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On the role of transformer grounding and surge arresters on protecting loads from lightning-induced voltages in complex distribution networks

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ABSTRACT

This paper presents a study of overvoltages caused by cloud-to-ground lightning strikes on loads connected to a complex low-voltage distribution network. The importance of the transformer grounding in the resulting load overvoltages is discussed for two different lightning events. These events emphasize either the induced-voltage component or the surge transference through the distribution transformer as the main source of overvoltages on the connected loads. A brief discussion is also presented on the efficiency of low-voltage surge arresters in protecting loads connected to complex low-voltage networks. The obtained results indicate that the effectiveness of improving the transformer grounding and of installing surge arresters at specific points of the low-voltage network is limited in terms of load protection if a complex network topology is considered. In some cases, especially for a lightning strike close to the low-voltage line, improving the transformer grounding can even increase load overvoltages.

1. Introduction

One of the main difficulties regarding the study of lightning overvoltages on loads connected to complex distribution networks is in the fact that there are too many possibilities of interaction between lightning and the connected loads [1–3]. For example, in the case of a lightning strike to a building in an urban area, part of the energy associated with the lightning current will penetrate the distribution system through voltage gradients created in the ground, which will inject currents into nearby medium-voltage (MV) and low-voltage (LV) lines through the existing grounding points [4]. Another part of the energy associated with the lightning current will be injected into the LV line through the back-flow of common-mode currents from the building to the low-voltage line conductors [4–6]. Also, the electromagnetic fields radiated by the lightning channel will induce voltages on both MV and LV distribution lines [7,8]. Finally, part of the surges induced on the MV lines will be transferred to the LV lines through distribution transformers and/or insulation breakdown [8–10].

In addition to the myriad of possibilities regarding the interaction of lightning with complex distribution lines, another difficulty regarding the analysis of this phenomenon is the fact that there are too many parameters to be considered, each of them playing a different role on the resulting load overvoltages [8–13]. This often makes it difficult for the analyst to take a decision about the most appropriate protection design for a given line topology. For example, it is believed that for reducing load overvoltages due to the surge transference from MV to LV distribution lines through distribution transformers the R_t/R_c ratio should be kept low, where R_t and R_c are, respectively, the transformer and consumer grounding resistances [14]. However, in a different scenario considering a lightning strike to the ground in the vicinity of a complex distribution network [e.g., 8–10], the resulting load overvoltages will be caused not only by the transference of surges from the MV line to the LV line through the distribution transformer, but also by the effect of the lightning electromagnetic fields that illuminate the LV line. In such case, the effect of reducing the R_t/R_c ratio on the associated load overvoltages is, in principle, not known.

In this paper, an attempt is made to identify the influence of transformer grounding and LV surge arresters on overvoltages caused by nearby cloud-to-ground lightning strikes on loads connected to a complex distribution network typically found in urban areas. The analysis considers the simultaneous effect of surges transferred from the MV line to the LV line through the distribution

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transformer and the illumination of the LV lines by the incident lightning electromagnetic fields. The obtained results are believed to give an indication of actions that power utility companies may take or not for reducing lightning-related problems in LV networks.

2. Developments

2.1. Simulated system

The simulated system is shown in Figs. 1 and 2. It reproduces the complex distribution network studied in [10], except that now the occurrence of flashovers at the MV and LV insulators is considered. The network topology consists of two MV lines connected to four LV lines through distribution transformers. The transformers are protected by ZnO surge arresters at their primary and secondary sides. The system topology is such that a continuous, effectively grounded neutral conductor is shared by the MV and LV lines. The connecting point of the neutral of each LV line to the neutral of the MV line is located at the transformer poles, more exactly at the transformer grounding, R_t. The neutral is also grounded at every service entrance with a single grounding rod, named R_c. The use of a continuous, effectively grounded neutral conductor is a requisite for the short-circuit protection of the lines, as adopted by many power utility companies in Brazil. In principle, it has no relation with the lightning protection of the lines.

The MV lines adopt the open-wire configuration shown in Fig. 1. The neutral wire is laid down 1.2 m below the phase conductors. It is grounded at poles P1, P2, P3, P5, P7, P8, P9, P10, and P11 with a single vertical rod, while at the transformer poles P4, P6, P10, and P12 three vertical grounding rods are used. As discussed above, the grounding points at poles P4, P6, P10, and P12 are shared by the neutral conductors arriving at the MV and LV sides of the transformers. To avoid reflections, the MV line 1 is matched at both ends. Each of the LV networks is formed by a three-phase line with four vertically stacked wires as shown in Figs. 1 and 2.

