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LIGHTNING IMPULSE MODELING AND SIMULATION OF DRY-TYPE AND OIL-IMMERSED POWER- AND DISTRIBUTION TRANSFORMERS

SUMMARY

This paper presents in detail numerical methods and techniques for lightning impulse (LI) modeling and simulation of power and distribution transformers. The modeling methods are based on equivalent circuits of transformer winding entities resulting from the initial winding discretization determined by the required accuracy. The parameters of the equivalent circuit such as resistances and self- and mutual capacitances and inductances are obtained from field simulations (FEM). The circuit equations of the transformer's equivalent circuit written in the state space form yield a large system of differential equations that is solved in time-domain by using the standard Runge-Kutta numerical integration technique. The obtained solution represents the voltage distribution over the winding in each moment of the LI-time (50μs). The results verification by comparison against measurements is presented in detail.

Key words: Lightning impulse, transformer winding modeling, transient simulation, electric and magnetic coupling, lumped parameters, and distributed parameters.

1. INTRODUCTION

Dielectric winding design of power- and distribution transformers is a complex task involving several conflicting requirements. The distances between the windings as separate entities, the internal winding arrangement (topology), and the spatial separation of the sections within a single winding are mainly determined by the basic lightning-impulse (LI) insulation level (BIL) (more severe) and/or by the AC-test voltage levels (less severe) [1]. The geometrical arrangement of the winding system is defined in such a way that the electric field between and within the windings stays below critical values of the involved insulation materials for both the LI- and AC-test voltage levels. On the other hand, if the winding system is dielectrically oversized, the winding losses and material cost are increased and they consequently reduce the competitiveness of the design on the market. The ultimate goal of the dielectric design is a reliable winding system capable of withstanding the expected overvoltage surges in operation over the required lifetime (some tens of years) at the minimal material cost and electromagnetic losses.

To reach a sub-optimal solution for winding system from the dielectric design point of view a reliable simulation tool is required. Within the framework of this tool an accurate transformer modeling and simulation over the entire frequency range of the standardized 1.2μs/50μs LI-surge should be possible. An FFT-Analysis of the LI-surge reveals the wide frequency range (0-1MHz) that poses a difficult numerical problem for accurate transformer modeling considering the underlying complicated capacitive and inductive couplings.

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Due to its relevance and importance for the design, the modeling and simulation of the LI voltage distribution over transformer windings has a long history. Already in the 1940s and 1950s a solid theoretical basis of this analysis was developed [3]. 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's differential equations. 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 [4], [5], and [6].

The common characteristics of the existing models can be summarized as follows: (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.

The original contribution of this paper is manifold: (a) to present a fast and experience enhanced method for simulationg the LI-voltage distribution based on analytical compution of distributed winding parametrs and based on the second order (wave) differential equations, (b) to present a new recently developed method based on a detailed lumped parameters modeling of the highest possible resolution (each turn is a separate entity) and based on the first order ordinary differential equations, and (c) to show the obtained results and their experimental verification for several real-life transformers.

The paper is organized as follows. Section 2 describes in detail the developed numerical methods and techniques. Section 3 shows the obtained results and their experimental verification. Section 4 concludes the paper.

2. NUMERICAL METHODS AND TECHNIQUES

If the LI-distribution over transformer winding is considered, it is evident that full-Maxwell modeling and simulation of the transformer and its surrounding space in time-domain is required [7]. This practically means that the second order partial differential equation describing the electromagnetic field in and around the transformer should be numerically solved. As shown in [7] this approach is possible for a relatively simple 3-D structures but not for real-life transformer windings due to their complex geometrical arangement (the corresponding CPU-time would be unacceptable and the memory requirements are simply unrealistic) [7].

