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LIGHTNING SURGES TRANSFERRED TO THE SECONDARY OF DISTRIBUTION TRANSFORMERS DUE TO DIRECT STRIKES ON MV LINES, CONSIDERING DIFFERENT LV LINE CONFIGURATIONS

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Abstract **- This paper aims at analyzing the behaviour of lightning surges transferred to low-voltage lines due to direct strikes on medium voltage networks considering two cases: open wire and twisted conductor low-voltage lines. The analysis considers the influences of parameters such as stroke current front time (t_f), ground resistance (R_g) and ground resistivity (ρ_g) on the overvoltages transferred to low-voltage lines. The overvoltages are calculated employing the Alternative Transients Program (ATP) and the simulations refer to a typical rural distribution network of the Electrical Distribution Company of the State of Tocantins (CELTINS), Brazil. To evaluate the surges transferred to the low-voltage line, a high frequency model was developed for the distribution transformer. The results show that the use of twisted conductors configuration for the secondary circuit can reduce the magnitudes of the surges transferred through the distribution transformers.**

1 INTRODUCTION

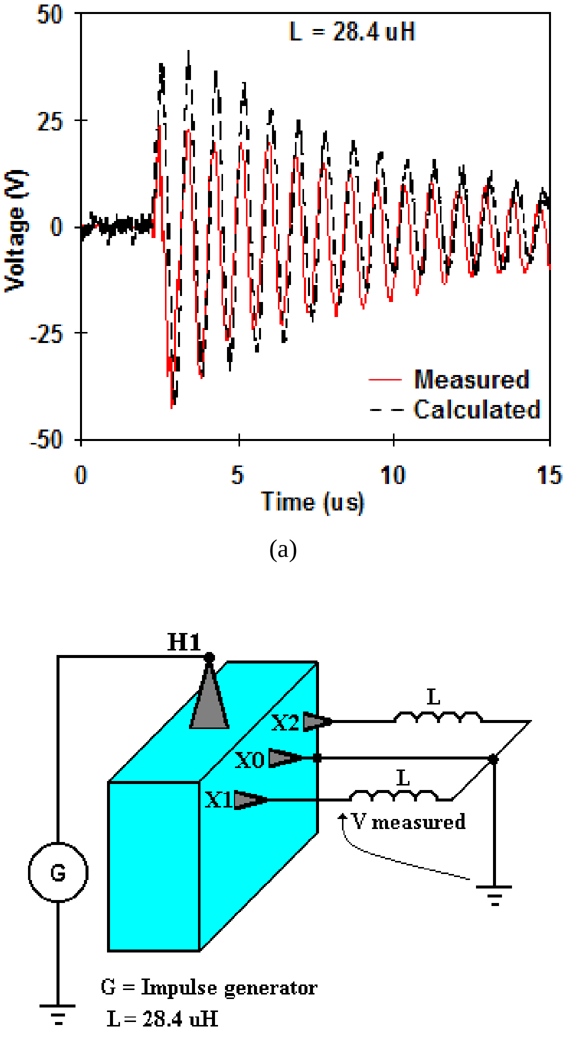
Lightning discharges are responsible for a significant amount of unscheduled supply interruptions in electrical overhead lines, usually causing permanent damages to equipment such as distribution transformers. There are various ways by which lightning can disturb medium (MV) and low-voltage (LV) lines. Transients may be caused by direct strokes to the MV or LV line conductors, by lightning induced overvoltages, and by surges transferred through the distribution transformer. In recent years, several studies have been developed concerning transferred surges to LV networks [1-3].

In this work, the characteristics of surges transferred from the primary to the secondary side of distribution transformers due to direct strikes on MV lines are evaluated considering open wire and twisted conductor LV line configurations. In the simulations a typical rural distribution network of the feeder Nova Olinda – Arapoema, of CELTINS, is adopted. CELTINS is the company responsible for electricity distribution in the State of Tocantins, in the North of Brazil. The feeder Nova Olinda – Arapoema supplies power to a great number of consumers and was selected as the most critical with relation to transformer damages caused by lightning in the period 2006 - 2008. The rural distribution networks of CELTINS are located in regions characterized mainly by pastures with stunted vegetation so that the MV line conductors correspond, in general, to the highest points in these regions. Thus, the typical rural distribution network adopted in the simulations is highly exposed to lightning and the overvoltages in the primary and secondary circuits may be caused by direct and indirect strokes. However, a significant number of transient events in LV lines also can be due to surges transferred to the secondary circuit through distribution transformers [4, 5].

