A SIMPLE TRANSFORMER MODEL FOR ANALYSIS OF TRANSFERRED LIGHTNING SURGES FROM MV TO LV LINES

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ABSTRACT

This paper presents a distribution transformer model which has been developed aiming at the analysis of transferred lightning surges from MV to LV lines, taking into account the load conditions, as well as the experiments that were conducted for the verification of its validity. The results of the comparisons between measured and calculated voltages indicate that the proposed model can be an useful tool for the evaluation of transferred surges, taking into account the compromise between accuracy and simplicity. Some examples of the applicability of the model, in terms of the calculation of surges in LV networks are also presented.

INTRODUCTION

Voltage and current surges transferred from the medium voltage lines are important sources of disturbances on secondary circuits. Such transients, usually caused by direct or nearby lightning, have to be dealt with in any analysis of the performance of overhead distribution lines. A common way of calculating the voltages on the low-voltage side is to represent the transformer by a capacitive network. This method, however, may be highly inaccurate, as has been demonstrated by laboratory tests. Furthermore, although more sophisticated models have been proposed [1], their validity is usually limited to no-load conditions.

In this paper a simple distribution transformer model is developed, aiming at the analysis of voltages and currents transferred to the low-voltage side, taking into account the load conditions, when lightning strikes the primary conductors. As the main motivation for the study was related to the surges on the low-voltage network, the transformer is considered to be protected by a set of arresters at the MV side. Under this condition it can be considered linear, and therefore it is treated as a quadripole.

TRANSFORMER MODEL

Transformer characteristics

Initially, tests were performed on a distribution transformer commonly used in Brazil (three-phase, with rated power of 30 kVA, 13.8 kV - 220/127 V, delta-star connection), so as to determine its characteristics in terms of input, output and transference impedance as a function of frequency. As the transformer was supposed to be protected by arresters, it was assumed that the voltages on the three phases have approximately the same amplitude. The input impedance Z11 was then obtained with the HV terminals interconnected and with the LV terminals in open circuit. Voltage signals of approximately 16 V peak-to-peak, in the frequency range of 10 kHz to 1 MHz, were applied to the HV terminals. A digital storage oscilloscope with sampling rate of 500 MS/s and bandwidth of 300 MHz was used for measuring the applied voltage and the current at the HV terminals 1 (external) and 2 (middle), as well as the phase shift between voltage and current signals. A probe associated with an amplifier was used for current measurements.

Fig. 1 shows the circuit used for the determination of Z11. For each frequency its modulus was calculated by the ratio of the amplitudes of the voltage at point P1 and the current at point P3. The phase shift was given by the difference in time between the zero crossings of the voltage and current signals. The output impedance Z22 was obtained analogously. For the determination of the transfer impedance Z21 the calculations considered, with reference to Fig. 1, the voltage transferred to secondary (at the point P2) and the current at the point P3.

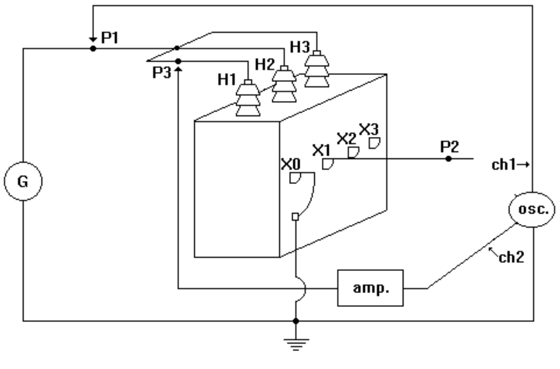


Fig. 1 - Circuit for the determination of the transformer input impedance Z11. G: signal generator; amp.: amplifier; osc.: oscilloscope.

Figs. 2 to 4 present the curves, as functions of frequency, of the transformer impedances.