What remains after the full-Maxwell approach is, for the above practical reasons, eliminated is the so-called equivalent circuit approach. The basic idea of this approach is rather simple. The winding is split into several winding sections (entities) and at the begining of each section the transient voltage over the entire LI-time should be computed. Each section is, of course, coupled electrically (capacitance) and magnetically (inductance) with all the other sections. The matrix of the magnetic and electric couplings between the winding sections could be obtained analytically. Since the LI covers the frequency range up to 1MHz, the corresponding voltage waves propagating along a straight conductor far from the ground in free space (air) would cover the wavelength range down to 300m [7]. Considering the fact that voltage waves initiated by the LI travel along the transformer winding system, they wavelength is significantly shorter than 300m for two reasons: the electric permittivity of the insulation around winding turns is higher than that of air (epoxy resin for example $\varepsilon_r \approx 4$) and the speed of the waves of a transmission line is lower compared to the speed of the EM-wave in free space. Thus the wavelength limit of the LI voltage wave inside of the winding system insulated with epoxy resin could be roughly estimated to 100m. This practically means that each winding entity used in the modeling longer than 10m (this is again a rough estimate) must not be represented by simple lumped parameters in its equivalent circuit but the distributed parameters must be used and correspondingly the second order differential equations (wave equations) must be solved. Until recently, this approach was almost exclusevily used for LI simulations of transformers [2]. The drawbacks of this approach are obvious: low resolution of the obtained data (the voltage is obtained at the beginning of each modeling entity, i.e. at the beginning of each winding section), the electric and magnetic couplings within the modeling entities are neglected, the need for empirically obtained correction factors and consequently the lack of generality.

As an alternative to the above approach based on the distributed parameters and wave equations a new numerical method was recently suggested [2]. The new method 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 determined by performing 2-D or 3-D electric and magnetic field simulations (a highly accurate analytical approach remains as a possible alternative). To clarify this method a simple four-turn winding is modeled and its equivalent circuit is depicted in Figure 1. It is worth mentioning that the state space variables of the system are the voltages and currents of each turn.

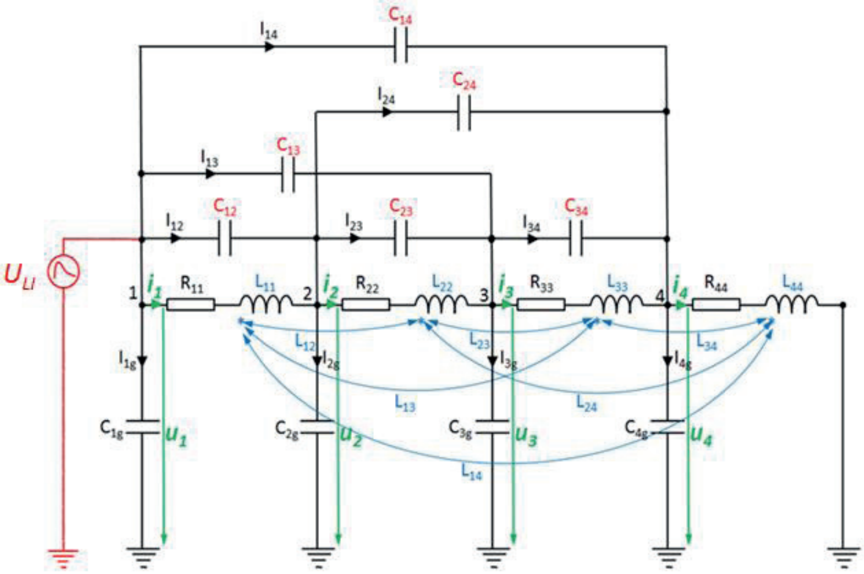


Figure 1 – An equivalent circuit of a simple four-turn winding chosen as a modeling example

According to the well known circuit theory equations, it is possible for the equivalent circuit shown in Figure 1 to write the following:

