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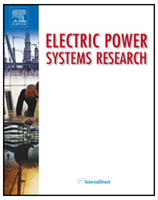

On the role of transformer grounding and surge arresters on protecting loads from lightning-induced voltages in complex distribution networks

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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

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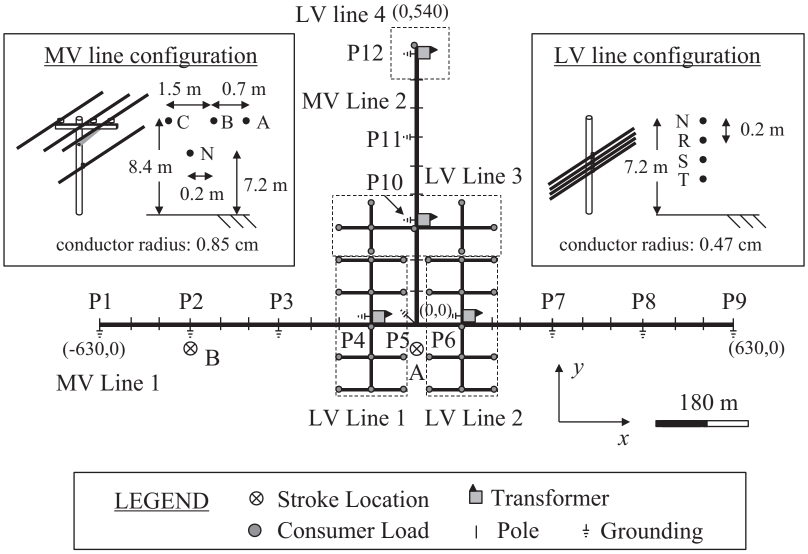

Fig. 1. Simulated system and respective (x, y) coordinates in meters [10].

currents flowing into the LV conductors are attenuated, together with the associated load overvoltages. In the particular case of a direct lightning strike to the MV line it is thus desirable to obtain a low R_t/R_c ratio, where R_t and R_c refer to the transformer and consumer grounding resistances, respectively, with both R_t and R_c reaching values as low as possible [13,14].

In this section, an attempt is made to verify whether the same reasoning is valid for load overvoltages caused by cloud-to-ground strikes in the vicinity of the complex distribution network of Fig. 1. However, the analysis is more difficult in the present case because load overvoltages are now the result of two simultaneous events, namely the voltage induction due to the electromagnetic fields generated by the lightning discharge and the transference of surges through the distribution transformer. To simplify the analysis, it is assumed that all consumer loads have identical grounding resistances of $R_c = 173\ \Omega$, obtained from the grounding model of Section 2.2 for $\sigma = 0.002$ S/m, while the transformer resistance R_t is varied. Following the value assumed for σ, the non-intentional grounding resistance of the poles were set as $R_p = 200\ \Omega$. All remaining grounding points of the neutral conductor at poles P1, P2, P3, P5, P7, P8, P9, and P11 of the medium-voltage line were assumed to have grounding resistances of 173 Ω corresponding to the use of a single grounding rod as detailed in Section 2.2. This value remained unchanged in all calculation results presented in the text.

3.1. Influence of transformer grounding and insulation breakdown on the waveforms of load overvoltages

To exemplify and illustrate the effect of transformer grounding on the waveforms of load overvoltages associated with event A, which corresponds to a cloud-to-ground strike at a position close to the LV lines, Fig. 3 shows phase-to-neutral and phase-to-ground

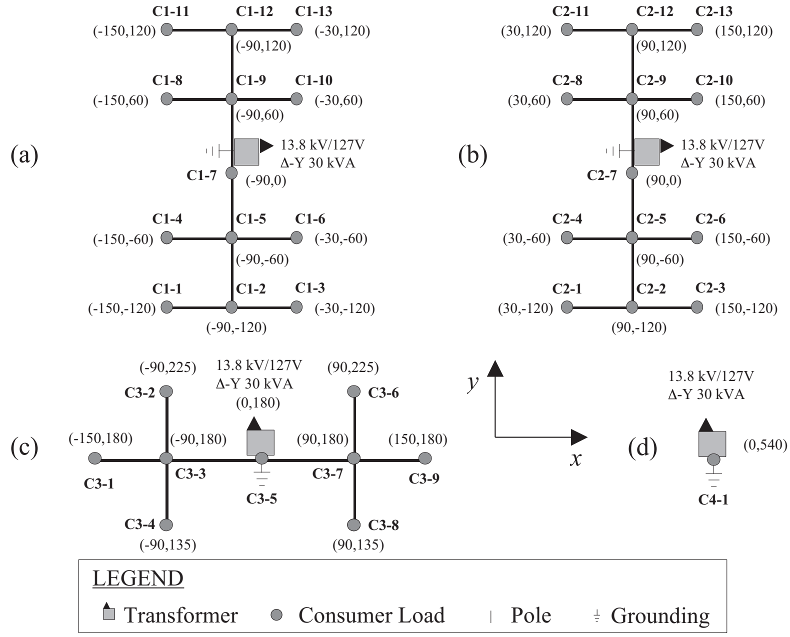

Fig. 2. Details of LV lines (a) 1, (b) 2, (c) 3, and (d) 4 with respective (x, y) coordinates in meters [10].