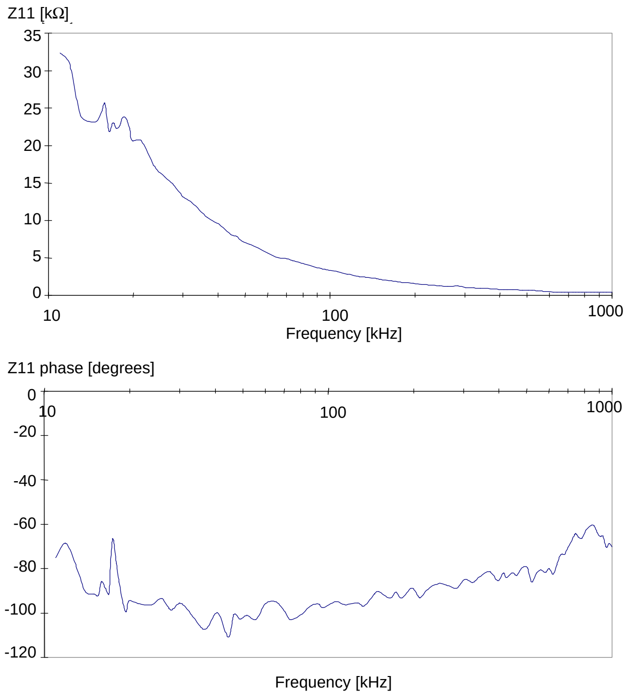


Fig. 2 - Transformer input impedance Z11 as function of frequency.

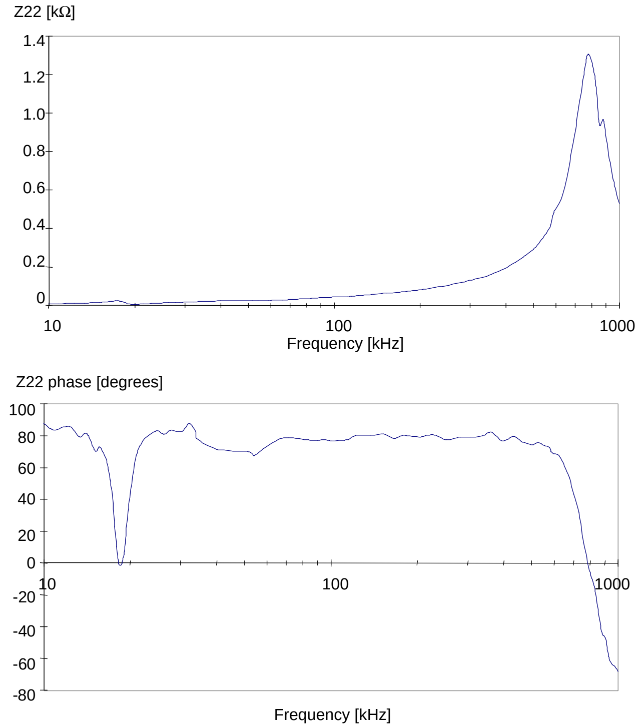


Fig. 3 - Transformer output impedance Z22 as function of frequency.

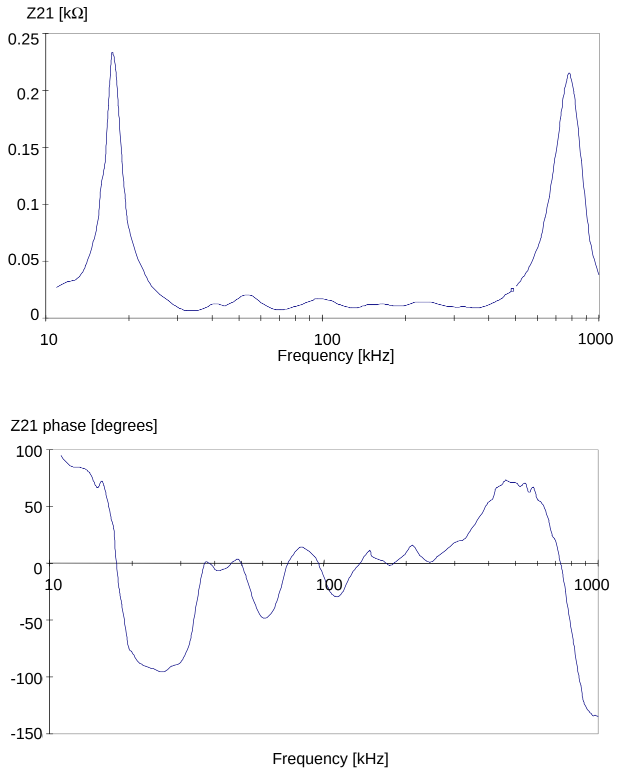


Fig. 4 - Transformer transfer impedance Z21 as function of frequency.

