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SURGES TRANSFERRED TO THE LOW-VOLTAGE NETWORK VIA TRANSFORMER – THE INFLUENCE OF THE LOAD CONNECTED TO THE SECONDARY

A. G. Kanashiro A. Piantini
Institute of Electrotechnics and Energy / University of São Paulo
Brazil

Abstract – One kind of overvoltage in the secondary network refers to the surges transferred from the primary through the transformer. These surges are caused by lightning discharges and should be correctly evaluated aiming at an effective protection of the secondary network. This work presents waveforms of the transferred voltages where the effect of the load connected to the secondary of the transformer can be observed. Results of the tests performed in the laboratory and of computer simulations are shown, with a model developed to represent the distribution transformer being used. Simulations using the ATP are also presented, with the waveforms of the transferred voltages in some points of a typical secondary network, when direct discharges in the primary occur, being shown.

1 - INTRODUCTION

Surges due to lightning discharges are the main causes of disturbances in distribution lines, having significant influence on the quality of the energy supplied. Therefore, the knowledge of the several induction mechanisms of the overvoltages is necessary, so as to make it possible to adequately analyse the techniques to minimise the problem. Some investigations on the characteristics of the lightning induced voltages on low-voltage lines have been conducted in [1-4]. One kind of overvoltage that occurs in the secondary network is due to the surges transferred through the transformer. The analysis of these surges requires the utilisation of reliable models to represent the elements involved in the phenomenon. As regards the distribution transformers, however, the models that are normally utilised for that purpose are, in general, inadequate, like the π-capacitive model, or excessively complex [5]. It is important to emphasise that even the models classified in the last category, generally speaking, have their validity restricted to the no-load condition, making it impossible then to determine the effect of the load connected to the secondary in the amplitudes and waveforms of the transferred surges [6-9].

The study of the voltages transferred depends on the knowledge of the characteristics of the voltages induced in the primary networks and on the high frequency behaviour of the transformer. Many studies have been carried out on the induced voltages due to lightning discharges [10-12]. As regards the behaviour of the transformers, the non-existence of a simple model which adequately represents the transformer for high frequencies and which also takes into account the effect of the load connected to the secondary, should be emphasised.

In [13], an extremely simple and reliable model, though restricted to the no-load condition, to represent three-phase distribution transformers, was presented. This model provided the development of the studies presented in [14,15] concerning the voltages transferred to the secondary. These studies developed so that a model which represents the distribution transformer reasonably well also in the under load condition was presented in [16]. The development was based on the transference characteristics (ratio between the voltages on the secondary and on the primary, as a function of the frequency) of a typical distribution transformer. A further improvement of the model was presented in [17]. The good results which were obtained motivated the continuation of the research, with the aim of checking if the proposed model could be applicable to other distribution transformers. Nine transformers of different manufacturers and rated powers were then considered, with their characteristics as a function of frequency, which resulted in the generic model to represent three-phase distribution transformers [18].

This work presents waveforms of the transferred voltages with several load conditions being taken into account. These waveforms refer to the 45 kVA distribution transformer, in which voltages impulses with standardised waveform (1,2/50 μs) are applied. The voltages transferred through the transformer are compared with the ones obtained through the model proposed in [18]. Afterwards, simulations using the ATP are performed, with the transferred voltages when direct discharges in the primary line in a typical distribution network occur, being analysed. In these simulations, a 30 kVA distribution transformer, represented through the transformer model [18], was considered.

2 – TRANSFORMER MODEL

To develop the model, a 30 kVA, 13.8 kV / 220-127 V, three-phase distribution transformer was used, delta connected in the high voltage and star connected in the low voltage.

The transformer, represented as a quadripole, was subject to the voltage impulse with standardised waveform to determine the input (Z_{11}), output (Z_{22}) and transfer (Z_{12}) impedances. The voltage values were measured with a resistive divider and the current values were obtained through a shunt resistor. A 250 MHz digital osciloscope was utilised for signal acquisition. Figure 1 shows the test circuit which was used to determine Z_{22}.