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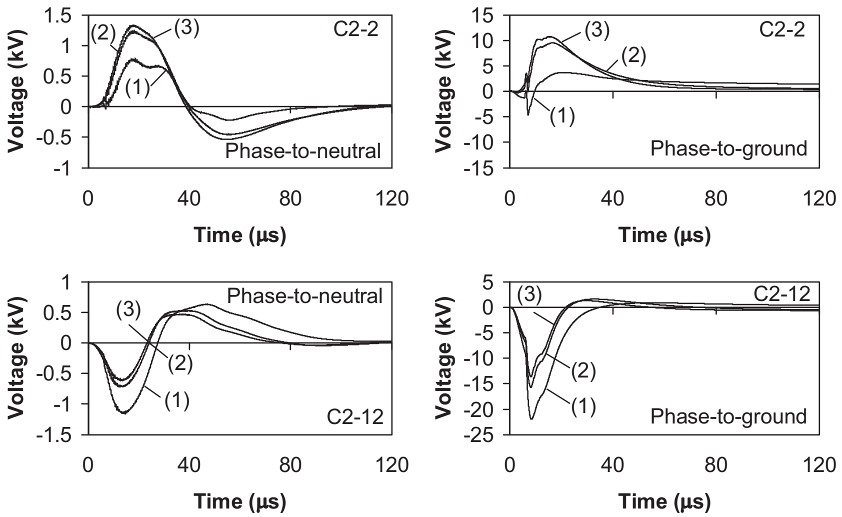

Fig. 3. Voltages calculated on loads C2-2 and C2-12 for event A considering three different values for R_t, namely (1) 6 Ω, (2) 60 Ω or (3) 600 Ω, and neglecting insulation breakdown in LV line 2.

voltages calculated on loads C2-2 and C2-12 considering three different values for R_t, namely 6, 60 and 600 Ω. The value of 60 Ω is derived from the grounding model of Section 2.2 for $\sigma = 0.002$ S/m. The remaining values represent a tenfold variation of R_t above and below the base value. The corresponding R_t/R_c ratios are 0.0347 ($R_t = 6$ Ω), 0.347 ($R_t = 60$ Ω), and 3.47 ($R_t = 600$ Ω). For simplicity, the waveforms shown in Fig. 3 were calculated neglecting insulation breakdown in the LV lines. In Fig. 4, the analysis is repeated assuming the occurrence of flashovers.

First analyzing the waveforms shown in Fig. 3, which were calculated neglecting insulation breakdown, it is seen that increasing R_t from 60 Ω to 600 Ω does not have a significant effect on the load overvoltages. This suggests that instead of using three grounding rods at the transformer pole, which leads to $R_t = 60$ Ω for $\sigma = 0.002$ S/m, a simpler transformer grounding consisting of a single rod could be used, which would lead to $R_t = 173$ Ω for the same ground conductivity. On the other hand, if R_t is reduced from 60 Ω to 6 Ω a significant voltage reduction is observed on load C2-2. This is in line with the recommendation of a low R_t/R_c ratio based on the analysis of transferred lightning surges from MV to LV lines [13,14]. Conversely, a low R_t/R_c ratio leads to a voltage increase on load C2-12. One possible reason for this behavior, at least regarding phase-to-neutral overvoltages, is the fact that if the grounding of the neutral conductor is improved, the voltage induced on the neutral with respect to ground by the incident electromagnetic field is reduced more significantly than the voltage induced on the phase conductors with respect to ground, thus increasing the differential voltage between phase and neutral [31]. However, in the present case load overvoltages are the combination of induced voltages and surges transferred from the MV to LV line [10], which let the analysis less straightforward. In fact, the polarity of the induced voltage component on LV line 2 due to event A is essentially positive in the immediate vicinity of the stroke location and typically negative at farther points due to the influence of ground conductivity [32]. On the other hand, it can be shown that the transferred voltage component is of positive polarity along the LV line 2 for event A. The combination of the induced and transferred surge components will therefore determine either an increase of the total voltages (most likely at an observation point close to the stroke location, e.g., at load C2-2, where the surge components are of the same polarity) or a relative reduction in the total voltages (most likely at an observation point relatively far from the stroke location, e.g., at load C2-12,