As the HV terminals were short-circuited, the inductive effect of the windings is practically eliminated, since the primary windings are connected in delta. This explains the essentially capacitive behaviour of the input impedance Z11. On the other hand, as the LV windings are connected in star, the inductive effect of the windings leads to a predominantly inductive behaviour of the output impedance Z22 up to the frequency of approximately 750 kHz. The transfer impedance Z21 has a more complex frequency-dependent behaviour, alternating between capacitive and inductive characteristics, with various ressonance points.

Considering these results, simulations were then made in order to obtain a circuit, as simple as possible, that could reasonably reproduce the transformer behaviour in the frequency range adopted in this study (from 10 kHz to 1MHz). After some attempts the model shown in Fig. 5, composed by resistive, inductive and capacitive elements, was considered to be representative of the transformer.

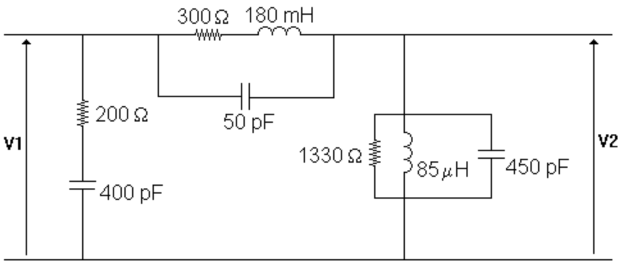
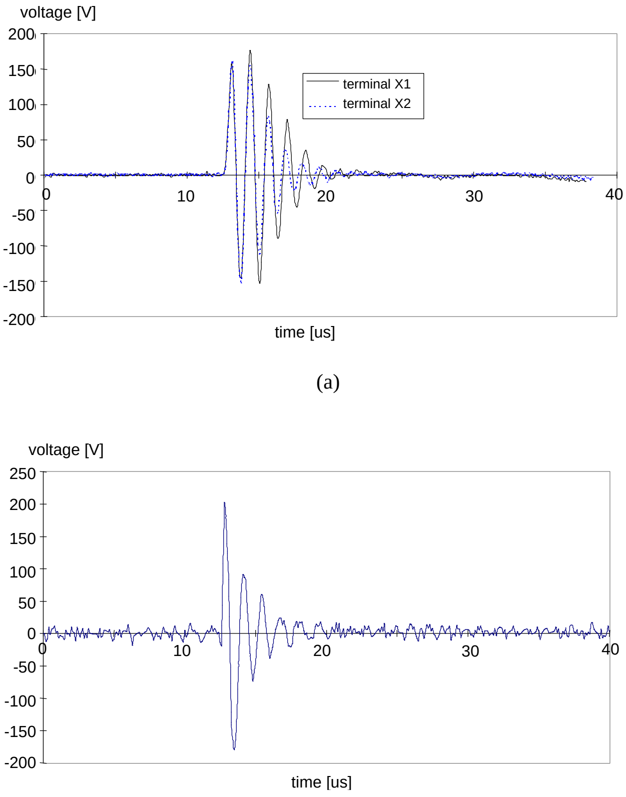


Fig. 5 - Transformer model for calculation of transferred surges.