2.2. Modeling of system components

The distribution system shown in Figs. 1 and 2 was implemented in the Alternative Transients Program (ATP) [15]. The grounding model used in the simulations reproduces the frequency response of grounding configurations comprising either one or three vertical rods up to a few MHz. It consists of an RC parallel circuit with $R = 0.346\sigma$ and $C = 0.0256\varepsilon_r$ (for the case of one 2.4-m long vertical rod buried in the ground) and $R = 0.119\sigma$ and $C = 0.0743\varepsilon_r$ (for the case of three parallel rods of 2.4 m buried in intervals of 3 m) [16]. In such expressions, R and C are given in Ω and nF, respectively, and σ and ε_r are the conductivity and the relative electric permittivity of the ground, which for the base case considered here are respectively assumed as 0.002 S/m and 10. All grounding down-conductors were modeled as 7.2-μH inductances.

The transformer model reproduces the frequency response of a typical 30-kVA (13.8 kV/220-127 V, delta-wye) three-phase distribution transformer up to a few MHz [17]. The ZnO surge arresters protecting its primary and secondary sides present a nonlinear behavior that, for currents ranging from 0.1 to 1 kA, assure terminal voltages between 25 and 30 kV at the primary side, and around 0.65 kV at the secondary side [10].

Loads were connected between phase and neutral. They were represented as a linear circuit that fits the frequency response of typical consumer installations in the lightning frequency range [18]. Each load was connected to the LV line through a non-illuminated, 15-m long service drop consisting of twisted conductors.

For representing insulation breakdown, the MV line insulators were modeled as ideal switches controlled by the integration method, $\mathrm{DE} = \int_{t_o}^{t} [U(t) - U_0]^k dt$, where DE is the so-called disruptive effect, $U(t)$ is the incident voltage, U_0 is the onset voltage, k is a constant, and t_o is the time at which $U(t) \geq U_0$ [19]. For representing the central insulator of the MV line, it was assumed that $U_0/\mathrm{CFO} = 0.8$, $\mathrm{DE}/\mathrm{CFO} = 1.545 \times 10^{-6}$, and $k = 1$, where CFO = 165 kV is the critical flashover overvoltage [20]. Insulation breakdown was neglected at the outer insulators because their CFOs are usually high enough to withstand lightning-induced voltages. In the LV lines, a simpler flashover model was used. It considers insulation breakdown from the phase and neutral wires to ground whenever the incident voltage exceeds 1.1CFO, where CFO = 35 kV and the factor of 1.1 accounts for the turn-up in the insulator volt-time curve [20]. Following [11,21], each pole was represented as a non-intentional grounding resistance given by $R_p = 0.4/\sigma$.

2.3. Simulation details

Two stroke locations were considered as illustrated in Fig. 1. Event A corresponds to a lightning strike to ground at a point 50 m far from MV line 1, in the area between LV lines 1 and 2 (coordinates $X = 0$ m, $Y = -50$ m). Event B corresponds to a lightning strike to ground also 50 m far from MV line 1 but about 500 m far from LV lines 1 and 2 (coordinates $X = -450$ m, $Y = -50$ m). As in [10], both events were chosen to simulate conditions in which either the direct illumination of the LV lines by the incident lightning electromagnetic fields (event A) or the surge transference through the distribution transformers (event B) is expected to prevail in terms of load overvoltages.

Lightning-induced voltages were calculated in most cases assuming a 31-kA lightning current with shape and time-characteristics reproducing the median parameters of first stroke currents of downward negative lightning measured at Mount San Salvatore, Switzerland (see [22] for details). For obtaining the spatial and temporal current distribution along the lightning channel, the modified transmission line model with linear current decay with height (MTLL) with a propagation speed of 130 km/μs and a channel height of 7.5 km was considered [23]. Remote lightning electromagnetic fields were calculated assuming the lightning channel to consist of a vertical antenna [24]. The influence of ground conductivity on remote lightning electromagnetic fields was taken into account with the Cooray-Rubinstein formulation [25,26]. The field-to-line coupling was performed with the model of Agrawal et al. [27], and the interaction of the incident fields with the lines was implemented in ATP as shown in [28].

In theory [29,30], a lightning discharge with a prospective current of 31 kA would result in a direct strike to MV line 1 or to LV lines 1 or 2 if events A and B are considered. Here, it is assumed that some protruding object such as a tree or tower diverts the lightning discharge from the lines, although for simplicity both the field distortion caused by the strike object and the injection of currents into the LV lines due to voltage gradients created in the ground are neglected.

3. Influence of transformer grounding on load overvoltages

In distribution systems in which the neutral conductor is shared by the MV and LV lines, the transformer grounding can reduce the amplitude and energy of surges transferred from the MV line to the LV line [13,14]. This conclusion, which stems from studies considering direct lightning strikes to MV lines, relies on the fact that reducing R_t will reduce the potential rise caused by the currents drained to ground by the surge arresters that protect the transformer primary. As a consequence, common-mode