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Response of distribution networks to direct and indirect lightning: Influence of surge arresters location, flashover occurrence and environmental shielding

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ABSTRACT

The paper deals with the response of distribution networks to direct and indirect lightning. The response of the network is analyzed with the aim of inferring the mean time between failures of the connected transformers. This is accomplished taking into account the voltage at the utility frequency, the flashovers occurrence in the line insulators, the location of surge arresters, and the shielding provided by nearby buildings. Two different transformer failure criteria are assumed: a critical value and a disruptive effect model.

The results make reference to multi-conductor overhead systems with two different topologies: simple straight line and a real feeder with laterals. It is shown that such a detailed lightning performance analysis is useful in order to select the most appropriate strategy for the installation of surge arresters, which may allow the achievement of the desired mean time between failures at affordable costs.

1. Introduction

The protection methods of medium voltage (MV) power distribution lines are described in the Cigré brochure 441 [1] and references therein, which account also economical aspects and power quality. One of the important issues to be addressed is the protection of the connected distribution transformers against lightning, which is in several cases accomplished by means of surge arresters (SAs).

In this respect, the interest by power utilities to investigate the possibility of reducing the number of installed surge arresters is justified. This may be the case, for example, when the change of the neutral earthing method from solidly earthed to resonant one is planned [2], and the reduction of the number of installed surge arresters becomes therefore a possibility worth of investigation as, in principle, all SAs would need to be replaced. Such a reduction is possible only after the accurate assessment of the protection distance of the SAs, which has to make reference to the most realistic representation of the phenomena involved.

In this study, the effectiveness of location of SAs for the protection of the connected medium voltage/low voltage (MV/LV) transformers has been assessed by developing a procedure able to take into account both direct and indirect lightning strikes, the bus voltage at the utility frequency, the flashovers occurrence in the line insulators, and the shielding provided by nearby buildings. This paper presents such a procedure and the results obtained for two different topologies: a simple straight line and a more complex one, represented by a feeder with laterals. Also, two different transformer failure criteria are assumed: a critical withstand voltage and a disruptive effect model.

The structure of the paper is the following. Section 2 describes the main characteristics and assumptions of the calculation procedure. Section 3 presents the results of the analysis for the case of a straight multiconductor line with typical pole configuration. Section 4 presents the results for the case of a realistic feeder. Section 5 concludes the paper.

2. Calculation method and simulation environment

The approach adopted for the estimation of the lightning performance is based on the application of the Monte Carlo method, as presented in Refs. [3,4]. The developed procedure 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

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coordinates x and y. The lightning current parameters are assumed to follow the Cigré log-normal probability distributions [5,6] 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 lightning events that could cause voltages larger than the minimum voltage value of interest for the analysis.

In general (e.g. Ref. [7]), 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 voltage value reported in abscissa:

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

where n is the number of events causing overvoltages 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 the results shown 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 (e.g., 100 km of line, as usually done for transmission lines). However, the indirect lightning performance of a network with complex topology (e.g. a distribution feeder with several laterals) may significantly deviate from the one of a straight line of equal length [4]. Therefore, since the project that motivates this paper is focused on the protection of MV/LV transformers, such a performance is here expressed with the expected values of mean time between failures (MTBF), which are given by the inverse of the relevant F_p values calculated by applying Eq. (1) to each MV bus where a transformer is connected, where n is calculated by comparing the lightning voltage with the relevant withstand voltage. The withstand voltage of the transformers is assumed to be known (in order to take into account the withstand probability distribution of transformer insulation a more complex procedure would need to be applied [8]).

In this paper, the lightning current waveform at the channel base is approximated by a ramp up to the peak value I_p at time t_f, followed by a constant value. In Ref. [9] a Monte Carlo procedure able to take into account the typical functions adopted to represent the waveform of the lightning current at the channel base (e.g., the Heidler function and the Cigré function) has been proposed. The comparison between the results obtained by using different current waveforms shows that the simple trapezoidal current waveform represents a good compromise between computational effort and conservative assessment of the lightning performance.

2.1. Calculation of the overvoltages due to indirect lightning events

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. For the calculations of this paper, we have adopted the electro-geometric model suggested in Ref. [7].

In the literature, several approaches have been proposed for the evaluation of the lightning electromagnetic pulse (LEMP) response of distribution networks (e.g., Nucci et al. [10], Orzan et al. [11], Høidalen [12], Perez et al. [13], Andreotti et al. [14]).

To obtain the results shown in this paper, the calculation of the induced voltages caused by indirect lightning strikes are performed by using the LIOV–EMTP-RV code [15,16]. 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 [17]. The LEMP is calculated by using the analytical formulation presented in Ref. [18] with the assumption that the lightning return stroke current pulse propagates along a straight vertical channel according to the transmission line (TL) model [19]. The assumed value for the return-stroke propagation speed is 1.5×10^8 m/s.

The lossy ground effect on the LEMP are accounted by means of the Cooray–Rubinstein formula [20–22]. The bus voltage at the utility frequency is taken into account by using the procedure described in Ref. [23].

In order to appraise the indirect lightning performance in a reasonably low computational time also for the case of large networks equipped with SAs, the heuristic technique proposed in Ref. [2] has been applied. The procedure avoids to perform the time-domain simulation for the events that are expected to be less harmful than previously calculated ones that have not caused flashovers, i.e., those 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 (assumed equal to 100 A).

SAs of 15 kV class are considered in the simulation and the relevant voltage–current characteristic is reported in Ref. [24].

2.2. Calculation of the overvoltages due to direct lightning events

The overvoltages corresponding to each of the events classified as direct strikes to a line conductor by using the electro-geometric model are calculated by using an EMTP-RV model. The direct strikes are represented by current sources connected to the pole closest to the randomly-generated stroke location coordinates.

Direct strikes to distribution overhead lines are always expected to cause flashovers at line insulators, unless very close SAs are installed [7], even in presence of ground wires [25,26]. The overvoltages at buses not equipped by 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. The insulators flashovers is represented by means of ideal switches that close according to the disruptive effect criterion [27]: a flashover occurs if the time integral D of the line-to-ground voltage exceeds a given value DE. Integral D is given by the following expression

$$D = \int_{t_0}^{t} [|v(t)| - V_0]^k dt \quad (2)$$

where $v(t)$ is the voltage at the pole insulator, V_0 is the minimum voltage to be exceeded before any breakdown process can start, k is a dimensionless factor, and t_0 is the time at which $|v(t)|$ becomes greater than V_0.

The effect of soil ionization at the grounded poles is accounted by using the Weck's approximation [6], with soil breakdown gradient taken equal to 400 kV/m.

3. Single multiconductor overhead distribution line with typical pole configuration

Recent papers addressed the issue of the lightning performance of distribution lines appraisal taking into account both direct and indirect lightning events [28,29]. When assessing the lightning performance of distribution lines, major attention is in general devoted to calculation of the induced voltages from nearby strikes rather than to those caused by direct strikes to the line since the latter are all expected to cause a fault in the line. However, a detailed calculation of the overvoltages due to direct strikes is needed when for the evaluation of the expected frequency of faults at specific locations of medium voltage distribution networks [24].

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