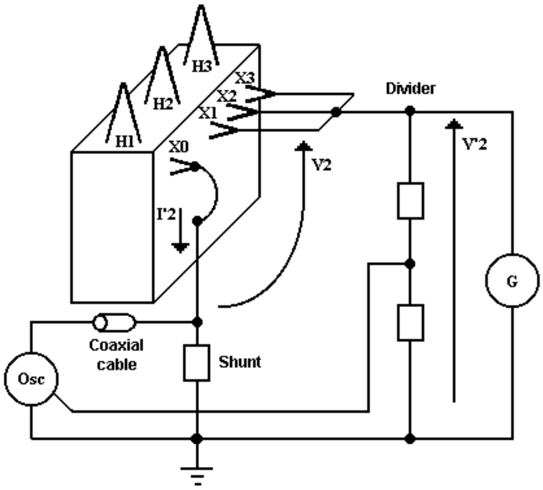


Figure 1 – Test circuit to determine Z_{22}.

Voltage impulse (V'_2) was applied in terminals X_1, X_2 and X_3, simultaneously, and current (I'_2) was obtained through a shunt. Terminal X_0 and the transformer tank were grounded through the shunt. V_2 and I_2 were determined based on the values of V'_2 and I'_2 with the constants of the measuring system being taken into account, that is, the divider ratio (172:1), the value of the shunt (5 Ω) and the characteristic impedance of the coaxial cable (75 Ω). Voltage V_2 and current I_2 were registered in time domain and to determine the magnitude and phase of impedance Z_{22} the frequency components of each signal were obtained through the Fourier analysis. Impedance Z_{22} was obtained through the ratio V_2/I_2. So as to determine output impedance Z_{11}, a procedure similar to the one described to determine impedance Z_{22} was used, with voltage impulse V'_1 being applied simultaneously in terminals H_1, H_2 and H_3. Current I'_1 in the secondary was obtained through the shunt. The magnitude and phase of impedance Z_{11} were determined through the ratio V_1/I_1. To determine impedance Z_{21} voltage impulse was applied in the primary terminals, with the transferred voltage V_2 being obtained in terminal X_3 of the secondary winding. Current I_1 was obtained through the shunt. The magnitude and phase of impedance Z_{21} were determined through the ratio V_2/I_1.

The next step was to determine impedances Z_1, Z_2 and Z_3 as a function of the frequency using the values of impedances Z_{11}, Z_{22} and Z_{21}. From the characteristics of Z_1, Z_2 and Z_3, the representation of each one of these impedances was investigated, separately, through resistive (R), inductive (L) and capacitive (C) elements.

In [17], the equivalent circuit for the 30 kVA transformer is presented, where the resistive, inductive and capacitive parameters referring to impedances Z_1, Z_2 and Z_3 can be identified. Impedances Z_1 and Z_2 are represented by a capacitor and a parallel resonance circuit RLC, respectively. Impedance Z_3 is represented by a resistor in series with the parallel circuit consisting of two resonance circuits RLC and of a capacitor. The behaviour of the input, output and transfer impedances of the quadripole and of the equivalent circuit were compared. The PSpice program was used to obtain the impedances of the equivalent circuit.

The validation of the transformer model was reached through the comparison of the results obtained in the simulations and in the laboratory tests [17]. The load was placed directly in the secondary terminals of the transformer. The responses of the model and of the transformer were compared when impulse voltages with both standardised and typical waveforms of voltages induced by lightning discharges are applied. Afterwards, the same methodology was followed in order to verify the general applicability of the circuit. Eight typical three-phase distribution transformers, 13.8 kV / 220-127 V, delta-wye connected, with power ratings ranging from 45kVA to 225 kVA and of different manufacturers, were used in the investigation. The results of the laboratory tests performed in order to validate the model are shown in [18]. Figure 2 presents the model, which was found to be valid for all the transformers considered.

