The Use of TLM Modelling for the Analysis of the Behaviour of Continuous Transformer Windings Under Voltage Surge Incidence

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Abstract - **This paper presents the performance of TLM Method applied to the theoretical and experimental analyses of surge voltage distribution along windings of power transformers. TLM method has already been successfully applied in many studies of similar nature, like the problem of wave propagation on transmission lines. By considering inherent characteristics of TLM method, this work is developed in such a way that programs for this kind of analysis can be implemented in spreadsheets, which allows them to be developed in every personal computer. It is strongly recommended that reader have basic notions of TLM method.**

Keywords: TLM method, Transformer windings, voltage surges, overvoltages.

I. INTRODUCTION

Problems related to insulation failures inside transformers due to surge incidences have been extensively investigated ever since power transformers have been used [1,2]. Nevertheless, studies of this kind are still quite unreachable for many of them who deal with transformers. Some reasons of this distance lie in the fact that these studies are inherently complex since they require special mathematical and software tools. Consequently, even designer Engineers have had small chances to deal with this theme. Thus, insulation designs of power transformers are normally based on personal experiences, which is a practice that is not efficient.

In view of presenting TLM-Transmission Line Modelling method as being an efficient tool for the analyses of problems of this nature, computational results are shown for comparisons to theoretical results, that are quite available in literature, and also for comparisons to experimental results, obtained from uniform winding, here presented. All these comparisons have shown good agreement among obtained TLM results and computational or theoretical results [2,3]. Finally, this work is intended for helping Engineers who deal with transformers and who wants to develop their own software tools. Presented results are thus suggested to be a reference. Also this work presents some hints on programming in such a way that TLM programs can be implemented in spreadsheets, which allow intense and prompt graphical interaction, are very friendly-use and they can be easily found in any personal computer. Solutions of this nature have been constantly searched by most of Brazilian producers of transformers.

II. THEORETICAL ANALYSIS

A. Premises for a Reference Model

Today, there are too many different designs of power transformers. Ever different designs present specific characteristics related to the behavior of the windings after a voltage surge strikes it. Therefore, it is reasonable that he most simple case is used as reference and every additional complexity from this case can be adapted by the Engineer to her/his design. Therefore, the most simple case is the one continuous and uniform air-core winding exposed to the incidence of a step-voltage surge on one of its end, while other end is firmly connected to ground [3]. This premise is based on the fact that only high-voltage windings are important for the analysis of surge incidence. After all, low-voltage windings have larger conductors, which causes relatively large effective capacitance between their terminals. This and other consequent characteristics cause smaller concerns about the development of overvoltages due to surge striking, unless the fact that low-voltage windings can transfer surge to the high-voltage winding through the distributed capacitance between them. Even in this situation, every surge will only give origin to overvoltages when it will reach the high-voltage winding. Therefore, this winding is the aim of presented study. An important effect of low-voltage winding is only its proximity to the high-voltage winding, since low-voltage potential is relatively close to ground one. This distance has influence on the value of distributed capacitances to ground, which is decisive for the development of overvoltages after surge striking. Air-core winding is considered since it is assumed that electric transients are much faster than magnetic dominions transients are, which causes no change in the magnetic permeability[3].

B. Periods of Analysis

As a step-voltage surge is applied to a uniform winding, there are clearly three periods of analysis. The first one corresponds to the sudden voltage distribution along the whole winding, regardless the time of wave propagation. This distribution is related to inherent capacitances of the windings, solely. The second period corresponds to voltage oscillations along the winding, with the possibility of voltages along the winding with maximum amplitude even higher than the amplitude of the applied step voltage. These oscillations are a consequence of electromagnetic interactions among mutual and series capacitances and inductances of the winding. Mutual inductances and capacitances are present among coils of the winding. Series resistances are negligible as well as transversal conductances, for the sake of conservative analysis. Third period corresponds to stabilization of oscillations and consequently uniformly decreasingly distributed voltage along the winding, with zero potential at its grounded end.

