Simulation and Measurement of Lightning-impulse Voltage Distributions over Transformer Windings

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***Abstract*— This paper presents: (a) a novel method for accurate high-frequency modeling of dry-type transformer windings based on magnetic and electric field simulations for parameter extraction of the detailed equivalent circuit of the entire winding system; (b) a method for fast and accurate transient solution of the circuit differential equations that describe the voltage distribution over the winding system; (c) an efficient, cheap, and non-destructive low-voltage measurement system based on a self-developed lightning-impulse generator; and (d) verification of the simulation results by comparison with measurement.**

***Index Terms* — Impulse testing, electromagnetic modeling, numerical simulation, coils, and transformers.**

I. INTRODUCTION

Dielectric winding design of dry-type distribution transformers is mainly determined by standardized insulation voltages, e.g. the basic lightning-impulse insulation level (BIL) (more severe) or the AC test voltage levels (less severe) [1]. The BIL of a transformer is tested by applying a standard 1.2μs / 50μs lightning impulse (LI) to its windings. Due to different ratios of series to ground capacitance of different winding sections/turns and the possibility for exciting internal resonances, the insulation of different sections can be stressed in a very non-linear way. Thus, to avoid high development and prototyping costs, oversizing and high material costs, it is of paramount importance to accurately model and simulate transformer windings over the entire high-frequency range covered by this standard LI.

Modeling and simulation of the voltage distribution over transformer windings during LI tests has a long history, due to its relevance and importance for the design. Already in the 1940s and 1950s a solid theoretical basis of this analysis was developed [2]. The dominant idea from the beginning of this development was to translate a geometrically complicated winding structure into a simple equivalent circuit described by the known circuit differential equations. Since the BIL-impulse covers the frequency range up to 1MHz (the wavelength down to 300m), it is not necessary to consider winding turns as transmission lines with distributed parameters. Considering this frequency range, it is enough to find a suitable lumped representation of winding sections consisting of equivalent capacitances, inductances and resistances [2]. Early models from the 1950s were very simple and relatively easy to solve with early computers. Over the years the models of increasing complexity and predictive power emerged, as reported for example in [3], [4], and [5]. The common characteristics of the existing models are: (a) they are based on various analytical approximation methods for computing the capacitive and inductive coupling between different winding sections; (b) they represent radically simplified winding structures in order to stay within an affordable CPU-time; and (c) they are not general but they are valid only for a certain winding type and voltage range.

On the other hand, to solve this problem in general and to have always a high level of accuracy one could avoid winding simplification and solve it in its full complexity. As reported in our previous publication [6], it is possible for a simple 3-D transformer structure to solve directly Maxwell equations in time-domain and obtain a qualitative picture of the electromagnetic processes in the winding exposed to the BIL-impulse [6]. However, this method is still not possible to apply to a winding in its full geometrical complexity.

In this paper a new method for modeling and simulation of the voltage distribution during LI tests is presented, that is somewhere between the existing analytical modeling approach [2-5] and our previously reported full-Maxwell modeling [6]. This new approach in the end still solves a very large system of differential equations based on the electric circuit theory, but its parameters, i.e. its capacitive, inductive and resistive matrices are numerically computed by means of FEM field simulations for the transformer winding in its full complexity.

II. HF-MODELING OF WINDINGS IN THEIR FULL COMPLEXITY

As already elaborated, the existing methods for the impulse analysis of transformer windings are based on radical simplifications of the winding system. The simplifications are done in such a way that groups of winding turns are lumped together into sections and the capacitive and inductive couplings between the sections are analytically estimated. The impulse voltage distribution is then found as a solution of the system of ordinary differential equations written for the simplified equivalent electric circuit [2-5].

The main drawback of this approach is that it lacks a mathematical basis for the winding simplifications and therefore it is not valid in general.

The method suggested in this paper abandons from the beginning any winding simplification and considers the winding system as it is in its full complexity by taking into account each single turn and its capacitive and inductive couplings against all the other turns of the system. Moreover, these couplings are not determined by using some analytical approach but they are obtained by performing 2-D or 3-D electric and magnetic field simulations.

This approach is evidently very demanding in terms of the geometrical modeling and CPU-time, but it is general, accurate and applicable in every situation. As an illustration the magnetic and electric field of the transformer with “model coils” used for the analysis presented in this paper are shown in Figure 1, and the corresponding capacitance and inductance matrix are depicted in Figure 2. Their structure is determined by the winding geometry and topology, insulation, and distances to the core limb and yoke.

The inductance L-matrix is obtained as a result of a large number of magnetostatic 2-D axisymmetric FEM simulations. The number of simulations is equal to the number of turns in the HV-coil (the LV-coil is in short-circuit and connected to ground during the LI test). Similarly, the capacitance C-matrix is obtained as a result of the same number of electrostatic 2-D axisymmetric FEM simulations. If the effect of the coupling between different winding phases is to be analyzed the simulations for obtaining the L- and C-matrix must be 3-D, which is also reachable with modern hardware resources. For computing the L- and C-matrix the commercial Infolytica solvers MagNet and ElecNet were used, respectively.