2 SYSTEM DESCRIPTION AND MODELING

For the calculations, initially a high frequency model of a single-phase transformer (15 kVA, 20.25 kV / 440 V - 220 V) was developed according to the procedure described in [6]. The model gives good results for simulations considering the transformer both in the no-load condition and for resistive and inductive loads. To illustrate the results obtained with the model, Fig. 1a presents a comparison between measured and calculated transferred voltage waveforms for the experimental set up depicted in Fig. 1b. The transformer model is presented in Fig. 2, which shows a good agreement between the two waveforms.

Simulations were then performed with the ATP (Alternative Transients Program) considering direct strokes to the MV line, and the surges transferred to the low-voltage line were calculated. The simulations refer to the Nova Olinda – Arapoema line, whose schematic circuit is shown in Fig. 3



(a)

(b)

Fig. 1 – Impulse response of the distribution (15 kVA, single-phase) transformer with inductive load.

a) measured and calculated waveforms

b) experimental set up

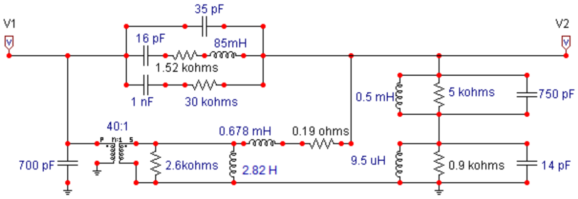


Fig. 2 – High frequency distribution transformer (15 kVA, single-phase) model.

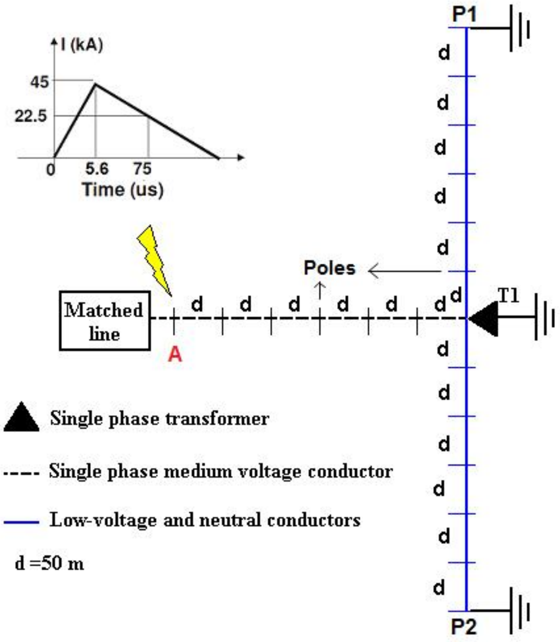


Fig. 3 –Nova Olinda – Arapoema distribution line configuration.

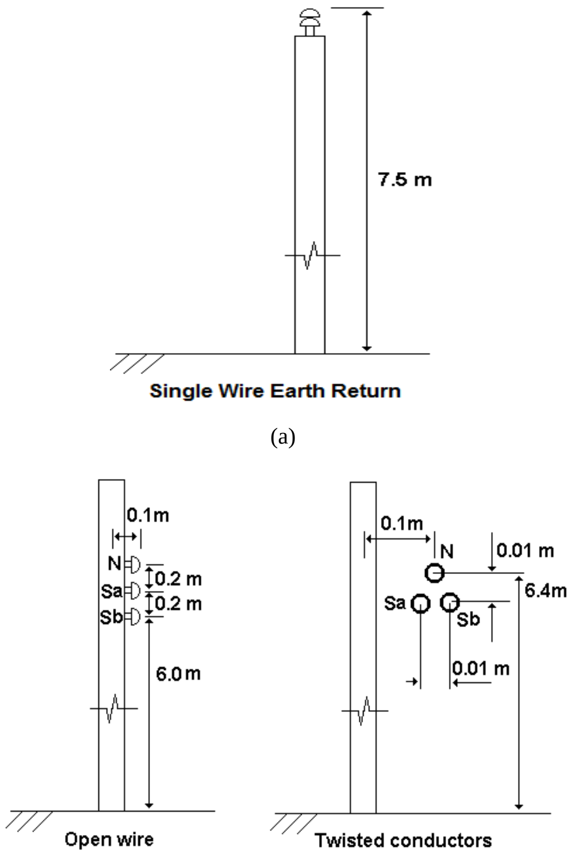
For the LV line, two configurations were taken into account: open wire and twisted conductors.