The values of the parameters referring to the 45 kVA transformer are as follows:

-resistances (kΩ): 0,6 (R2), 1,0 (R3), 9,0 (R5) e 20(R7);
-capacitances (pF): 773 (C1), 53 (C2), 110 (C3), 1,0(C4), 500 (C5) and 1000 (C7);
-inductances (mH): 1,1472 (L2), 0,2 (L3), 0,015 (L5) and 0,020 (L7).

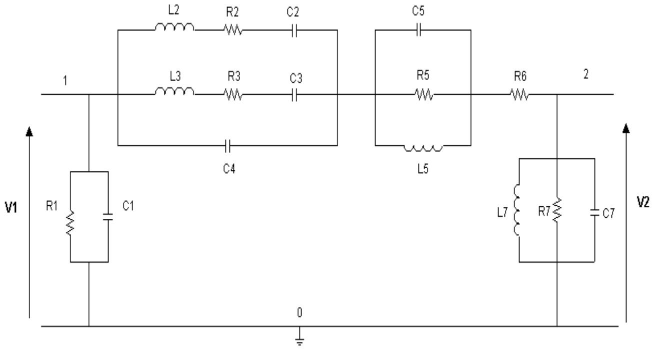
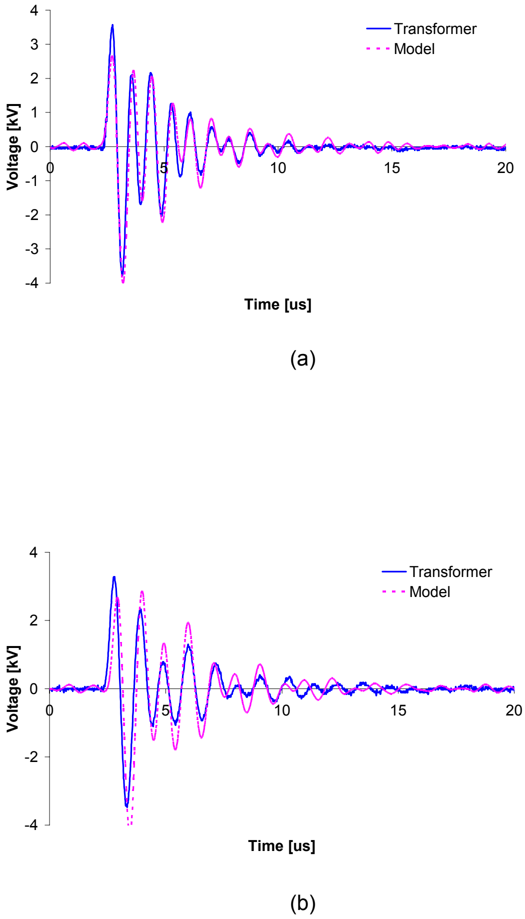


Figure 2 – Model to represent three-phase distribution transformers with the transference of surges taken into consideration.

Waveforms of voltages transferred to the secondary of the 45 kVA three-phase distribution transformer, obtained through tests, under several load conditions, are shown. Comparisons with the results obtained through the utilisation of the model developed to represent the transformers, are also presented.