$$
\begin{bmatrix}
L_{11} & L_{12} & L_{13} & L_{14} & 0 & 0 & 0 \\
L_{21} & L_{22} & L_{12} & L_{24} & 0 & 0 & 0 \\
L_{31} & L_{32} & L_{33} & L_{34} & 0 & 0 & 0 \\
L_{41} & L_{42} & L_{43} & L_{44} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & C_{21}+C_{2g}+C_{23}+C_{24} & -C_{23} & -C_{24} \\
0 & 0 & 0 & 0 & -C_{32} & C_{31}+C_{32}+C_{3g}+C_{34} & -C_{34} \\
0 & 0 & 0 & 0 & -C_{42} & -C_{43} & C_{41}+C_{42}+C_{43}+C_{4g}
\end{bmatrix}
\cdot
\begin{Bmatrix}
\frac{di_1}{dt} \\ \frac{di_2}{dt} \\ \frac{di_3}{dt} \\ \frac{di_4}{dt} \\ \frac{du_2}{dt} \\ \frac{du_3}{dt} \\ \frac{du_4}{dt}
\end{Bmatrix}
=
$$

$$
=
\begin{bmatrix}
-R_{11} & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & -R_{22} & 0 & 0 & +1 & -1 & 0 \\
0 & 0 & -R_{33} & 0 & 0 & +1 & -1 \\
0 & 0 & 0 & -R_{44} & 0 & 0 & +1 \\
+1 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & +1 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & +1 & -1 & 0 & 0 & 0
\end{bmatrix}
\cdot
\begin{Bmatrix}
i_1 \\ i_2 \\ i_3 \\ i_4 \\ u_2 \\ u_3 \\ u_4
\end{Bmatrix}
+
\begin{Bmatrix}
u_1 \\ 0 \\ 0 \\ 0 \\ C_{21} \cdot \frac{du_1}{dt} \\ C_{31} \cdot \frac{du_1}{dt} \\ C_{41} \cdot \frac{du_1}{dt}
\end{Bmatrix}
\tag{1}
$$

Provided that the structure of Equation (1) is clear, it is straightforward to generalize it to the level of winding system with N turns:

$$
\begin{bmatrix} [L] & [0] \\ [0] & [C] \end{bmatrix} \cdot \frac{d}{dt} \begin{Bmatrix} \{i\} \\ \{u\} \end{Bmatrix} = \begin{bmatrix} [R] & [K] \\ [K^T] & 0 \end{bmatrix} \cdot \begin{Bmatrix} \{i\} \\ \{u\} \end{Bmatrix} + \begin{Bmatrix} \{a\} \\ \{b\} \end{Bmatrix} \tag{2}
$$

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,
[K] is a special topological matrix, and
{a} and *{b}* are the source terms.

Due to the fact that the L-matrix and C-matrix are obtained from electromagnetic field simulations, this approach is very demanding in terms of the geometrical modeling and CPU- time. On the other hand, the method is general, mathematically well founded, accurate and applicable in every situation. This method has an additional important advantage. Due to the fact that each turn is a separate modeling entity it is possible to use a lump parameters equivalent circuit (a turn is shorter than 10m, which is not fullfild in large power transformers). The resulting equation system is a first order ordinary differential equation system which is more stable and faster to solve from the numerical integration point of view.

At the end of this section it is important to emphasize that the following two numerical methods for simulating the LI-distribution over transformer windings are considered:

- **Method 1**: a fast and experience enhanced method based on analytical computation of distributed parameters (capacitances and inductances) of the winding sections and based on the second order ordinary differential equations describing the voltage wave propagation along the winding structure.
- **Method 2**: a recently developed new method [2] based on a detailed lumped parameters modeling of the highest possible resolution (each turn is a separate entity) and based on the first order ordinary differential equations describing the voltage transients in the winding structure. This method is represented by Equation (1) and (2).

Method 1 is widely used in daily design due to its high speed and reliable results. Method 2, however, requires much longer CPU-time, but offers a very high level of accuracy. Therefore, it is used only for highly accurate simulations in development of new winding technologies and new transformers of exceptional importance. The main reason for the long CPU-time and the high accuracy of Method 2 is its accurate computation of the capacitive and inductive couplings between the winding turns by using electric and magnetic field simulations [2]. Thus, Method 2 is somewhere between the analytical Method 1 and the previously reported full-Maxwell modeling [7].

Method 2 utilizes a general time-dependent voltage source and can be used for simulation of various transients interactions of the transformer and adjacent equipment such as cables, vacuum circuit breakers, reactors, etc. (for example the analysis of the fast EM transients).