The lightning current was assumed to have triangular waveform with amplitude $I = 45$ kA, front time $t_f = 5.6$ μs, and time to zero of 150 μs [7]. The MV line is matched at one end, whereas at the other end a single-phase transformer (T1), protected by surge arresters, is connected. The distance between the lightning strike point (identified as point "A" in Fig. 3) and the transformer T1 was assumed as 300 m and the LV line has a total length of 600 m. It is considered, also, that a consumer is connected to each pole of the LV line through a 30 m long service drop. Consumers were represented by 30 μH inductances [8] connected between the phase conductors and the neutral. Line conductors were characterized by the following parameters:

- MV line (Single Wire Earth Return Distribution System, SWER): diameter = 0.636 cm and low-frequency resistance $R_{DC} = 1.3548$ Ω/km;
- LV line with open wire configuration: diameter = 0.741 cm and $R_{DC} = 0.8535$ Ω/km;
- LV line with twisted conductors configuration: diameter = 0.676 cm and $R_{DC} = 1.0$ Ω/km;
- 30 m long service drop (twisted conductors configuration): 2 conductor and neutral with diameter = 0.3568 cm and $R_{DC} = 3.08$ Ω/km.

Fig. 4 shows the MV and LV conductor configurations adopted in the simulations, in which "N" is the neutral and "Sa" and "Sb" are LV phase conductors.

Insulators were represented by switches that close when their CFO (critical impulse flashover voltage) is reached. Table 1 gives the CFO values adopted in the simulations.



(b)

Fig. 4 - MV and LV line configurations adopted in the simulations.
a) MV line (b) LV line

Table 1: CFO values adopted in the simulations.

Insulator	**CFO (kV)**
MV line	156
LV line and neutral	20

Unless otherwise indicated, the ground resistance R_g was assumed to be 60 Ω (mean value obtained from measurements made in the area near the feeder) for poles that are grounded (transformer T1 and points P1 and P2, as indicated in Fig. 3). For poles without grounding, it is assumed that in the case of an insulator flashover (of either the MV or LV lines), the surge current will flow to ground through a resistance that has a value twice that of a grounded pole, according to [9]. The value of the ground resistance at the consumers' entrance is $R_g = 60$ Ω and the ground lead is 1 m long. The soil is assumed homogeneous, with resistivity $\rho_g = 2300$ Ω.m (mean value obtained from measurements made in the area near the feeder). The inductance of all connection wires and accessories was assumed to be 1 μH/m. Ionization effects of the soil were considered as described in [10]. In the simulations is assumed a typical *V*x*I* characteristic curve of the surge arresters connected at the distribution transformer HV terminals.

3 RESULTS AND DISCUSSION

The overvoltages transferred to the secondary circuit resulting from direct strokes to the MV line were studied at the transformer (T1) LV terminals, taking into account the variations of some parameters.

Initially, a comparison can be made between the surges transferred through the transformer to the secondary line, in the cases of open wire and twisted conductor configurations. In the simulations, the lightning current was assumed to have a triangular waveform with the parameters shown in Fig. 3. The strike point A (Fig. 3) is 300 m from transformer T1.

Fig. 5 presents the transferred surges at the LV transformer terminals (conductors "Sa" and "Sb") for both the twisted conductors and the open wire configurations shown in Fig. 4b.

It can be observed that the voltage waveforms have a significantly smaller amplitude for the configuration with twisted conductors. This is due to the cable geometry, in which the phase and neutral conductors are closely assembled. This proximity of conductors results in a stronger electromagnetic coupling, causing a reduction in the voltage amplitudes. Owing to the effect of the transformer, the voltages on phases "Sa" and "Sb" present, at the very beginning, opposite polarities. Then, the current injected into the neutral (transformer terminal

X0) due to the operation of the primary arrester tends to equalize the phase-to-neutral voltages at the transformer terminals. This behaviour can be observed for both LV line configurations, but it is particularly evident in the case of the line with twisted conductors.

In the following items, the influences of the stroke current front time, ground resistance, and ground resistivity upon the overvoltages in the transformer LV terminals are evaluated, taking into account both the twisted conductors and the open wire configurations.

