previously calculated event that causes a current in the SAs below a predefined minimum value, I_{sa}. The adopted value is I_{sa} = 100 A so that very similar results both with and without the application of the heuristic procedure are obtained for a test case composed by a straight three-conductor line with equally spaced SAs.

2.2. Direct lightning performance

In order to take into account the effects of direct events on the lightning performance of the network, the overvoltages corresponding to each of the Monte Carlo events classified as direct strikes to the line are calculated by using a LIOV-EMTP-RV model. A direct strike is represented by a current source connected to the pole closest to the randomly-generated stroke location coordinates. As for the calculation of the induced voltages, the waveshape of the lightning currents is represented by a linear front and a flat top. The surge impedance of the lightning channel is assumed much larger than that of the line and, therefore, neglected. The LEMP effect is accounted also in case of a direct strike, assuming the stroke location 10 m far from the line in order to avoid numerical singularities. This approximation is justified since, near the stroke location, the overvoltages due to the current injection prevail over those induced by the LEMP. Direct strikes to distribution overhead lines are always expected to cause flashovers at line insulators, unless very close SAs are installed [8], even in presence of ground wires [18,19]. The overvoltages at buses not equipped with SAs are greatly influenced by the occurrence of flashovers at the line insulators and by the number of SAs along the path from the stricken point to the observed buses. A larger number of flashovers along the feeder would result in a worst lightning performance of the line, but in an increase of MTBF of the transformers not equipped by surge protective devices.

The implemented model represents the insulator flashovers by means of ideal switches that close according to the disruptive effect criterion [20]: a flashover occurs if the time integral of the line-to-ground voltage exceeds a given value DE.

The adopted DE values stand on the ones provided by De Conti et al. in [21], which are inferred from experimental tests on a pin-type ceramic insulator of the same type installed in the AES Sul networks. For the insulator of the central conductor, due to the its vicinity to a metallic crossarm brace, we assumed the same values proposed in [21] for the insulator alone, i.e. DE = 60.9 kV μs and V_0 = 90 kV, where V_0 is the minimum voltage for the initiation of the breakdown process. For the insulators of the two outer conductors we assumed DE = 255 kV μs and V_0 = 164 kV taking into account that the insulators are in series with a 60 cm long wooden crossarm. The latter value, larger than the value proposed in [21] for insulators in series to 40 cm of wooden crossarm, has been obtained by assuming a per unit-length increase of the CFO due the wood equal to