3. RESULTS AND THEIR VERIFICATION

For testing of Method 1 the oil-immersed 40MVA , 115kV ± 15% / 11 kV power transformer was used. The winding arrangement of this transformer for the LI-testing is shown in Figure 2.

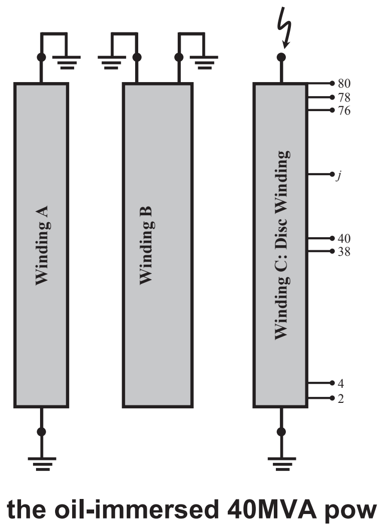


Figure 2 – Terminal condition of the oil-immersed 40MVA power transformer during the LI-test

The HV disc winding consists of 80 discs and is a partially interleaved winding. The discs from 1 to 44, numbered from bottom of the winding, are ordinary disc, while the discs from 45 to 80 are interleaved. The LI voltage source was connected to the disc 80 and the disc 1 was grounded. In the upper part of winding (the discs from 38 to 80) the voltages between two successive disc pairs and the voltages between the discs and ground were measured and calculated. In other words, the following voltages were computed and measured:

- disc-to-disc voltages: 80-78, 78-76, 76-74, ... , 44-42, and 42-40
- disc-to-ground voltages: 80-Grd, 78-Grd, 76-Grd, … , 40-Grd, and 38-Grd

These results are presented in Figure 3. Evidently, the accuracy in terms of the voltage peaks and frequency of the winding eigenoscillations is very good. At the begining of the LI-time the curves almost overlap. Later on, however, the difference between the curves is slightly increasing which is normal in time domain simulations (the disagreement accumulates over time). This is, however, not so significant as the voltage peaks are at later stage of the simulation not so high due to the internal damping (the resistance of the turns).