Once the matrices are obtained from the FEM simulations the following system of ordinary differential circuit equations is assembled and numerically solved:

$$\begin{bmatrix}[L] & [0]\\ [0] & [C]\end{bmatrix}\cdot\frac{d}{dt}\begin{Bmatrix}\{i\}\\ \{u\}\end{Bmatrix}=\begin{bmatrix}[R] & [I_1]\\ [I_2] & 0\end{bmatrix}\cdot\begin{Bmatrix}\{i\}\\ \{u\}\end{Bmatrix}+\begin{Bmatrix}\{a\}\\ \{b\}\end{Bmatrix} \qquad (1)$$

where $[L]$ is the inductance L-matrix, $[C]$ is the capacitance C-matrix, $[R]$ is the resistance R-matrix, $\{i\}$ is the vector of the unknown turn-currents, $\{u\}$ is the vector of the unknown turn-voltages, $[I_1]$ and $[I_2]$ are special topological matrices, and $\{a\}$ and $\{b\}$ are the source terms. The structure of this linear system of equations and the equivalent circuit behind it will be explained in detail in the full paper.

The numerical solution of this system of ordinary differential equations was implemented in the well-known software Matlab.

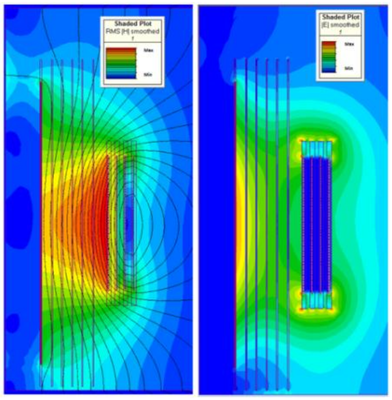

Fig. 1. Magnetic (left) and electric field (all the turns of the HV-coil are on the same potential of 1V) in the air window of the chosen testing ABB RESIBLOC® dry-type transformer.

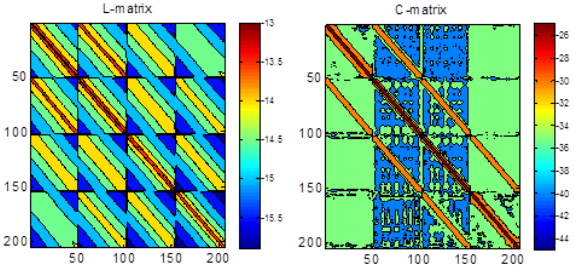

Fig. 2. The inductance L-matrix (left) and the capacitance C-matrix of the chosen testing ABB RESIBLOC® dry-type transformer are visualized in logarithmic scale.

III. RESULTS AND CONCLUSIONS

The obtained numerical simulation results are verified by comparison with measured results. For this purpose a simple low-voltage lightning-impulse generator was developed and used. The comparison of the simulation and measured results is given in Figure 3 and the obtained very good agreement is evident.

The detailed analysis of the measured and simulated results revealed the accuracy of the winding oscillation frequency and voltage amplitude of 19% and 9%, respectively. This analysis will be presented in detail in the full paper.

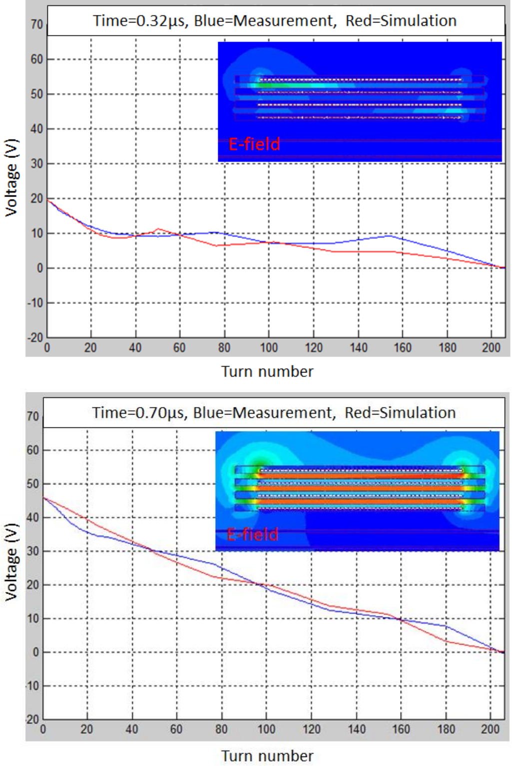

Fig. 3. The BIL-impulse distribution over the HV-winding of the chosen ABB RESIBLOC® dry-type transformer is visualized at the time of 0.32µs and 0.70µs. The corresponding electric field distribution inside the HV winding is depicted.

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