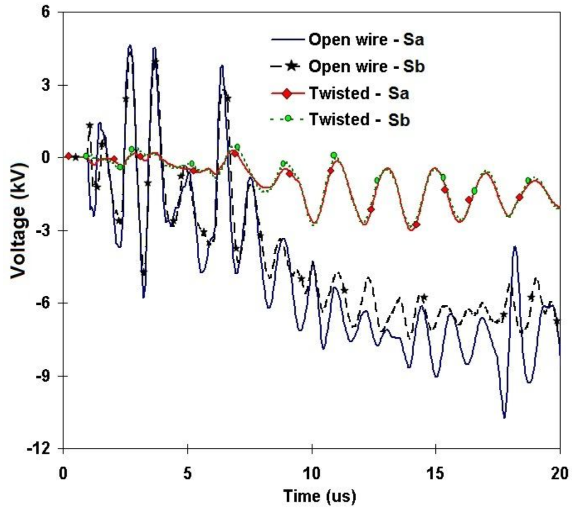


Fig. 5 – Transferred voltages (phase-to-neutral) at the LV transformer terminals (twisted conductors and open wire configurations) - t_f = 5.6 µs; Rg = 60 Ω; ρ_g = 2300 Ω.m.

3.1 Stroke current front time

Regarding the influence of the stroke current front time, the values of t_f = 2.8 µs, t_f = 5.6 µs were considered, with the remaining parameters unaltered. In general, the greater the current steepness, the greater the magnitude of the transferred voltage.

Fig. 6 presents the overvoltages at the “Sa" terminal of the transformer LV side for t_f = 2.8 µs, considering the open wire and twisted conductors configurations. The influence of the current front time upon the transferred voltages can be observed by comparing Fig. 5 (t_f = 5.6 µs) with Fig. 6 (t_f = 2.8 µs). It can be seen that, for both current front times, the transferred voltages present lower magnitudes in the case of the line with twisted conductors.

3.2 Ground resistance

In order to evaluate the influence of the neutral ground resistance (R_g) on the transferred voltages, simulations were performed considering the values of 60 Ω (Fig. 5) and 20 Ω (Fig. 7). The difference between the magnitudes of the phase-to-neutral transferred voltages for the two line configurations increases with the ground resistance.

The influence of the ground resistance on the transferred voltages is more significant in the case of the open wire line. In general, the greater the ground resistance, the greater the absolute value of the transferred voltage magnitude. For instance, the voltage peak values in the case of the open wire configuration are |5.05 kV| and |10.8 kV| for ground resistances of 20 Ω and 60 Ω, respectively.

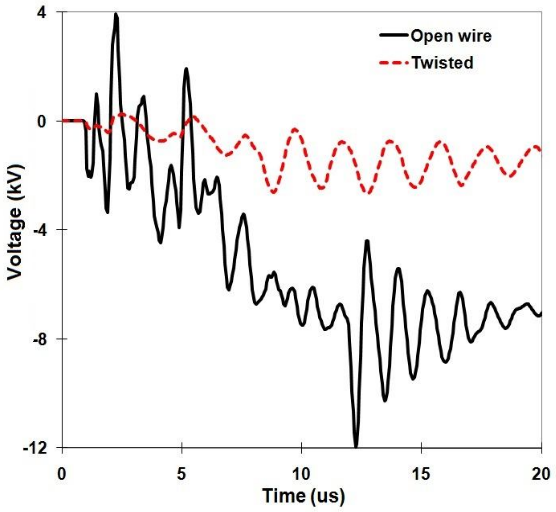


Fig. 6 – Transferred voltages (phase-to-neutral) at the transformer LV terminal “Sa” for twisted conductors and open wire configurations – t_f = 2.8 µs; Rg = 60 Ω; ρ_g = 2300 Ω.m.

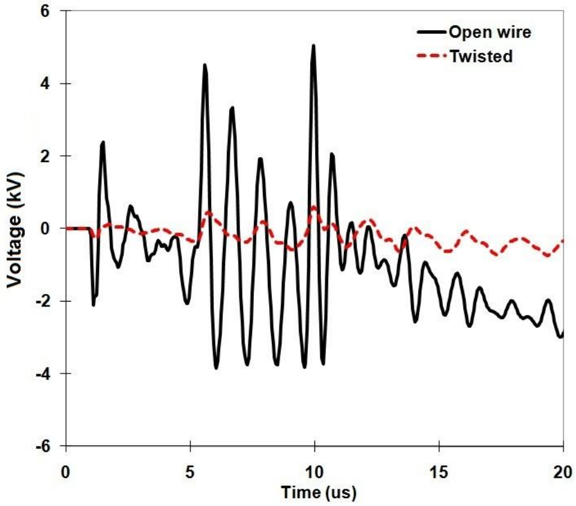


Fig. 7 – Transferred voltages at the transformer LV terminal "Sa" for twisted conductors and open wire configurations – t_f = 5.6 µs; Rg = 20 Ω; ρ_g = 2300 Ω.m.