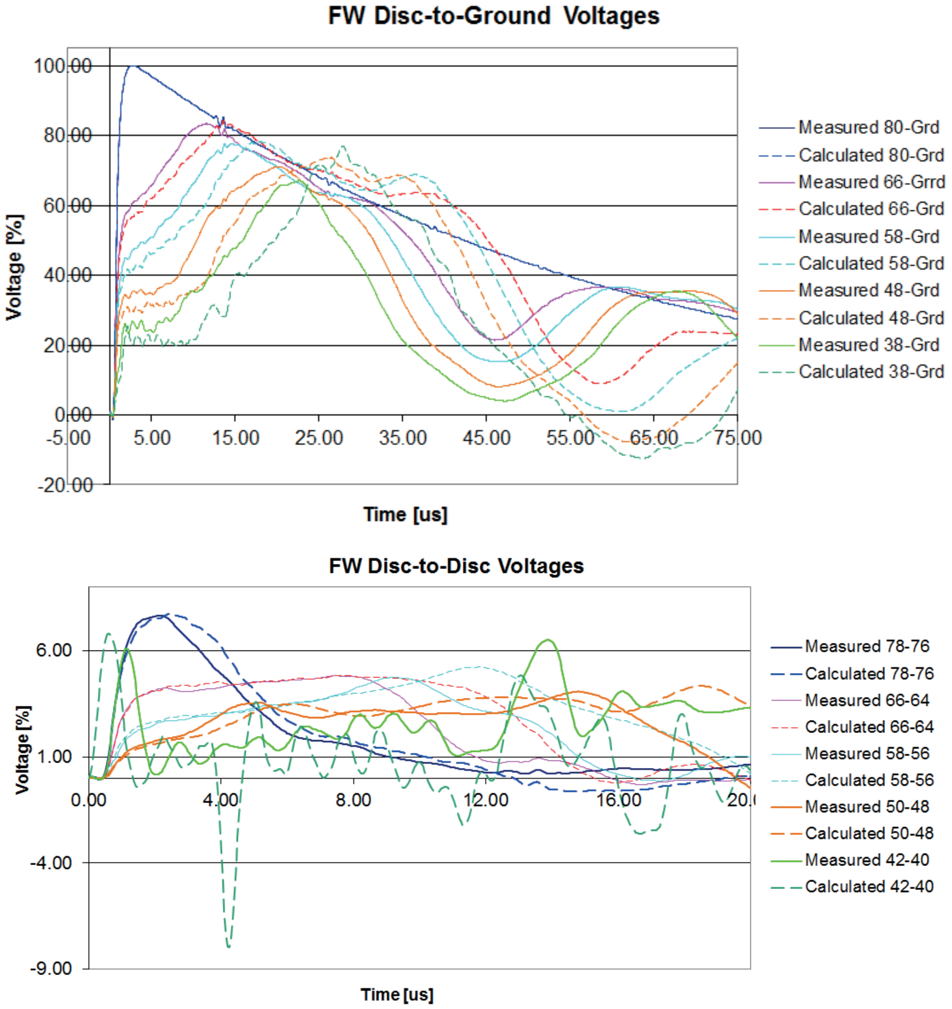


Figure 3 – The comparison of the simulation and measured results for the oil-immersed 40MVA power transformer

Method 2 has been tested on two dry-type distribution transformers. The first of them is the 24kV / 900kVA Resibloc®-transformer. The following Figure 4 shows a principal sketch of a layer winding design with four sections of a cast-resin Resibloc®-transformer. The obtained results in form of the differences of layer-to-layer voltages and section-to-section voltages are shown in Figure 5. Evidently in the first 20µs the agreement between simulation and measurement is very good. In this time interval occur the highest and most hazardous voltage peaks. Therefore is the accuracy in this time interval of paramount importance. For the reasons already emphasized, the disagreement accumulates of the LI-time and later on (for the time period longer than 20µs) and is getting more and more significant.

For testing of Method 2 also a dry-type 1600 kVA, 20 kV / 725 V distribution transformer was used. In fact only a HV and a LV phase, without magnetic core, were used. The test arrangement of this transformer is shown in Figure 6 (left). The HV winding consists of 22 ordinary discs e.g. not interleaved. The links connecting adjacent discs in series also were used as measuring points and so it is there were the voltages were simulated. The numbering of the HV measuring taps is shown in Figure 6 (right). The LI voltage source was connected to tap 1 and tap 0 was grounded, while the LV winding had both terminals grounded. The tap to ground voltages were measured and simulated in all taps.