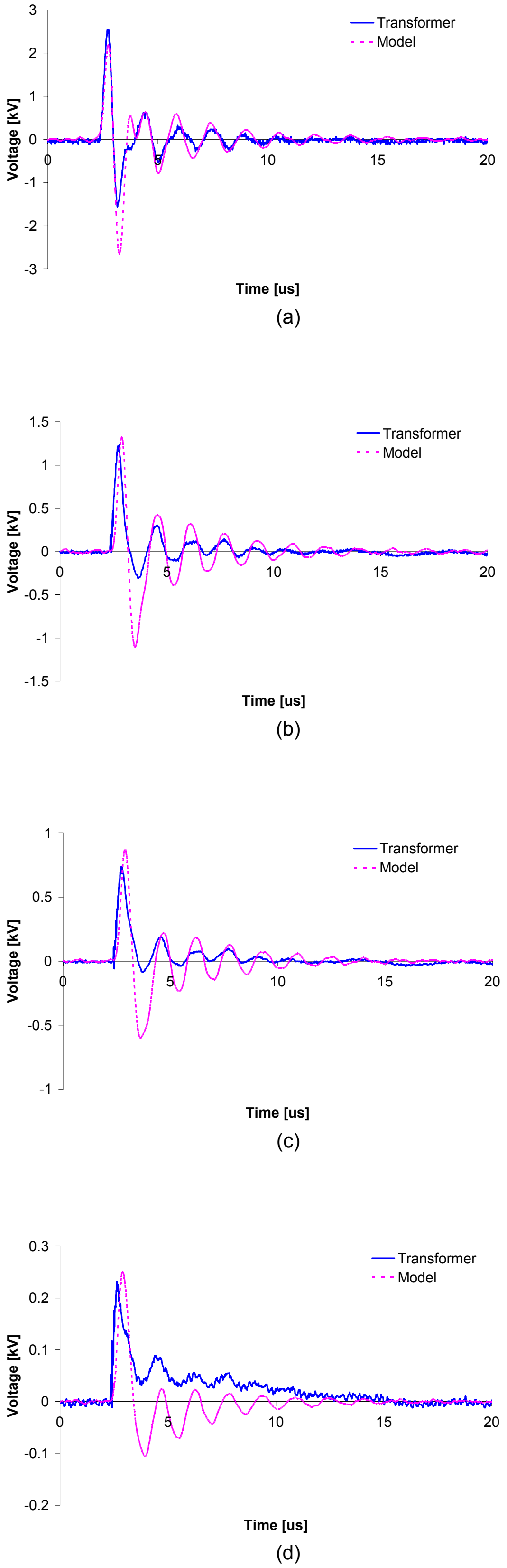
During the tests, voltage impulses with standardised waveform (1,2/50μs) were applied to the high-voltage terminals (interconnected) of the transformer, with the voltages transferred to the secondary being simultaneously measured. The peak values of the voltage impulses applied were 1.86 kV and 1.87 kV, depending on the load. The waveform was kept unaltered in all applications. Figures 3 and 4 show the comparisons between the transferred voltages presented by the model and the ones presented by the 45 kVA transformer, under different load conditions. In order to analyse the results, the voltage values were standardised to 100 kV (this value applied to the distribution transformer instead of 1.86 kV and 1.87kV). Although the analysis presented in this paper refers to the applied impulse voltage (standardised waveform), in [14] other situations are considered, with the transferred voltages being evaluated with the transformer in the no-load condition, though.



(a)

(b)

Figure 3 – Measured and calculated transferred voltages.
(a) no-load condition (b) load = 330 pF



(a)

(b)

(c)

(d)

Figure 4 – Measured and calculated transferred voltages for different load conditions (resistive).
(a) 510 Ω (b) 100 Ω (c) 50 Ω (d) 10 Ω

3 – EXAMPLE OF AN APPLICATION IN PRACTICAL SITUATIONS

In order to evaluate the performance of the low-voltage network taking into account lightning discharges and to establish criteria for its protection, it is necessary to evaluate the levels of surges that are transferred from the primary to the secondary via transformer. The surges can be caused by both direct lightning discharges in the primary and discharges that strike close to a distribution line. In this item, examples of the utilization of the model developed to represent distribution transformers, with a typical secondary network configuration being considered, are presented. Besides the transformer, the most relevant components of the system, such as surge arresters, insulators, ground resistances, etc., are represented in the simulations. The ATP (Alternative Transient Program) was used to perform the simulations for the analysis of voltage surges in the transformer and in the consumers, with the presence of protection devices being also considered. The influence of various parameters of the components of the network and of the discharge is investigated in the case of direct lightning discharges in the primary line. A lightning current with triangular waveform, peak value of 45 kA, front time of 2,25 μs and time to half value 80 μs, was adopted in the simulations. This current was taken as representative of the lightning discharges with median value since, according to the data registered by CEMIG [19], the median value of the peak current is approximately 48 kA.