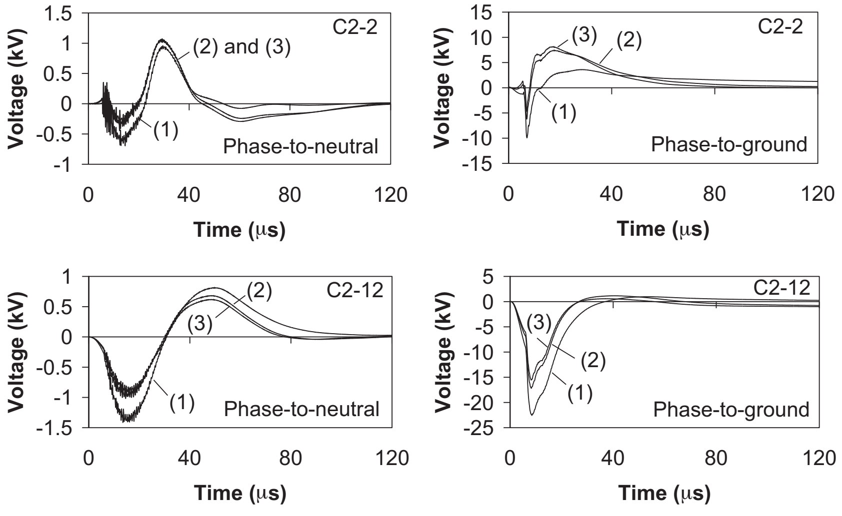

Fig. 4. Same as Fig. 3 but including insulation breakdown in LV line 2.

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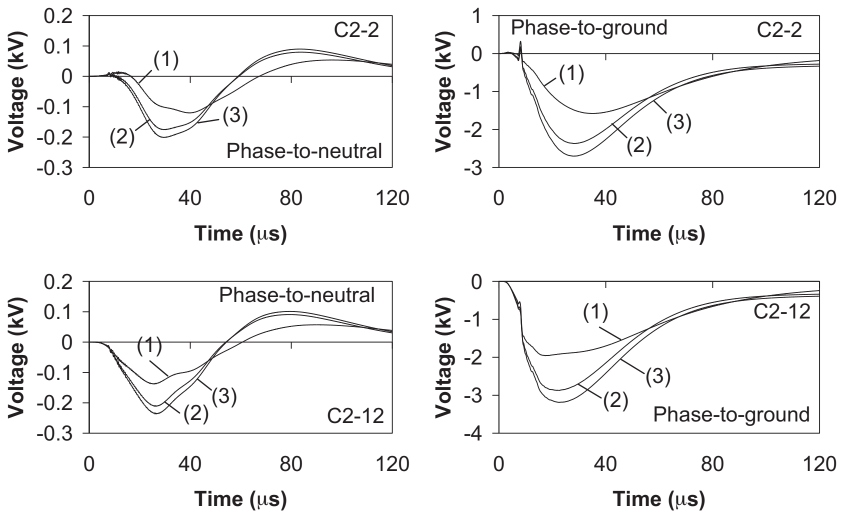

Fig. 5. Voltages calculated on loads C2-2 and C2-12 for event B considering three different values for R_t, namely (1) 6 Ω, (2) 60 Ω or (3) 600 Ω, and including the possibility of insulation breakdown in LV line 2.

where the surge components are of opposite polarity). Since the amplitude of the positive voltage component associated with the surge transference from the MV line to the LV line is less significant for $R_t = 6\,\Omega$ than for $R_t = 60\,\Omega$, the total overvoltages observed on load C2-2 are therefore less positive if R_t is reduced from 60 Ω to 6 Ω, while the overvoltages observed on load C2-12 are more negative for the same condition, which could in part explain the behavior observed in Fig. 3.