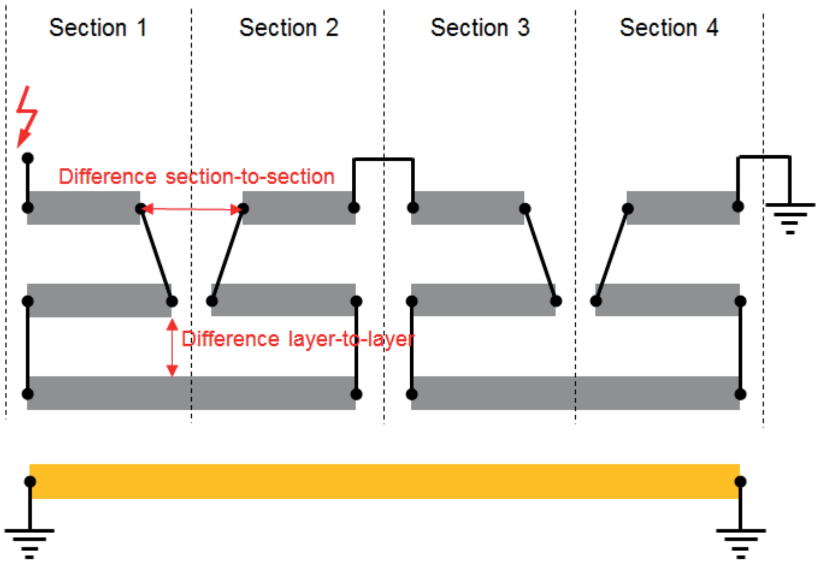
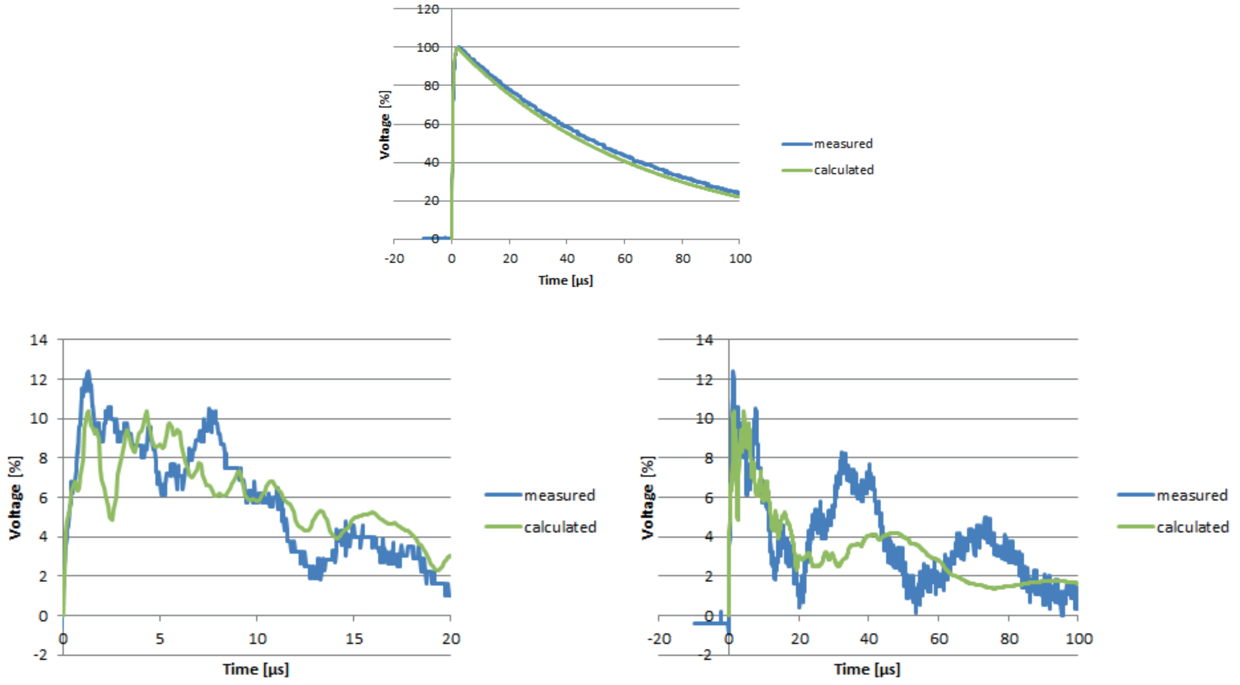