Validation

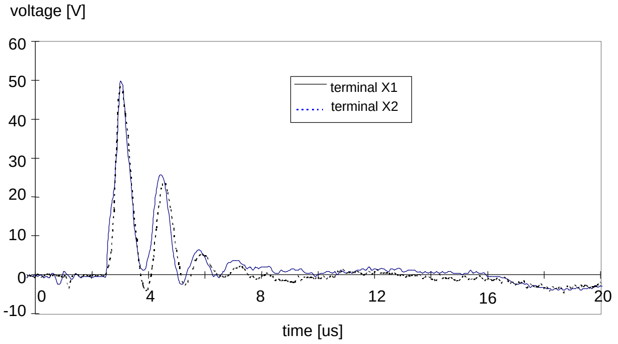
Two kinds of tests were performed in order to verify the validity of the transformer model. In the simplest configuration, impulse voltages (1.2/50 µs waveform) with amplitudes of approximately 8 kV were applied to the high-voltage terminals interconnected, and the voltages transferred to the secondary side were measured under different load conditions. Figs. 6 to 8 present some comparisons between measured (at terminals X1 and X2) and calculated transferred voltages, obtained for different load conditions.



(a)

(b)

Fig. 6 - Voltages transferred to the secondary under no-load conditions.
a) measured b) calculated



(a)

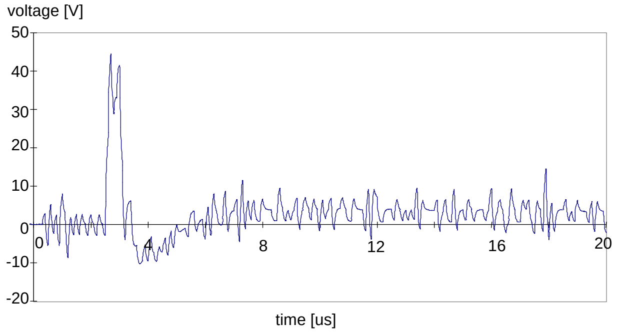


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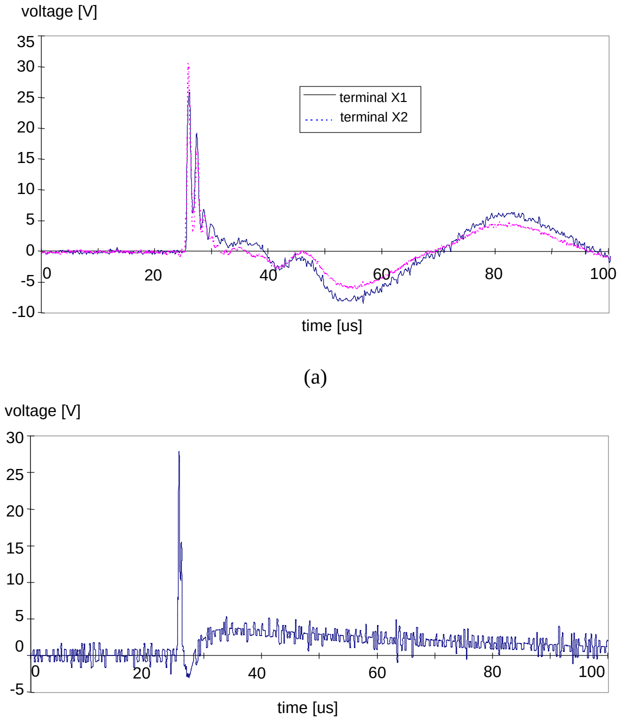
Fig. 7 - Voltages transferred to the secondary (resistive load of 100 Ω).
a) measured b) calculated



(a)

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Fig. 8 - Voltages transferred to the secondary (resistive load of 50 Ω).
a) measured b) calculated

The second configuration included also the presence of a simulated low-voltage line and of a medium voltage ZnO arrester (rated current of 10 kA). Either resistors or capacitors, placed at the end of the line and connected between phases and neutral, were used to simulate different load types. Impulse currents with amplitudes of about 5 kA were applied to the arrester; the voltages were measured not only at the transformer terminals (low-voltage side) but also at the end of the line. The arrester was connected either to the HV terminals short-circuited or only to the terminal H1, as shown in Fig. 9. Fig. 10 shows the current injected into the circuit.