The analysis above regarding the influence of R_t on the voltages calculated on loads C2-2 and C2-12 is still valid if a more realistic case including the possibility of flashovers in the LV line 2 is considered. The obtained results, which are shown in Fig. 4, suggest that insulation breakdown tends to reduce the relative importance of R_t on the calculated phase-to-neutral overvoltages in LV line 2 for the considered event. This happens because additional grounding paths are created through the poles due to the flashovers. These new grounding paths also modify the calculated waveforms, which becomes apparent if the voltages calculated on load C2-2 considering or neglecting flashovers are compared in Figs. 3 and 4. Interestingly, in the particular case of load C2-2 flashovers lead to a relative reduction in the phase-to-neutral overvoltages, but in the case of load C2-12 the occurrence of flashovers contributes to a relative increase in the calculated overvoltages. A detailed analysis of the mechanisms leading to one condition or the other requires the consideration of multiple reflections at the discontinuity points of the line, resonant phenomena involving the natural frequencies of the circuit, the location and characteristics of the flashovers (if phase to ground, neutral to ground or both), and the relative position of the stroke location respective the observation point, among others. Such analysis is not straightforward and is out of the scope of this paper.

To conclude this section, Fig. 5 illustrates overvoltages calculated on loads C2-2 and C2-12 associated with event B, which corresponds to a cloud-to-ground strike on a point relatively far from LV line 2. In this particular case, the transferred surge component is expected to prevail over the induced voltage component [10]. From the point of view of the load overvoltages, the evaluated condition thus approaches that of a direct lightning strike at some point of the MV line, except that the associated voltage levels are much lower. In this case, the analysis becomes qualitatively similar to the one presented in [14] and a reduction in R_t will always be expected to contribute for reducing load overvoltages. This happens because the voltage rise at the transformer grounding is responsible for injecting currents into the phase and neutral conductors of the LV line. These currents circulate through the loads and return to the transformer pole through the ground. For this reason they are usually referred to as common-mode currents. If the transformer grounding is improved, the voltage rise at the transformer pole is reduced due to the more effective grounding of the neutral and, as a consequence, both the common-mode currents affecting the loads and their associated overvoltages are reduced. Following the same reasoning, a poor transformer grounding is expected to increase the associated load overvoltages in this case. This behavior is observed in Fig. 5, but interestingly a tenfold increase of R_t from 60 Ω to 600 Ω again does not change the calculated voltage waves significantly. This can be due to the fact that in the particular case considered here the equivalent consumer grounding impedance seen from the transformer pole is much less than 173 Ω because of the parallel association of all connections to ground in LV line 2. Therefore, a transformer grounding resistance of 60 Ω is already too large for characterizing a favorable R_t/R_c ratio in the considered case, and a transformer grounding resistance of 600 Ω will perform similarly. On the other hand, if R_t is reduced from 60 Ω to 6 Ω a more significant reduction is observed in both phase-to-neutral and phase-to-ground overvoltages. However, the voltage levels, especially the ones appearing between phase and neutral, are already much lower than the ones observed for event A. It is to be noted that the voltages illustrated in Fig. 5 were calculated including the possibility of insulation breakdown on the LV lines. However, the voltage levels on LV line 2 were insufficient to cause flashovers.

3.2. Analysis of the R_t/R_c ratio

To better illustrate the effect of the R_t/R_c ratio on the load overvoltages associated with events A and B, additional simulations were performed for the same conditions considered in the previous section, except that R_t was varied to assure an excursion of the R_t/R_c ratio from 0 to 2. The obtained results are illustrated in Fig. 6, which shows the peak values of phase-to-neutral and phase-to-ground overvoltages calculated on loads C2-2, C2-5, C2-7, C2-9, and C2-12 for events A and B, all cases considering insulation breakdown.

First analyzing Fig. 6(a), which refers to a cloud-to-ground strike close to the LV line 2 (Event A in Fig. 1), it is seen that the effect of reducing R_t on the phase-to-neutral overvoltages is significant only for very low R_t/R_c ratios. This is a consequence of insulation

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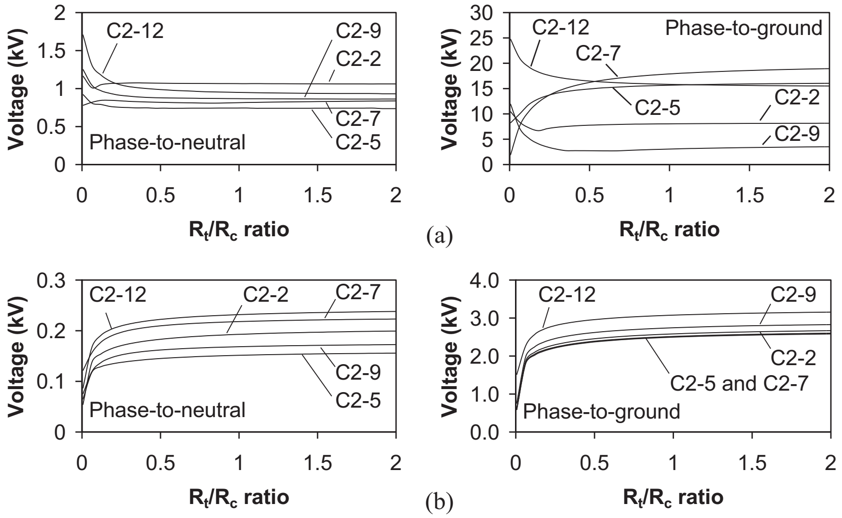