Figure 4 –Principal cross sectional sketch of a 4-section layer winding design



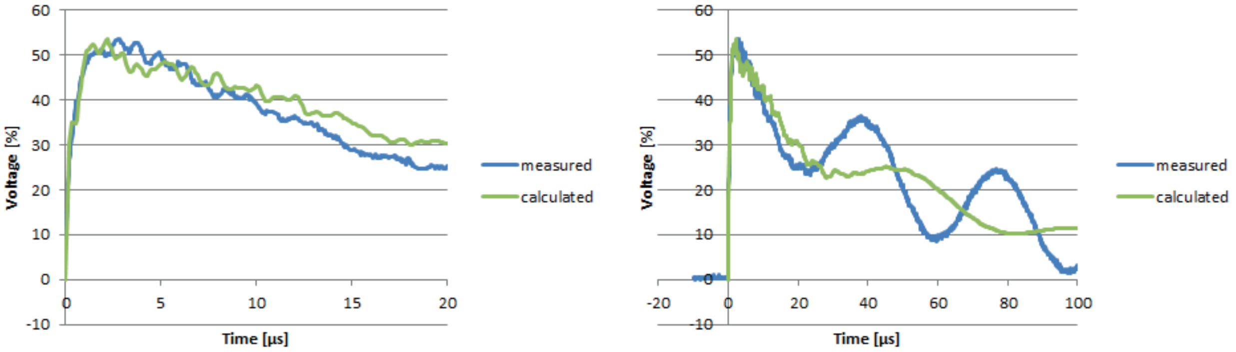


Figure 5 - Comparison of the simulation and measured results for the cast-resin Resibloc®-transformer, top: at winding input, center: layer-to-layer insulation, bottom: section-to-section-insulation.

Figure 6 – Test arrangement (left) and HV measuring taps for the dry-type 1600 kVA transformer (right)

The comparison of the simulation and measured results are presented in Figure 7. The degree of approximation is good, as can be seen comparing the characteristic points of the curves e.g. maximums, minimums and its corresponding delays. Anyway, as in the first case, the difference between simulation and measurement increases with the time, and from around 50 µs and later on it is quite evident. As stated before it is not so important since the voltage is quite reduced then from its first peak.

In order to illustrate the structure of the equation system (2) the capacitance and inductance matrix of the 1600kVA transformer are depicted in Figure 8. Those matrices are obtained by performing electric (C-matrix) and magnetic (L-matrix) field simulations. This is the most time cosuming part of the simulation algorithm.