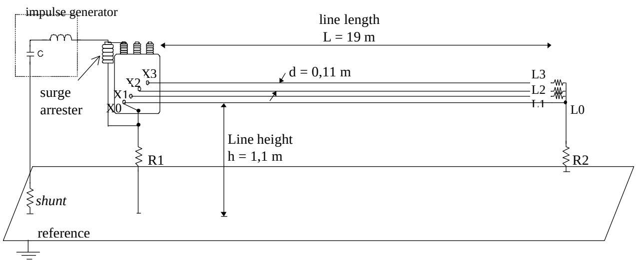


Fig. 9 - Test configuration. Shunt resistor = 2.62 mΩ;
R1 = 4.5 Ω; R2 = 2.5 Ω.

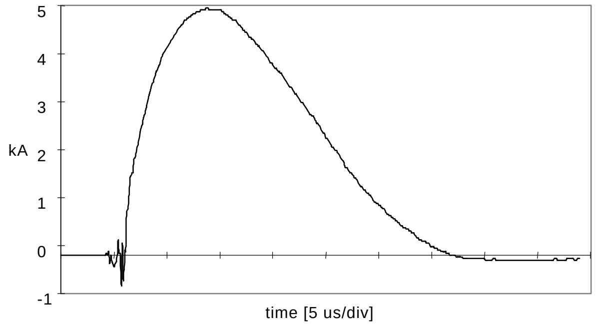
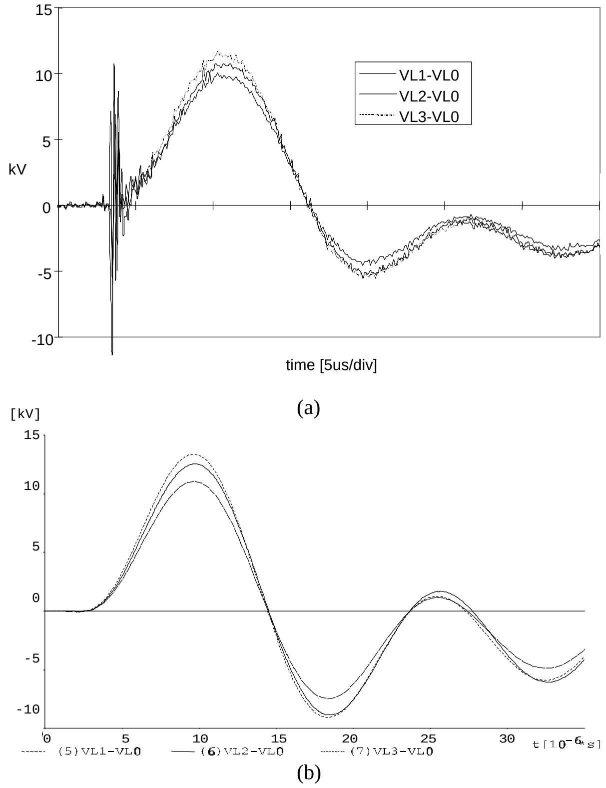


Fig. 10 - Current injected into the test circuit.

Figs. 11 to 14 present some comparisons between measured and calculated phase-to neutral voltages at the loads, in different situations. For the calculations, the *ATP (Alternative Transients Program)* was used.



(a)