Fig. 6. Peak value of overvoltages calculated on loads connected to LV line 2 for events (a) A and (b) B as a function of the R_t/R_c ratio.

breakdown in LV line 2, which creates additional grounding paths and minimizes the influence of R_t on the voltages across the load terminals, at least for the considered event. As discussed in the previous section, depending on the observation point on the line, reducing R_t can lead either to an increase or a decrease in load overvoltages. A similar analysis can be addressed to the phase-to-ground overvoltages associated with event A, except that they are comparatively more sensitive to the R_t/R_c ratio. For lightning currents of larger amplitudes, the effect of the R_t/R_c ratio on the associated load overvoltages is likely to become less smooth and less predictable because of the greater number of flashovers.

Now analyzing Fig. 6(b), which refers to a cloud-to-ground strike relatively far from the LV line 2 (event B in Fig. 1), it is seen that a reduction of the R_t/R_c ratio will always contribute to reduce the associated load overvoltages, as discussed previously. It is to be noted, however, that the protection effect propitiated by reducing R_t is only effective for very low R_t/R_c ratios. This is because the equivalent consumer grounding impedance seen from the transformer pole is too low because of the many grounding points existing at LV line 2. Also, the voltage levels associated with event B are much lower than those associated with event A, which in theory would minimize the need for a significantly improved transformer grounding when dealing with load protection.

3.3. Cumulative overvoltages

Although illustrative of the effect of the R_t/R_c ratio on lightning-induced overvoltages on loads connected to complex LV networks, the analysis of the previous sections is focused on a small group of loads connected to LV line 2. Also, since a low R_t/R_c ratio can lead either to an increase or a decrease on load overvoltages associated with the simulated lightning events, the analyses of the previous sections remain inconclusive about the possible benefits or drawbacks of reducing the R_t/R_c on the load overvoltages. Here, the analysis is extended to all the 36 loads connected to the LV lines 1–4. For this, a base case considering $R_c = 173\,\Omega$ for all consumer loads and $R_t = 60\,\Omega$ for all transformers is assumed as in Section 3.1, with two cases representing a tenfold variation of R_t above and below the base case, namely $R_t = 6\,\Omega$ and $R_t = 600\,\Omega$. In all cases, insulation breakdown was considered. Also, in addition to the 31-kA lightning current considered in the previous sections, a more severe lightning current of 90 kA (obtained simply by scaling up the 31-kA lightning current waveform) was taken into account to give a better idea about the effect of the R_t/R_c ratio on the load overvoltages. The obtained results are shown in Fig. 7, which presents cumulative phase-to-neutral and phase-to-ground overvoltages on the connected loads for events A and B.

First analyzing the phase-to-neutral voltages in Fig. 7, it is observed that about 80% percent of the voltages associated with event A are below 1.5 kV and 5.0 kV for currents of 31 kA and 90 kA, respectively, while for event B there are no phase-to-neutral overvoltages exceeding 2 kV. Overvoltages exceeding a few kV are expected to cause flashovers in electrical appliances [33]. Although neglected here for simplicity, this phenomenon can be important in a more rigorous analysis of lightning overvoltages in LV networks.

With regard to the influence of the transformer grounding on the resulting overvoltages, it is apparent from Fig. 7 that a reduction of R_t from 60 Ω to 6 Ω leads to an overall reduction both on the phase-to-neutral and phase-to-ground overvoltages associated with event B, regardless of the considered peak current. As discussed before, this happens because for a cloud-to-ground strike on a position relatively far from the LV lines the surge transference from the MV line to the LV line is expected to play a more significant role on the load overvoltages than the illumination of the LV lines by the incident lightning electromagnetic fields. This lets the analysis analogous to that of a direct strike to the MV line [13,14] except for the lower voltage magnitudes. In Fig. 7, it is seen that a tenfold increase of R_t from 60 Ω to 600 Ω does not significantly change the overvoltages associated with event B.