The basic configuration used in the simulations has a 10km long primary line, with 3x336.4 MCM phase and 1x1/0 AWG neutral conductors (all of them aluminium), and grounded neutral every 300 m. The distribution transformer that supplies the secondary network analysed was located in the middle of the primary circuit. For the secondary circuit, the length of 300 m was adopted (150 m for each side of the transformer), this circuit being coupled with the primary line, with 1/0 AWG aluminium conductor and neutral common to the primary line. The branches of the consumers are connected to the secondary circuit every 30 m, with the neutral being grounded at the entrance of the consumers. The components of the network were represented as described in [20].

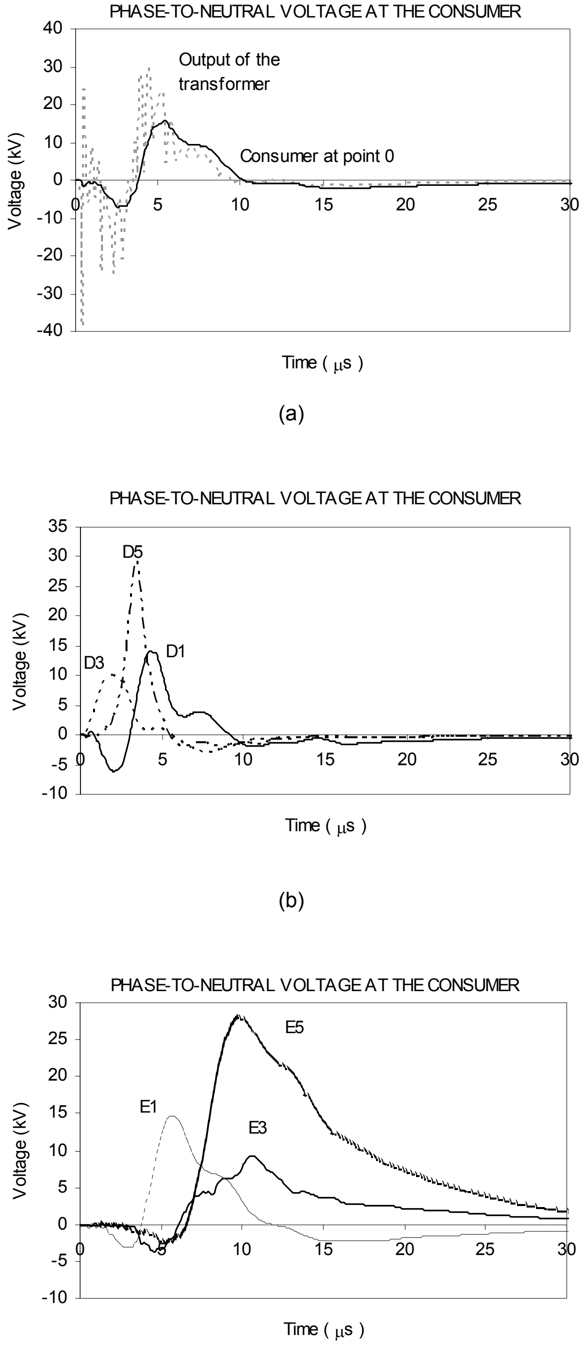
In order to represent the three-phase distribution transformer, the 30 kVA transformer model was used (Figure 2), whose parameters are as follows:

-resistances (kΩ): 14 (R2), 0,8 (R3), 1,1 (R6) and 1,62(R7);
-capacitances (pF): 493 (C1), 94,8 (C2), 21,51 (C3), 50(C4) and 759,5 (C7);
-inductances (mH): 16 (L2), 1,84 (L3) and 0,05 (L7).

Three configurations were analysed concerning the position of the low-voltage protection devices (surge protective devices – SPDs), connected to the secondary network. The first configuration refers to the secondary without protection. In the second configuration the SPDs were placed only at the low-voltage terminals of the transformer. The third configuration refers to the protection at the output of the transformer and at both ends of the secondary circuit. The voltage in the secondary can be divided into two parts, being the first one associated with the transference from the high to the low-voltage through the transformer, according to the phenomenon described in item 2. The second component is due to the current that flows through the neutral conductor as a result of the discharges of the high voltage surge arresters and of the flashovers through the insulators, both from the primary and the secondary. In general, this is the most important component of the voltage in the secondary when direct lightning discharges occur in the primary. It must be emphasised that the above conclusion was reached through the utilisation of a model proven to be adequate to represent the transformer. Although the model presented in this work is an improvement on the one proposed in [16], which was used in [21,22], the latter led to similar conclusions under the qualitative aspect.