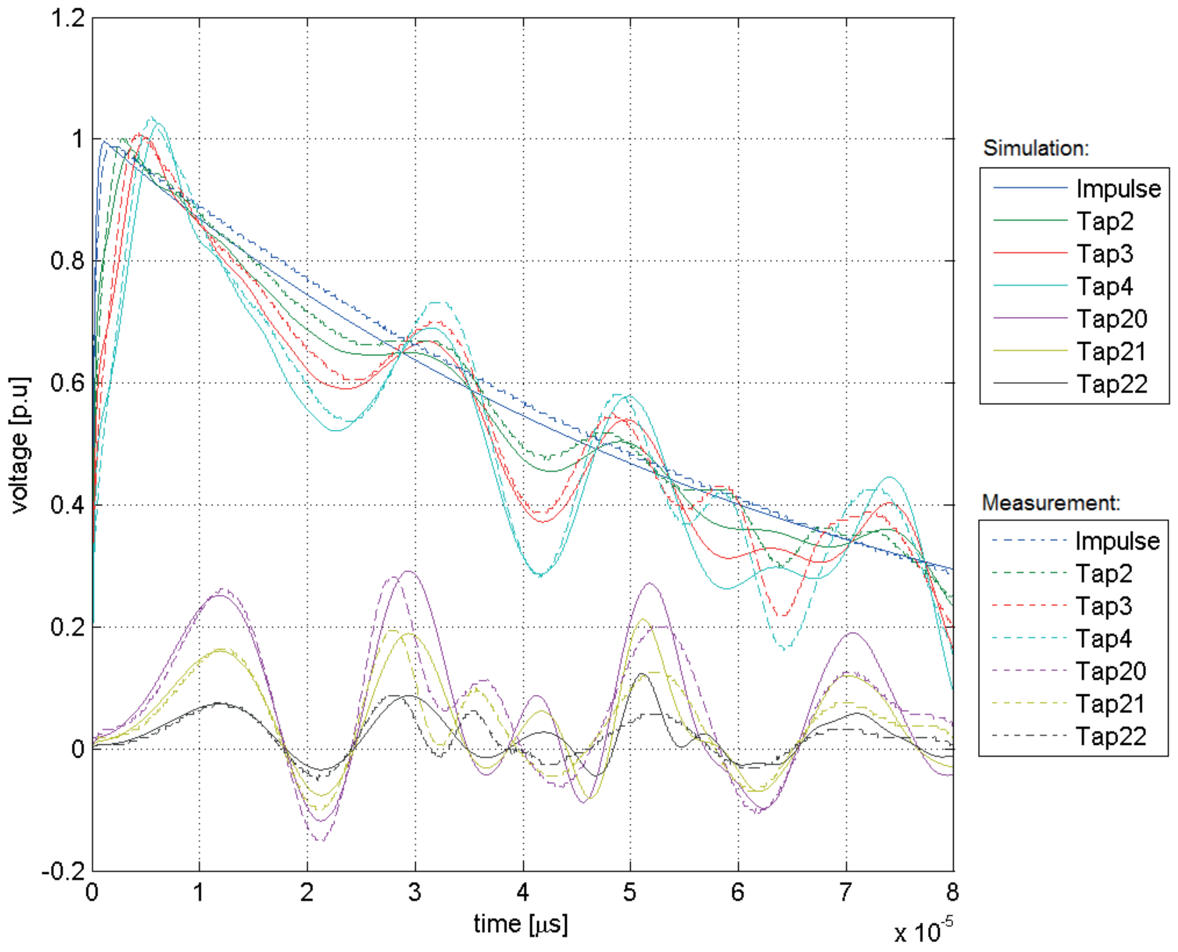


Figure 7 – Comparison of the simulated and measured results for the dry-type 1600 kVA transformer (disc to ground voltages)

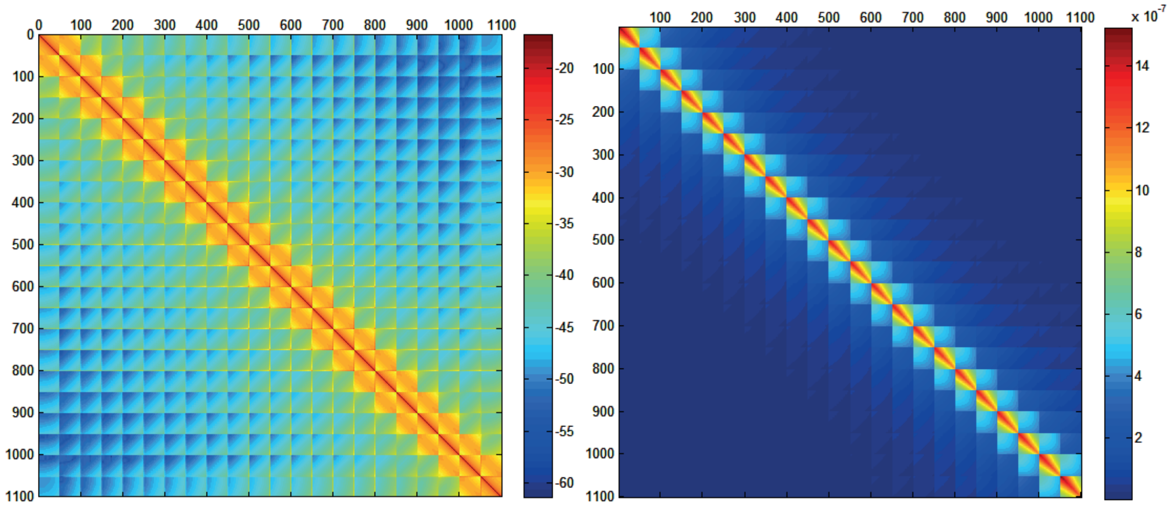


Figure 8 – The capacitance (left) and inductance (right) matrix of the dry-type 1600 kVA transformer, according to Equation (2).

4. CONCLUSIONS

Two general, mathematically well founded, stable, accurate and efficient methods for high frequency modeling of transformer windings are presented in detail. The obtained numerical results for the chosen transformers are verified by comparison against measurements.

The presented methods have a high accuracy level in the critical time interval of the LI (t<20μs) where the highest and most hazardous voltage peaks appear. Due to the transient nature of our simulation methods the dissagreeement acumulates over time and, later on, it is geting more and more significant. The internal damping of the system, however, radically reduces the voltage peaks in the later time interval (t>20μs) thus making the simulation error in this time-frame insignificant.

Considering the complexity of the winding structure and its high frequency modeling, the demonstrated level of accuracy of the suggested methods is sufficient for industrial transformer design.

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