These above descriptions mean basically what happens, if no insulation failure occurs. Therefore, any power transformer design should consider these facts and any transformer should present characteristics in such a way that the incident surge may promptly reach the final voltage distribution profile along the winding. Thus, the second period would not be present, because there would be no oscillations and consequently no overvoltages along the winding. Also, the initial and final voltage distribution should not cause no concentration of electric field, which would be another cause of insulation failures

C. *Characteristics of needed tools*

In order to design the winding with the ideal characteristics as described above, it is clear how simulation tools can be important for Engineers. Some years ago, adequate softwares were expensive, they required computers with specific configuration and they also required extensive training. Recently, powerful softwares have become available, but their use still means excessive cost because these softwares are intended to the general use, specially for electronic circuitry, which causes them to be only partially used, if purchased. On the other hand, numerical methods have been in constant development. Several methods have permitted the development of simpler softwares for dedicated analysis, that can be made by the user. Thus, TLM method, which is a recent one, is a very good example of powerful method that can be used in the development of a simple tool for analysis[4]. Since TLM method is inherently simple it is possible to develop programs in spreadsheets, which also simplifies the analysis of surges along windings.

D. *Premises and Recommendations for TLM Modelling*

As in any numerical method, TLM modelling of winding requires that its distributed parameters become concentrated along sections[4]. Therefore, the number of sections represents the degree of required accuracy. Also it is recommended the use of some simplifications, like the transformation of mutual inductances into effective series inductances [2]; Every voltage source and associated series-impedance are suggested to be transformed into their Norton's model, with current source and associated parallel-impedance. This is in view of using nodal analysis, which becomes easier programming of voltage calculus to be implemented in spreadsheets.

III. TLM RESULTS

Results of TLM method applied to winding modelling have good agreement with data obtained from literature [2,3]. Some of these results are now shown. Consider a step-voltage with amplitude **Vo** applied to a uniform air-core winding that is firmly grounded at its end. This winding has distributed capacitances to ground potential,. Cg, in Farad/meter; its series capacitance between ends is given by Cs, in Farad x meter; its length is ℓ, in meters; its series resistance is Rs and effective inductance, series, is Ls.

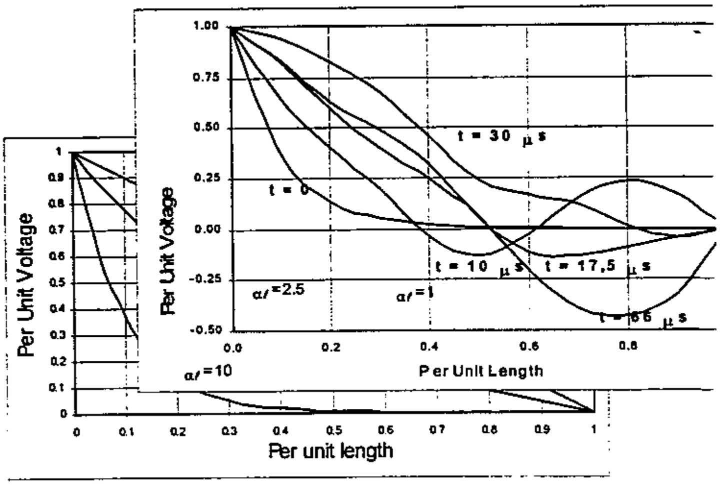
A. *First Period*

For the first period of analysis, voltage distribution depends on $\alpha\ell$ parameter, that is given by :

$$\alpha\,\ell=\sqrt{\frac{Cg}{Cs\,\ell}}\;\ell \qquad (1)$$

Fig. 1 shows curves of voltage profiles for three different values of $\alpha\ell$. It is important to notice that for $\alpha\ell = 1$ it corresponds to the uniformly decreasing distribution of voltage along the winding, which coincides with the steady state, that is the third period of analysis. The more $\alpha\ell$ grows the larger will be time interval for reaching the final distribution, with the possibility of overvoltages. From Equation (1) it is possible to notice that $\alpha\ell$ grows as winding length grows and as Cg is higher than Cs. This is one of the most important characteristics of high-voltage windings, with its relative excessive number of coils.