Regarding event A, which corresponds to a lightning strike to ground on a position relatively close to the LV lines, the effect of the incident electromagnetic field plays a more important role on the characterization of the load overvoltages than the transference of surges from the MV lines to the LV lines [10]. However, as for event B, the reduction of R_t contributes to an overall reduction in the phase-to-ground voltages regardless of the considered peak current. When it comes to phase-to-neutral overvoltages, a reduction in R_t from 60 Ω to 6 Ω leads to an apparent increase in the calculated voltages for a peak current of 31 kA. As explained before, this could be related to the increase in the differential voltage across the phase and neutral wires of the LV lines as the voltage of the grounded wires is reduced with the improvement of the transformer grounding. It could also be related with different compositions of the transferred and induced components, which can present opposite polarities depending on the observation points on the line. An increase in R_t from 60 Ω to 600 Ω, on the other hand, does not have any significant effect on the

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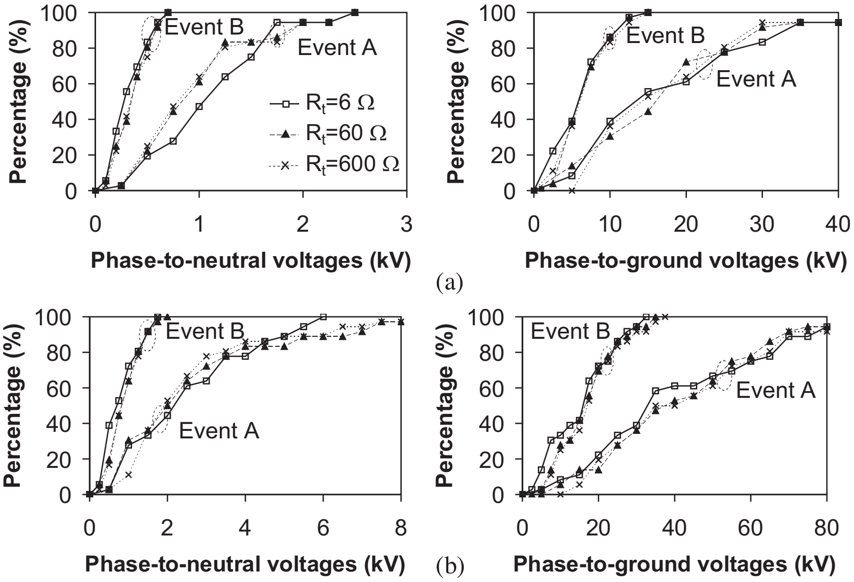

Fig. 7. Cumulative distributions indicating the percentage of overvoltages below the indicated value for a lightning current of either (a) 31 kA or (b) 90 kA considering all loads connected to LV lines 1–4.

phase-to-neutral overvoltages associated with the 31-kA lightning current. In the considered case, this indicates that using three rods at the transformer grounding would be essentially a waste of material; no significant differences would be observed in terms of phase-to-neutral load overvoltages if a simpler grounding configuration were used instead. For a peak current of 90 kA, the effect of R_t on the phase-to-neutral overvoltages is even less significant than for a peak current of 31 kA. This can be explained by the greater number of flashovers occurring for the 90-kA peak current, which creates additional grounding paths in the LV lines and minimizes the role of R_t.

For the sake of consistency, it is instructive to check to what extent the conclusions drawn from the results illustrated in Fig. 7 would still hold for a simpler LV line topology. This is made in Fig. 8, where the analysis of Fig. 7 is repeated for a simplified line topology based on Figs. 1 and 2, in which all laterals were removed from LV lines 1, 2, and 3, and only loads C1-2, C1-7, C1-12, C2-2, C2-7, C2-12, C3-1, C3-5, C3-9, and C4-1 were kept in the LV lines. Overall, it is seen that the results shown in Fig. 8 are qualitatively similar to the ones illustrated in Fig. 7. This gives support to the idea that improving the transformer grounding will not necessarily reduce overvoltages across loads connected between phase and neutral, because its action is dependent on the balance between the effects of the incident electromagnetic field and the transferred surge component on the resulting load overvoltages. Perhaps the most remarkable feature of the results illustrated in Fig. 8 is the fact that the voltages induced on the phase conductors with respect to ground are more significantly affected by the improvement of the transformer grounding than in the case of a LV line with a greater number of loads. This can be explained