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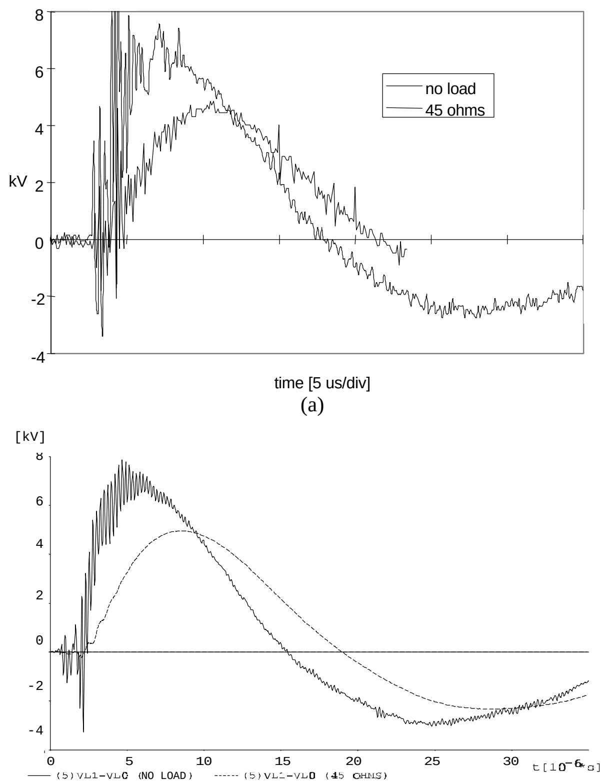
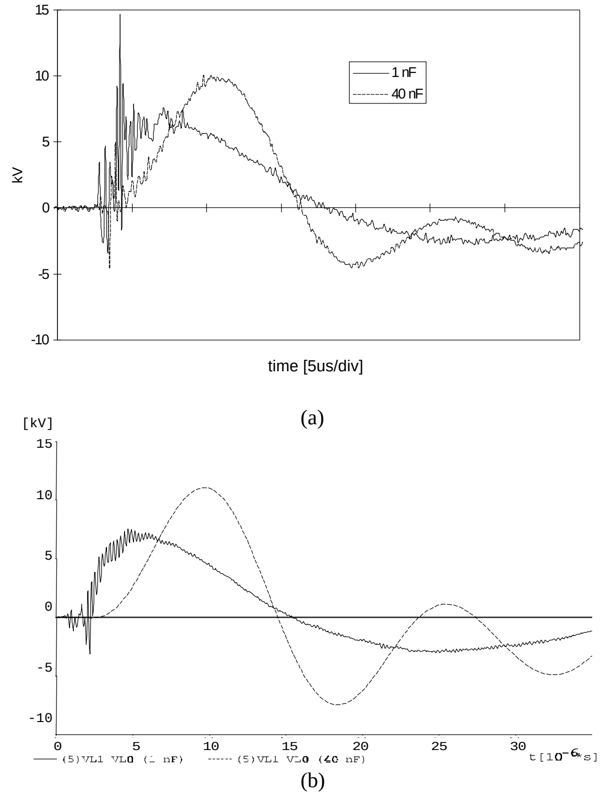
Fig. 11 - Phase-to neutral voltages at the loads (capacitances of 40 nF).
Arrester connected only to terminal H1.
a) measured b) calculated



(a)

(b)

Fig. 12 - Phase-to neutral voltages at L1 (VL1 - VL0), for two conditions: without loads and with resistive loads of 45 Ω. Arrester connected only to terminal H1. a) measured b) calculated



(a)

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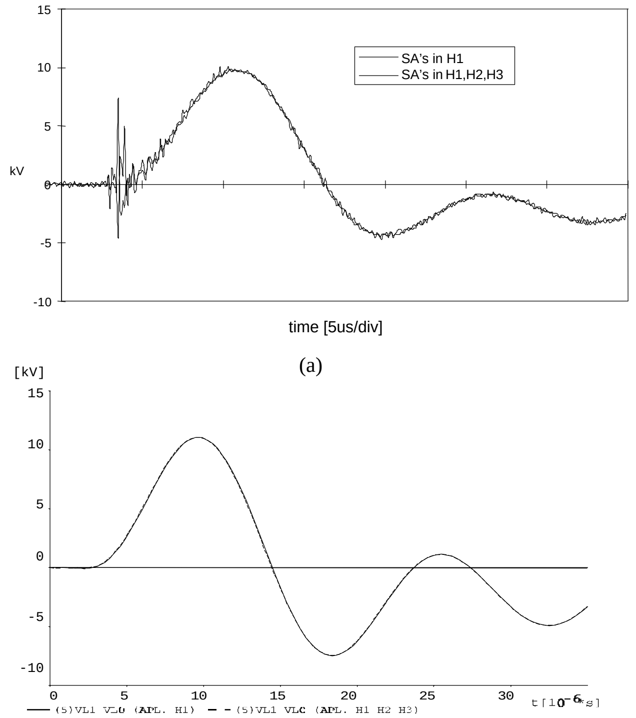
Fig. 13 - Phase-to neutral voltages at L1 (VL1 - VL0). Loads represented by capacitances of 1 nF and 40 nF. Arrester connected only to terminal H1. a) measured b) calculated