Fig. 1. TLM simulation results for $\alpha\ell = 1$; 2.5 and 10.



Voltage profile

Regarding to Fig. 1, it can be depicted from this how Electric field is concentrated along former coils of the uniform winding. Fig. 2 shows respective profiles of electric field distribution. The reference for per unit electric field is the ratio between Vo and length of the winding, ℓ. From this second figure, it is possible to notice that the sudden voltage distribution means a very strong voltage stress that can cause itself the insulation failure, as $\alpha\ell$ is higher than unity. It can be also depicted from this same figure that maximum value of electric field is the same as $\alpha\ell$. Therefore, the value of this parameter becomes into a very important information to the transformer designer. After all, transformer designer must be acquainted to the relationship between the distributed capacitances that define this parameter. These capacitances have values that inherently depend on the distributed mean distance between the winding coils and also between coils and ground potential, as well as they obviously depend on the characteristics of dielectric materials that are used as insulation. These materials are concerns of transformer designer.

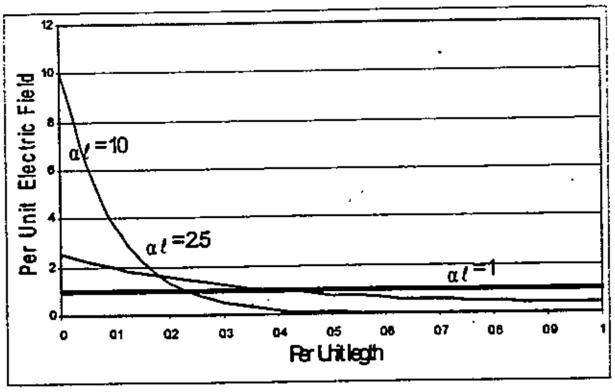


Fig. 2. TLM simulation result for $\alpha\ell$ = 1; 2.5 and 10. Electric Field Profile

B. *Second Period*

For the second period, Fig. 3 shows how voltage oscillates along the winding at four different instants after surge incidence. For this case, $\alpha\ell$ = 10. These oscillations comes from electromagnetic interactions among distributed series and parallel mutual inductances and capacitances. Usually, resistances can be neglected, as they are in these simulations. As winding behaves like a selective filter, only some frequencies are allowed to manifest. Nevertheless, this behavior gives origin to well-known overvoltages along winding, that cause insulation failures.

As mentioned before, these presented TLM results are very similar to those found in literature, based on analytical solutions derived from differential equations that are associated to this problem. For the sake of remarking the efficiency of TLM method for this kind of study, the spreadsheet used for the presented calculations has required less than 1 Mb file, which is very easy to allocate.

Fig. 3. TLM simulation result for voltage profile at four different instants. $\alpha\ell$ = 10.

IV. EXPERIMENTAL DATA

With the aim of obtaining experimental data for the comparison to TLM results, a test set-up was prepared. A special air-core winding was made and it was exposed to a step-voltage, in laboratory. This winding has approximate diameter of 200 mm; its copper conductor has 1 mm diameter, with 0.1 mm of enamel. As this winding has 300 turns, its length is very close to 300 mm. This winding is as uniform as possible.