Fig. 8 shows the phase-to-ground and neutral-to-ground transferred voltages at the LV terminal "Sa" for the open wire configuration, and it can be clearly seen that both voltages increase substantially as the ground resistance increases. The phase-to-neutral voltages, in general, have the same behaviour, but the variation is less significant.

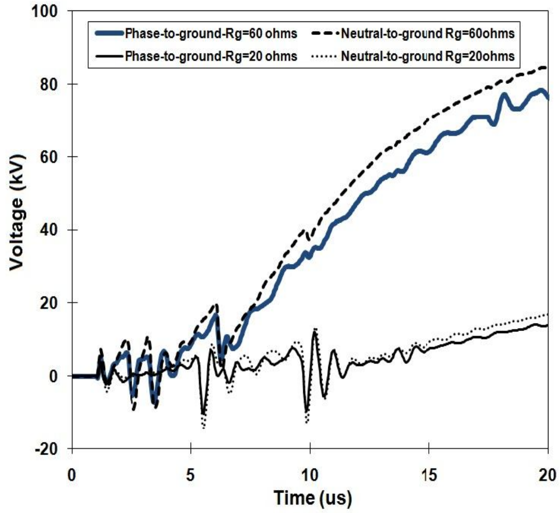


Fig. 8 – Phase-to-ground and neutral-to-ground transferred voltages at the transformer LV terminal "Sa" for open wire configuration - t_f = 5.6 µs; Rg = 20 Ω; ρ_g = 2300 Ω.m.

3.3 Ground resistivity

Two situations were considered regarding the ground resistivity (ρ_g): 2300 Ω.m and 100 Ω.m. Fig. 5 refers to the first situation, while Fig. 9 presents the transferred voltages for the latter case.

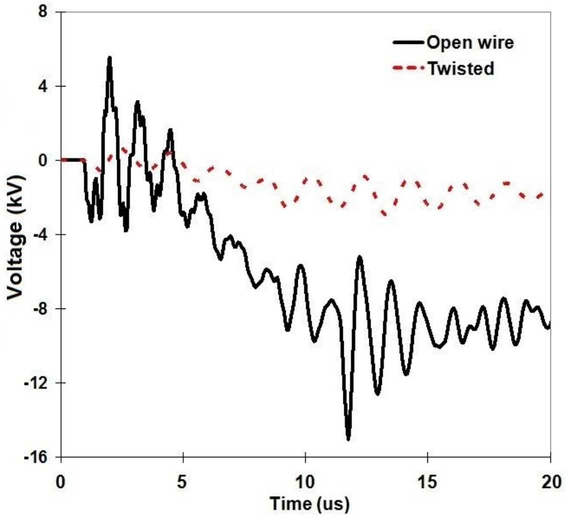


Fig. 9 – Transferred voltages at the transformer LV terminal "Sa" for twisted conductors and open wire configurations – t_f = 5.6 µs; Rg = 20 Ω; ρ_g = 100 Ω.m.

The larger the ground losses are, the lower the magnitudes of the voltages at the primary side of the distribution transformer will be. As a result, a high value for the ground resistivity results in a transferred voltage with lower magnitude. This influence, however, is usually not significant, mainly in the case of the line with twisted conductors. For the open wire configuration the effect is more visible.

4 CONCLUSIONS

In this paper, some features of the voltages transferred to the secondary of a distribution transformer in the case of direct strikes to the MV line were presented and discussed. The calculations were performed with the ATP considering, for the LV line, the twisted conductors and the open wire configurations. A high frequency transformer model, validated by comparisons of measured and calculated transferred voltages considering the transformer both under no-load condition and with different resistive and inductive loads connected to the secondary, was used.

Examples of surges transferred to the secondary, considering a typical rural distribution network, were presented. The influences of the lightning current front time, ground resistance and ground resistivity were analysed for the two LV line configurations. For all situations, the obtained results showed that the voltage surges transferred to the secondary in the case of a line with twisted conductors have significantly smaller magnitudes than those associated with the open wire configuration.

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