(a)

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Fig. 14 - Phase-to neutral voltages at L1 (VL1 - VL0). Loads represented by capacitances of 40 nF. Arrester connected to terminals H1, H2 and H3 (short-circuited) and only to terminal H1.
a) measured b) calculated

The results show that the proposed model gives a reasonable representation of the distribution transformer in terms of voltages transferred to the secondary. As shown in the comparisons relative to the simplest test circuit, the differences between measured and calculated voltages tend to increase as the impedance connected to low-voltage terminals decreases. The relatively good results obtained for the more complex test configuration indicates that the model is also adequate to more realistic situations.

LIGHTNING SURGES TRANSFERRED TO THE LV NETWORK

With the transformer represented by the model previously obtained, simulations were then performed with the ATP, in order to calculate voltages transferred to the secondary in some typical situations, such as in that presented in Fig. 15. In this topology the primary and secondary lines are partially coupled, and the transformer is placed at the end of the primary line.

The possibility of the occurrence of flashovers in the primary and secondary circuits, as well as from the neutral conductor to the ground, was taken into account by means of the switches shown in Fig. 15. They were placed at every pole; the Vxt characteristic curves were calculated using the standardised lightning impulse waveform (1,2/50 μs), with the integration method presented in [2].

The points labelled as *D1, D2*, ... and *E1, E2*, ..., in Fig.15, represent the poles, with a span distance of 30 m. Rc and Rs represent the ground resistances of the consumers. Different values were assumed for the ground resistances of the poles: Rt (effectively grounded) and Rp (not effectively grounded). The values of Rp were defined as twice the values of Rt, as obtained in tests reported in [3].

The consumers loads, connected between phase and neutral, were represented by a resistor of 30 Ω in parallel with a capacitance of 4 nF. The impedance modulus of this association lies in the range of the values presented in [4].

The lightning current, injected in the primary line at the D3 point (90 m distant of the transformer), was represented by a triangular waveform with a peak value of 31 kA, time to crest of 2 μs and time to half-value 50 μs. A typical VxI curve was used for representing the characteristic of the ZnO primary arrester.

For illustration purposes, Figs 16 to 18 show some examples of calculated voltages transferred to the secondary (each phase-to-neutral) in the case of a direct strike on the MV line at the point D3. In Fig. 16 the voltages were calculated at the point D1 (located 30 m from the transformer). Fig. 17 refers to voltages at point D5 (150 m far from the transformer) while the Fig.18 shows the voltages at the transformer terminals. Ground resistances of 100 Ω were assumed for Rt and Rc**.**

Another application of the transformer model for calculating surges in LV networks as well as associated currents and charges in protective devices is presented in [5].