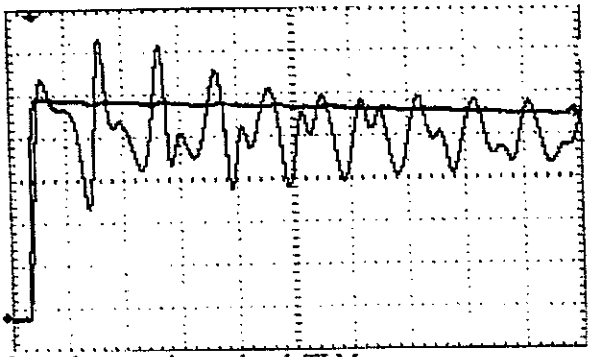
A 5 V step-voltage is applied to one of its end, while the other is firmly grounded. Uniformly distributed ground potential is simulated by a grounded cylinder made of aluminum, with 15 mm diameter. This cylinder is internal to the winding. Winding and inner cylinder are apart 1.5 m from floor, which is grounding reference. Winding has six intermediate taps from which voltage is measured as step-voltage is applied . Therefore, the winding has eighth sections, each with 25 turns.

Fig. 4 shows digital acquisition of applied voltage and also from the first tap of the winding. These voltages are shown along time. From this figure it can be depicted how the voltage oscillates at the first tap. These oscillations have maximum amplitude even higher than the original input voltage. Also , it can be depicted that oscillations have selected frequencies, that are natural frequencies from this winding. Presented results are coherent with analytical results.

Fig. 4. Experimental acquisition of voltages along winding - Scales : Vertical = 1.0 V/div ; Horizontal = 1.0 μs/div.

V. TLM SIMULATION FOR EXPERIMENTAL TEST

In view presenting the efficiency of TLM method, a program has been developed for reproducing the experimental test. Fig. 5 shows the TLM simulated voltages, analogous to those presented in Fig. 4. From the comparison between both figures it is possible to depict how similar they are in trending. By considering the experimental data as reference, it is important to remark some main reasons for the differences presented between both results, experimental and TLM :



- The premises of concentrated inductances and capacitances, instead of consideration of mutual elements ;
- The presence of natural non-uniformities of the winding, specially at the edges of the winding, which contributes to changes of capacitances to ground and also to change of series capacitances;
- The presence of oscilloscope probe, which behaves like a transmission line between measuring tap and the oscilloscope entrance.

All these above quoted main reasons can be easily considered on TLM computations. Nevertheless, presented TLM results are intended to show how TLM computation is efficient even if these facts are not considered. It is evident that presentation of TLM results by considering every of these quoted reasons would be impracticable. Therefore, presented results confirm how TLM method is robust and how it can be efficiently used in studies of this nature, in extension to the analysis of problems of wave propagation along uniform one-dimensional lines.

Developed spreadsheet for this calculations requires less than 2.6 Mb.

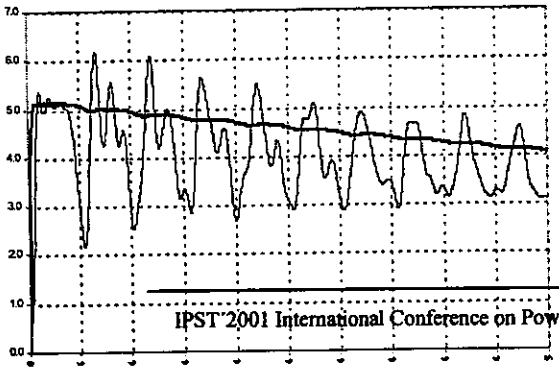


Figure 5 - TLM Result for comparison to experimental data - Scales : Vertical = 1.0 V/div ; Horizontal = 1.0 μs/div.

VI. CONCLUSIONS

Presented results have shown how the recent numerical method TLM can be used by Engineers in the development of software tools for the analysis of behavior of voltages along transformer windings when these are submitted to the incidence of steep voltage surges. Even though there are too many complexities related to this analysis, TLM still shows convincing behavior, even if some simplifying premises are considered. Literature based as well as experimental data have been used for the comparison to TLM simulation results.

Finally, it is important to emphasize that TLM method presents better performance if it is implemented in spreadsheets, which allow the prompt interaction between program and user, with extensive graphical interface.

VII. REFERENCES

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