Figures 5 and 6 present the voltages corresponding to the cases in which the network is without protection and, afterwards, with protection at the low-voltage terminals of the transformer and at the ends of the secondary circuit, respectively. In both cases, the lightning discharge occurs on the right side of the transformer, at a distance of 90 m (point D3). If the voltages at the output of the transformer are compared in both configurations, it is observed that the SPDs cause significant reduction of the voltage peak value, which varies from approximately 30 kV to 1.0 kV, this value corresponding to the residual voltage of the SPDs. As for the reduction in the maximum value of the voltage at the entrance of the consumer closest to the transformer (point 0), although smaller it is also significant: from approximately 15 kV to 5.5 kV. However, in the consumers located on the left side of the transformer, near points E1 and E3, the voltages decrease 45 %, approximately, with the installations of the SPDs; at point E5 the variation is smaller, of about 20 %.

For the consumers located on the right side of the transformer, in which the lightning strikes the primary line, it is observed that only the one corresponding to point D1, closest to the SPDs at the output of the transformer, has its voltage significantly reduced (about 45 %); the others are practically not affected by the presence of the SPDs. It is also observed that in case there is an absence of SPDs (Figure 5), the amplitudes of the voltages in the consumers that are equally distant from the transformer are approximately the same, although the voltages on its right side present shorter tails due to the flashovers in the insulators. However, when the network has SPDs (Figure 6), the voltages at the entrances of the consumers of points E1 and D1 have similar amplitudes and waveforms, whereas the consumers situated on the right side, at the ends of the secondary, present voltages with higher amplitudes, but shorter duration.

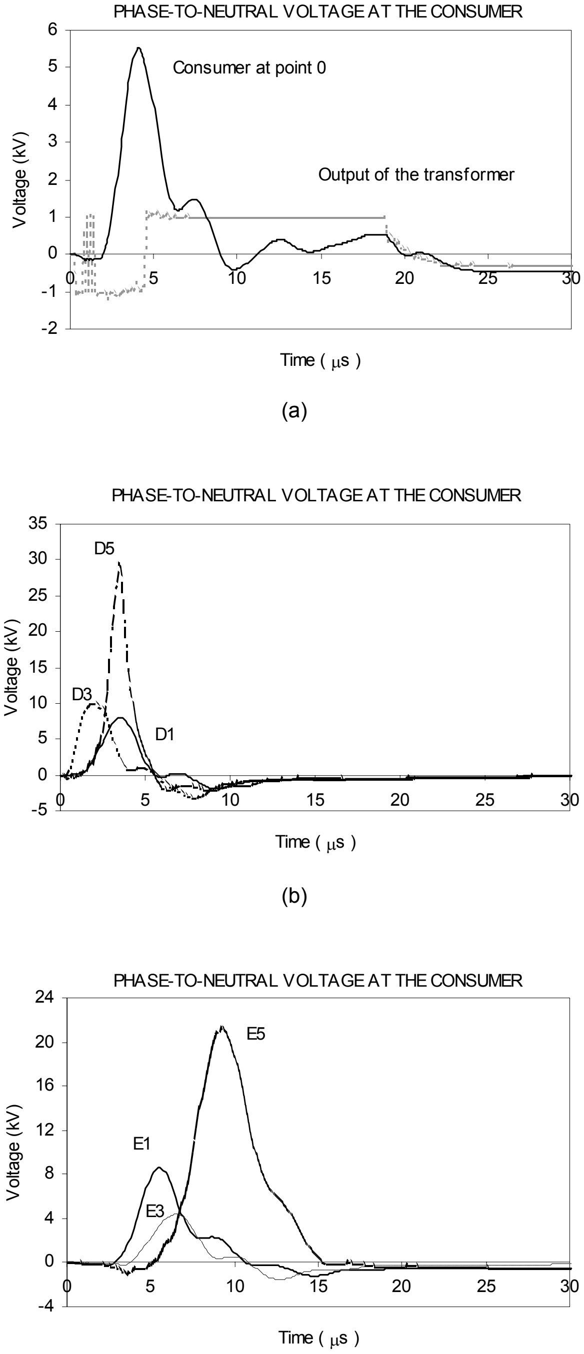


(a)