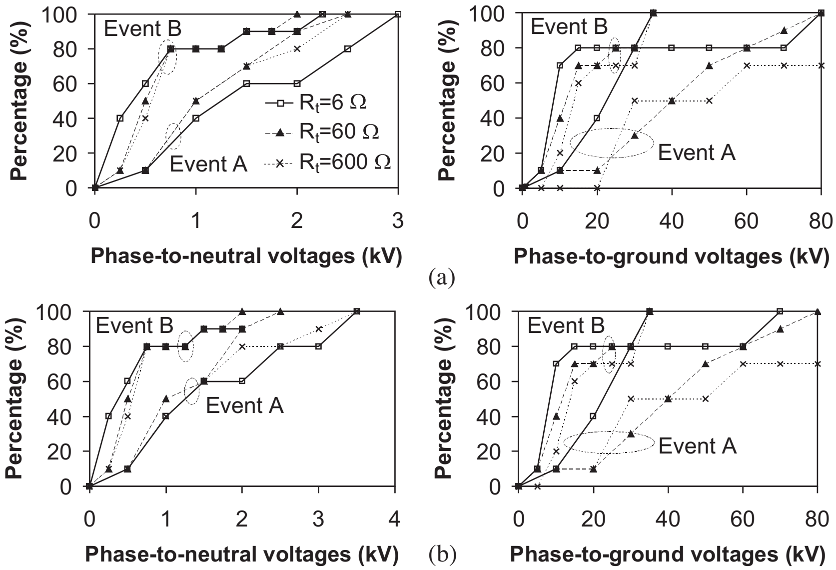

Fig. 8. Same as Fig. 7, except that all laterals were removed from LV lines 1, 2, and 3, and only loads C1-2, C1-7, and C1-12 (in LV line 1), C2-2, C2-7, and C2-12 (in LV line2), C3-1, C3-5, and C3-9 (in LV line 3), and C4-1 were considered.

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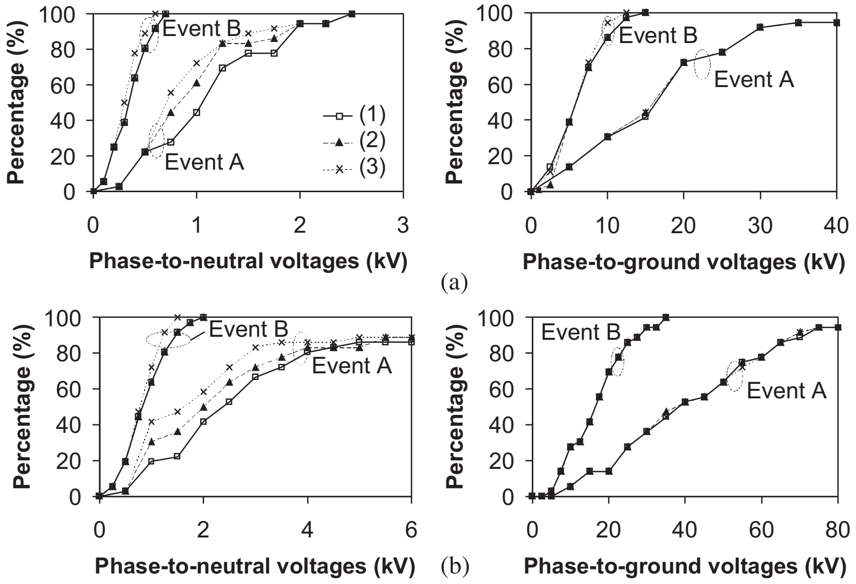

Fig. 9. Cumulative distributions indicating the percentage of overvoltages below the indicated value for a lightning current of either (a) 31 kA or (b) 90 kA considering (1) no LV surge arresters, (2) LV surge arresters at the transformer secondaries, and (3) LV surge arresters at the transformer secondaries and at the end of the LV lines.

by the reduced number of grounding points on the load side of the LV line, which increases the equivalent consumer grounding resistance seen from the transformer pole and let the influence of R_t alone more significant in reducing the total overvoltages than in the case where a greater number of grounding points is available on the LV line.

4. Influence of LV surge arresters

In the previous sections it is assumed that the transformer secondary is protected by LV surge arresters, which is a measure adopted by many power utilities to reduce lightning-induced failures in power transformers. Here, an attempt is made to identify whether LV surge arresters installed at the transformer secondary can protect loads connected to a complex LV line. For such, cumulative overvoltages were calculated on all 36 loads connected to LV lines 1–4 for events A and B considering three conditions as follows: (1) no surge arresters on the LV lines, (2) surge arresters only at the transformer secondary, and, to evaluate a possible action that power utilities could take to protect consumer loads, (3) surge arresters at the transformer secondary and at both ends of the LV lines (more specifically at the poles where the service drops feeding loads C1-2, C1-12, C2-2, C2-12, C3-1 and C3-9 are derived from). In all cases insulation breakdown was considered. It was assumed that $R_t = 60\,\Omega$ and $R_c = 173\,\Omega$.

