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Protection against lightning overvoltages in resonant grounded power distribution networks

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ABSTRACT

AES Sul, a Brazilian electric distribution utility, has recently started a project focused on the installation of neutral resonant grounding devices at the medium voltage side of some substation transformers previously operated with solid grounded neutral. As a consequence of the expected increase of the voltage in the sound conductors during phase to ground faults, all the surge arresters must be replaced with ones with increased rating. In order to minimize the number of required surge arresters, a procedure has been developed for the estimation of the annual number of lightning events causing concomitant faults in more than one phase conductor. The paper describes the procedure, which takes into account all the main factors that have a significant influence on line insulation flashovers caused by lightning, and presents results obtained for the case of an overhead line with and without protection means.

1. Introduction

AES Sul, a Brazilian electric distribution utility, has recently started a project focused on the installation of neutral resonant grounding devices at the medium voltage side of some substation transformers previously operated with solid grounded neutral. An improvement of the supply continuity is expected. In particular permanent phase-to-ground faults may not require the immediate opening of the three-pole circuit breakers. On the other hand, as a consequence of the increase of the voltage in the sound conductors during a phase-to-ground fault in resonant grounded distribution feeders, all the surge arresters must be replaced with ones with increased rating. The above motivates the effort to develop a procedure aimed at minimizing the number of required surge arresters, taking into account that the considered distribution feeders are composed mainly by overhead lines and they are located in a region characterized by high values of cloud to ground flash density [1].

The results of a preliminary study carried out by the authors in this respect have been presented in [2] which presents an analysis of the protective zone of surge arresters and an arcing-horn gap connected to a multiconductor overhead line exposed to lightning electromagnetic pulses (LEMP) caused by indirect strokes. The analysis presented in [2] is carried out by means of the statistical simulation procedure presented in [3,4][1] suitably adapted in order to take into account the effects of the utility frequency voltage for the calculation of the lightning induced voltages, which represents a novelty by comparison with the previous literature on the subject (e.g. [5–10]). This paper represents a further improvement with respect to the existing literature, as the mentioned procedure has been enriched in order to represent the flashovers in a way that the estimation of the annual number of lightning events causing concomitant faults in more than one phase conductor can now be calculated: this is of utmost importance for the protection design/coordination in resonant grounded feeders, aimed at minimizing the expected frequency for these events.

The structure of the paper is the following. Section 2 describes the procedure with particular reference to the representation of the utility frequency voltage and flashovers. Section 3 describes the type of overhead line taken into account in the analysis and the relevant protections. Section 4 shows the time domain voltage

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[1] Such a procedure has been also included in the new version of IEEE Std. 1410 [23].

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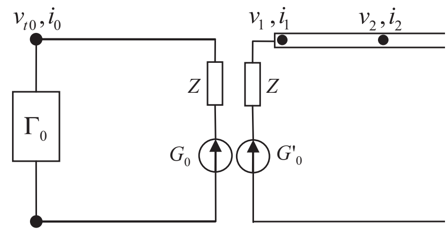

Fig. 1. Scheme of the interface between the LIOV-line and EMTP-RV model of its left termination.

waveforms calculated for some test cases. Section 5 presents the results of the statistical analysis. Section 6 concludes the paper.

2. The applied procedure

The procedure provides the graph of the expected number of annual voltages exceeding the value in abscissa at each pole of the line for each phase conductor. Moreover, with the implementation of the flashover model – which is one of the focuses of the present paper–it provides the expected frequency of flash at each pole of the line, and this for each phase of the multi-conductor line.

The procedure is based on the Monte Carlo method and on the LIOV-EMTP code, described in [11,12] which implements the LEMP-to-line coupling model based on that proposed by Agrawal et al. [13] and the analytical formulation presented in [14] for the fast calculation of the lightning electromagnetic pulse (LEMP).

The LIOV-EMTP model adopted in this paper has been further improved in order to take into account the presence of the utility frequency voltage, as described in Section 2.1. The procedure provides the estimation of the expected flashover rate by using the model of the withstand capability of the insulation described in Section 2.2.

2.1. Analysis of the effects of the induced voltage on energized lines

The LIOV-EMTP code is based on the interface between the LIOV (Lightning Induced Overvoltage) code [15,16] with the revised version of the Electromagnetic Transient Program (EMTP-rv) [17].