(b)

(c)

Figure 5 – Phase-to-neutral voltages. Grounding resistances: 300Ω. Secondary network without protection. Lightning discharge of 45 kA at a distance of 90 m from the transformer (point D3).
(a) vicinity of the transformer
(b) consumers (right side)
(c) consumers (left side)



(a)

(b)

(c)

Figure 6 - Phase-to-neutral voltages. Grounding resistances: 300 Ω. SPDs at the output of the transformer and at both ends of the secondary circuit. Lightning discharge of 45 kA at a distance of 90 m from the transformer (point D3).
(a) vicinity of the transformer
(b) consumers (right side)
(c) consumers (left side)

4 - CONCLUSIONS

This work presented the waveforms of the voltages transferred through the distribution transformer with several load conditions being taken into account. The results were compared with the voltages obtained through the model developed to represent the transformer. The model leads to very reasonable results when the calculated transferred voltages are compared to those obtained through the laboratory tests. Afterwards, simulations using the ATP were performed, with the transferred voltages, when direct discharges in the primary line in a typical distribution network occur, being analysed. The simulations performed took practical situations into consideration and were aimed at illustrating the complexity of the problem, having in mind the great quantity of parameters involved and the variation ranges of their values. Nevertheless, the information presented allows one to have an overall idea of the basic characteristics of the surges transferred to a typical secondary network when direct lightning discharges occur in the primary.

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6 - REFERENCES

[1] Galvan A., Cooray V., "Analytical simulation of lightning induced voltages in low voltage power installations", Proceedings of the 25th International Conference on Lightning Protection (25th ICLP), pp. 290-295, Rhodes, Sep. 2000.

[2] Piantini A, Janiszewski, J. M., "Lightning induced voltages on low-voltage lines", Proceedings of the V International Symposium on Lightning Protection (V SIPDA), pp. 234-239, São Paulo, May 1999.

[3] Joint CIRED/CIGRÉ Working Group 05, "Protection of MV and LV networks against lightning. Part I: basic information", Proceedings of the International Conference on Electricity Distribution (CIRED 97), Conf. Publication No. 438, pp. 2.21.1 - 2.21.7, Birmingham, 1997.

[4] Mirra C. et al., "Lightning overvoltages in low voltage networks", Proceedings of the International Conference on Electricity Distribution (CIRED 97), Conf. Publication n. 438. pp. 2.19.1 - 2.19.6, Birmingham, 1997.

[5] Morched, A.; Martí, L.; Ottevangers, J., "A High frequency transformer model for EMTP", IEEE Transactions on Power Delivery, n. 3, pp. 1615-1626, Jul. 1993.

[6] Vaessen P. T., "Transformer model for high frequencies", IEEE Transactions on Power Delivery, vol. 3, n. 4, pp. 1761-1768, Oct. 1988.

[7] Soysal, A. O., "A Method for wide frequency range modelling of power transformers and rotating machines", IEEE Transactions on Power Delivery, n. 4, pp. 1802-1810, Oct. 1993.

[8] Woivre, V.; Arthaud, J. P.; Ahmad, A.; Burais, N., "Transient overvoltage study and model for shell-type power transformers", IEEE Transactions on Power Delivery, n. 1, pp. 212-222, Jan. 1993.

[9] Ueda, T.; Neo, S.; Sugimoto, T.; Funabashi, T.; Takeuchi, N., "An improved transformer model for transfer voltage study", Proceedings of the International Conference on Power Systems Transients (IPST'95), pp. 107-112, Lisbon, Sep. 1995.