The results are shown in Fig. 9, where it is seen that the presence of surge arresters at the transformer secondary offers limited protection to the loads. In the case where arresters are installed at the ends of the LV lines, a greater reduction is observed in the phase-to-neutral overvoltages compared to the cases in which such arresters are absent. However, the observed reduction is insufficient to assure load protection, especially for event A. This becomes apparent if it is observed that over 60% of the overvoltages calculated for such event for a lightning current of 90 kA exceed 1 kV, even though the protective level of the installed LV arresters is of 0.65 kV. This result is indicative that that surge arresters should be installed in shorter intervals along the LV lines for improved load protection, preferably with surge protective devices connected close to sensitive loads inside the consumer installations. It is also clear in Fig. 9 that surge arresters installed between phase and neutral have a negligible effect on phase-to-ground overvoltages. This is explained by the order of magnitude differences observed in the voltages induced from phase to neutral (a few kV) compared with the voltages induced from phase to ground (tens of kV); reductions in the former are therefore expected to have nearly no effect in the latter.

5. Discussion

The obtained results indicate a limited effectiveness of improving the transformer grounding and of installing surge arresters at specific points of a complex LV network in terms of reducing phase-to-neutral overvoltages caused by nearby cloud-to-ground strikes. For stroke locations relatively far from the LV lines, assuring a low R_t/R_c ratio is always beneficial, which is in line with the recommendation of [13,14] applicable to direct strikes to MV lines. However, the sensitivity of the phase-to-neutral overvoltages to the R_t/R_c ratio is very low because of the great number of grounding points existing in a complex LV line. This fact, together with the observation that load overvoltages associated with lightning strikes at points relatively far from the LV lines are usually less harmful, poses a question about whether is justifiable or not to invest in a transformer grounding that be significantly better than the remaining grounding points in the LV lines. To complicate more, it has been shown that a very low R_t/R_c ratio can actually increase lightning overvoltages across the terminals of the loads, especially for a stroke location that is close to the LV line. Since in principle it is not possible to control the point where the lightning discharge will hit the ground, investing in a very low R_t/R_c ratio through a significant improvement in the transformer grounding remains questionable, at least from the point of view of phase-to-neutral overvoltages caused by cloud-to-ground lightning on loads installed in complex distribution networks. Similar conclusions can be extended to phase-to-ground overvoltages. Although a full statistical analysis using the Monte Carlo method would be preferred for a more accurate assessment of the influence of the R_t/R_c ratio, it is believed that the analysis presented here is able to give at least a qualitative indication about it. In fact, similar conclusions have been obtained for different stroke locations and lightning currents with characteristics that differ from the ones considered here [34].

With regard to the use of surge arresters in LV networks, some studies of the transference of surges from MV to LV lines point

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out to the possibility of surge arresters installed at the transformer secondary to actually increase load overvoltages [e.g., 14]. This condition, which would result from the bypassing of the transformer secondary impedance by the LV surge arresters and the consequent increase of common-mode currents associated with the voltage rise at the transformer grounding, was not verified in none of the cases investigated here. This can be due to the fact that all evaluations presented here consider the illumination of the LV lines by the incident lightning electromagnetic fields, an effect that was neglected in [14]. In any case, it must be expected that surge arresters installed at the secondary of distribution transformers will fail to extend their protective behavior to loads connected to complex LV lines.

The limited effectiveness of reducing the transformer grounding resistance and installing additional surge arresters at specific points of the LV line in reducing load overvoltages can be seen as a combination of many factors, such as the occurrence of insulation breakdown, the relatively large distances between loads, transformer grounding points, and surge arresters, the relative importance of the mechanisms responsible for generating load overvoltages, and the particularities of a system topology that involves laterals and many grounding points. Another factor that is expected to reduce the relative importance of the transformer grounding resistance on mitigating load overvoltages is the fact that in actual distribution networks the grounding resistances of the consumer loads are never uniformly distributed as assumed here, which makes it difficult to think objectively in terms of a uniquely defined R_t/R_c ratio.

6. Conclusions

This paper has investigated the efficiency of reducing the transformer grounding resistance R_t and installing additional LV surge arresters in the protection of loads connected to a complex distribution network subjected to lightning-induced voltages. The results show that it is not possible to assure that reducing the R_t/R_c ratio through the improvement of the transformer grounding will always contribute for reducing the resulting overvoltages on the connected loads. The presence of surge arresters at the transformer secondary was shown to be ineffective in terms of load protection. Similarly, surge arresters at the ends of the LV lines failed to assure a uniform protection to the loads. It is therefore expected that an improved load protection scheme in a complex LV line should not rely exclusively on reducing the R_t/R_c ratio, being recommended the installation of surge arresters at shorter intervals in the LV lines as well as the use of surge protective devices near sensitive loads.

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