For the case of a line with a single conductor, Fig. 1 illustrates the circuit that links the Agrawal et al. model of the illuminated line implemented in the LIOV code with the EMTP model of the left termination of the line (represented by function Γ_0). The meaning of the symbols reported in the figure is the following:

- $v_1, v_2, \ldots$, and $i_1, i_2, \ldots$, are the so-called scattered voltages and line currents, respectively, at nodes $1, 2, \ldots, k_{max}$-1 of the second-order finite-difference time-domain spatial grid used to solve the equations of the Agrawal et al. model;
- $v_{t,0}$ and i_0 are the total voltage and line current, respectively, at the left termination ($v_{t,k_{max}}$ and $i_{k_{max}}$ at the right termination);
- Z is the surge impedance of the line (assumed to be frequency independent);
- G_0 and G'_0 are the Bergeron equivalent generators [18] ($G_{k_{max}}$ and $G'_{k_{max}}$ at the right termination).

G_0^n and $G_{k_{max}}^n$ at the two line terminations at time step n are

$$G_0^n = v_1^{n-1} - Zi_1^{n-1} + v_{e,0}^n \tag{1}$$

$$G_{k_{max}}^n = v_{k_{max}-1}^{n-1} + Zi_{k_{max}-1}^{n-1} + v_{e,k_{max}}^n \tag{2}$$

where $v_{e,i}$ is the incident, or exciting, voltage at node i, i.e.

$$v_{e,i} = -\int_0^h E_{z,i}^e dz \tag{3}$$

with h the conductor height and $E_{z,i}^e$ the vertical component of the exciting electric field.

G'^n_0 and $G'^n_{k_{max}}$ at time step n are

$$G'^n_0 = v_{t,0}^n + Zi_0^n - v_{e,0}^n \tag{4}$$

$$G'^n_{k_{max}} = v_{t,k_{max}}^n - Zi_{k_{max}}^n - v_{e,k_{max}}^n \tag{5}$$

G_0^n, $G_{k_{max}}^n$, G'^n_0 and $G'^n_{k_{max}}$ are calculated by the LIOV code and defined in the EMTP-rv simulation environment by means of a specific dynamic link library.

As the time horizon usually adopted for induced voltage calculations is of the order of some tens of microseconds, the 50 or 60 Hz voltage is assumed equal to a constant value V, for simplicity, uniform along the line (positive sequence in three phase lines). Value V is added in the left side of both (1) and (2).

In induced voltage calculations, the overhead line of finite length is often assumed to be terminated on its surge impedance at one or both ends. This simplifies the analysis of the results as the effects of the reflections of the travelling surge waves at the line terminations are avoided.

In case of unenergized lines, a matched line is represented by defining Γ_0 equal to the surge impedance Z of the line (or a set of branches of coupled impedances in case of multiconductor lines). Then, total voltage $v_{t,0}$ is equal to the half value of sources G_0.

In order to preserve the possibility to represent a matched line at one or both ends also when stationary voltage V is taken into account, the line termination is kept open in the EMTP circuit. Sources G_0 and/or $G_{k_{max}}$ are calculated as the half of the value given by (1) and (2) plus V:

$$G_0^n = \frac{1}{2}(v_1^{n-1} - Zi_1^{n-1} + v_{e,0}^n) + V \tag{6}$$

$$G_{k_{max}}^n = \frac{1}{2}(v_{k_{max}-1}^{n-1} + Zi_{k_{max}-1}^{n-1} + v_{e,k_{max}}^n) + V. \tag{7}$$

Sources G'_0 and/or $G'_{k_{max}}$ are always null so to simulate the absence of voltage wave reflected inward the line at the matched termination.

The linking method described by (1)–(5) includes a time step difference between the calculation of G_0^n (or $G_{k_{max}}^n$) and the calculation of G'^n_0 (or $G'^n_{k_{max}}$) corresponding to the propagation time along the Bergeron line. Such a delay is avoided with the technique presented in [12], where the Bergeron line is included in the illuminated line. In this approach, (1) and (2) become

$$G_0^n = v_1^{n-1} - Zi_1^{n-1} + v_{e,0}^n - \frac{\Delta x}{2}(E_{x,0}^n + E_{x,1}^{n-1}) \tag{8}$$

$$G_{k_{max}}^n = v_{k_{max}-1}^{n-1} + Zi_{k_{max}-1}^{n-1} + v_{e,k_{max}}^n + \frac{\Delta x}{2}(E_{x,k_{max}-1}^{n-1} + E_{x,k_{max}}^n) \tag{9}$$

For the representation of the stationary voltage and the matched terminations G_0 and $G_{k_{max}}$ are calculated as half of the value given by (10) and (11) plus V. The value of the currents at the matched terminations is calculated in the LIOV code by

$$i_0^n = -\frac{G_0^n - V}{Z} \tag{10}$$

$$i_{k_{max}}^n = \frac{G_{k_{max}}^n - V}{Z}. \tag{11}$$