[10] Piantini A., Janiszewski, J. M., "Induced voltages on distribution lines due to lightning discharges on nearby metallic structures", IEEE Transactions on Magnetics, vol. 34, n. 5, pp. 2799-2802, Sep. 1998.

[11] Nucci, C. A.; Borghetti, A.; Piantini, A.; Janiszewski, J. M., "Lightning-induced voltages on distribution overhead lines: comparison between experimental results from a reduced-scale model and most recent approaches", Proceedings of the International Conference on Lightning Protection (24th ICLP), vol. 1, pp. 314-320, Birmingham, Sep. 1998.

[12] Piantini, A., "Contribution to the study of lightning induced voltages on distribution lines" (in Portuguese), São Paulo, 1991, 205 p., MSc Thesis, Dept. of Electrical Engineering, University of São Paulo.

[13] Piantini, A.; Malagodi, C. V. S., "Modelling of three-phase distribution transformers for calculating lightning induced voltages transferred to the secondary". Proceedings of the V International Symposium on Lightning Protection (V SIPDA). pp 59-64, São Paulo, May 1999.

[14] Piantini, A.; Malagodi, C. V. S., "Voltage surges transferred to the secondary of distribution transformers", Proceedings of the 11th International Symposium on High Voltage Engineering (11th ISH). vol. 1, pp. 1.365-1.368, London, Aug. 1999.

[15] Piantini, A.; Malagodi, C. V. S., "Voltages transferred to the low-voltage side of distribution transformers due to lightning discharges close to overhead lines", Proceedings of the V International Symposium on Lightning Protection (V SIPDA). pp.201-205, São Paulo, May 1999.

[16] Piantini A.; Bassi, W.; Janiszewski, J. M.; Matsuo, N. M., "A Simple transformer model for analysis of transferred lightning surges from MV to LV lines", Proceedings of the 15th International Conference on Electricity Distribution (15th CIRED), Nice, 1999.

[17] Kanashiro A. G., Piantini A., Burani, G. F., "A Methodology for transformer modelling concerning high frequency surges", Proceedings of the VI International Symposium on Lightning Protection (VI SIPDA), pp. 275-280, São Paulo, Nov. 2001.

[18] Piantini A., Kanashiro A. G., "A High frequency distribution transformer model for calculating transferred voltages" (To be presented at the 26th International Conference on Lightning Protection - 26th ICLP, Cracow, Sep. 2002).

[19] Schroeder, M. A.; Soares Jr., A.; Visacro F.; S.; Cherchiglia, L. C. L.; Souza, V. J.; Diniz, J. H.; Carvalho, A. M., "Evaluation of directly measured lightning parameters", Proceedings of the V International Symposium on Lightning Protection (V SIPDA). pp. 7-11, São Paulo, May 1999.

[20] Piantini A., Kanashiro A. G., "Surtos transferidos à rede de distribuição de baixa tensão via transformador – influência da carga conectada ao secundário" (To be presented at the XV Seminário Nacional de Distribuição de Energia Elétrica – SENDI 2002, Nov. 2002).

[21] De Conti, A. R.; Pereira, C.; Visacro F., S.; Duarte, J. V. P., "Lightning and consumer power quality", Proceedings of the VI International Symposium on Lightning Protection (VI SIPDA), pp. 335-340, São Paulo, Nov. 2001.

[22] Piantini, A.; Bassi, W.; Janiszewski, J. M.; Matsuo, N. M., "Overvoltages in the secondary network caused by lightning discharges" (in Portuguese), São Paulo, Center of Excellence in Distribution of Electrical Energy (CED), 102 p., 1998. (CED 294 / STRA 002 / RL 002 / OR).

Main author
Name: Arnaldo G. Kanashiro
Address: Av. Prof. Luciano Gualberto, 1289.
05508-010. São Paulo – SP – Brazil.
Phone: +55 11 3091-2574 Fax: +55 11 3812-9251
E-mail: arnaldo@iee.usp.br