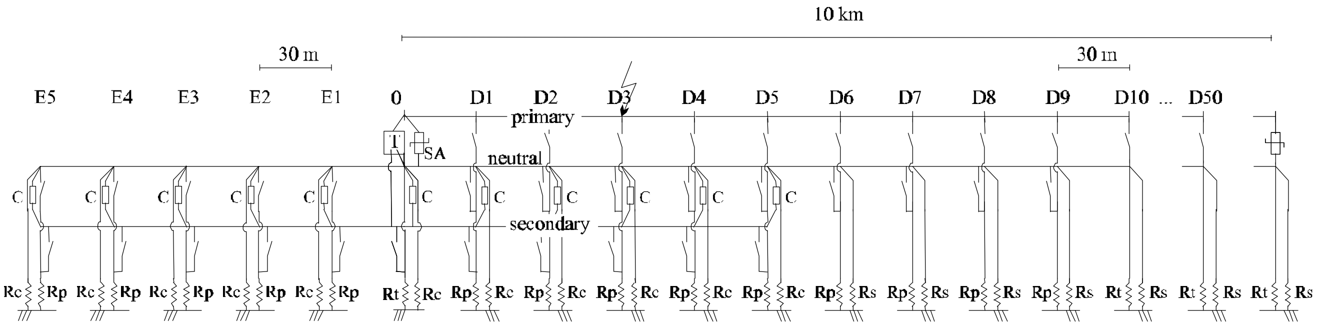

Fig. 15 – Line configuration used in the simulations

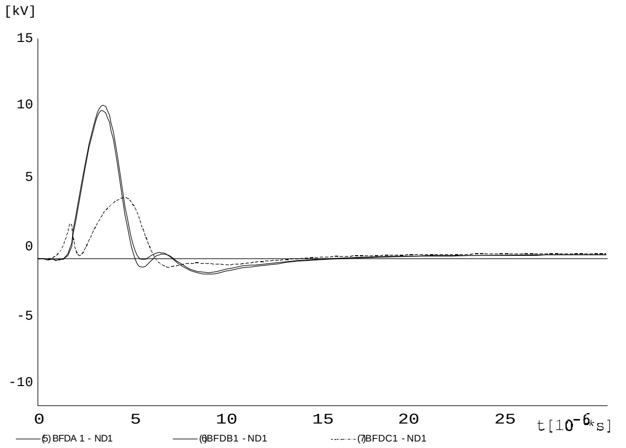

Fig. 16 - Phase-to-neutral voltages on the secondary line (at point D1).

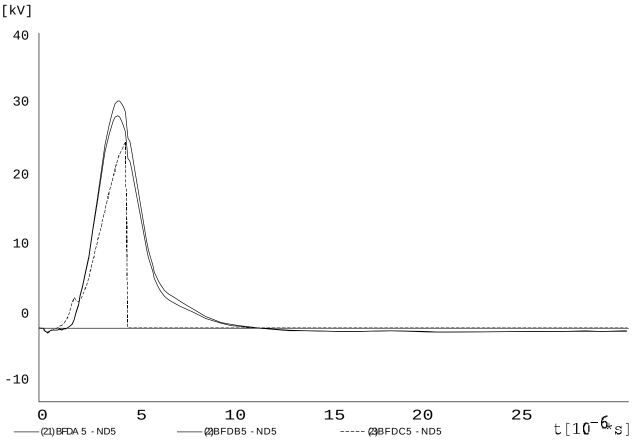

Fig. 17 - Phase-to-neutral voltages on the secondary line (at point D5).

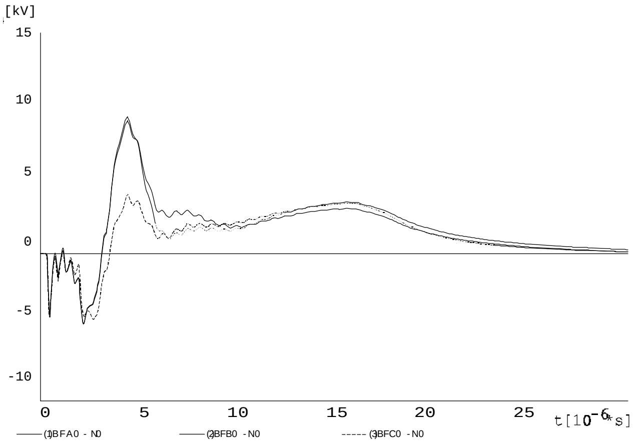

Fig. 18 - Phase-to-neutral voltages on the secondary line
(at the transformer terminals).

CONCLUSIONS

A simple model for representation of distribution transformers was developed, aiming at the calculation of surges transferred to the secondary. The results of the comparisons between measured and calculated voltages indicate that the proposed model can be an useful tool for the evaluation of transferred surges, taking into account the compromise between accuracy and simplicity.

ACKNOWLEDGEMENT

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