# Transformer Windings' RLC Parameters Calculation and Lightning Impulse Voltage Distribution Simulation

Tomislav Župan[1], Bojan Trkulja[1], Roman Obrist[2], Thomas Franz[2], Bogdan Cranganu-Cretu[3], and Jasmin Smajić[2]

[1]University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, 10000 Zagreb, Croatia, tomislav.zupan@fer.hr
[2]University of Applied Sciences of Eastern Switzerland (HSR), Oberseestrasse 10, Rapperswil, Switzerland, jsmajic@hsr.ch
[3]ABB Switzerland Ltd., Badenerstrasse 780, 8048 Zürich, Switzerland, bogdan.cranganu-cretu@ch.abb.com

**This paper presents a numerical method for calculating the resistance, inductance and capacitance matrices of transformer windings. Importance of their precise calculation is shown in the simulation of voltage distribution over the windings for lightning-impulse test. The results obtained in frequency domain analysis are in a good agreement with the measurement data. All the parameters are calculated using the self-developed solvers, the theory and novelty of which are described in this paper. The presented approach allows fast and accurate high-frequency modeling of transformer windings.**

***Index Terms*—transformers, coils, numerical simulation, electromagnetic transients**

## I. INTRODUCTION

SINCE POWER AND DISTRIBUTION TRANSFORMERS are electromagnetic devices built to operate for a couple of decades, it is of paramount importance to design them to withstand the high-voltage and high-frequency (HF) stresses that are bound to happen during their lifetime. The lightning-impulse (LI) test is one of the factory tests devised to proof the HF (impulse) behavior of a transformer. It shows the influence of the winding capacitances, which are usually negligible during the steady-state (low frequency) operation. The LI-test can be simulated numerically in order to accelerate the design process of the transformer and thus to reduce its development costs. The proposed approach is verified using the ABB RESIBLOC® dry-type transformer.

Compared to other approaches reviewed in [1], the original contribution of this paper is manifold: (a) application of the self-developed BEM based field solver for evaluating the capacitance matrix in order to avoid surface mesh of a complicated winding surface, (b) evaluation of the frequency dependent winding resistances by using a self-developed integral equation based field solver, and (c) LI-impulse simulations in frequency domain.

## II. RLC PARAMETERS CALCULATION

To accurately model the transformer's response to a high-frequency signal, a detailed equivalent circuit of the windings has to be made. The resistance, inductance and capacitance matrices are obtained using the methods briefly described in the subsequent subchapters. The transient solution of the circuit differential equations used in this work is described in [1].

### A. *Capacitance calculation*

Alternatively to [1], the method used here for calculating the capacitance matrix is based on the boundary element method (BEM) and the 2D axially symmetric approximation. This is convenient since the BEM discretization is done only at material interfaces and boundaries. The tiny conductors' dielectric insulation is taken into account. The solution to the unknown distribution of the surface charge density on each of the discretized segments is obtained by using the point matching technique. Figure 1 shows the obtained capacitance matrix for the test transformer.

### B. *Inductance calculation*

The inductance matrix is calculated using the 3D magnetostatic moment method. The iron core is divided into elements with uniform magnetization vector $\vec{M}$. For a uniformly magnetized prism, the equation for magnetic field is reduced to analytic formulation [2]. To solve for the unknown magnetization $\vec{M}$ over elements of the ferromagnetic core, a system of equations is assembled for the unknown magnetic field $\vec{H}_k$ at the center of each element $k$ of the prisms within the ferromagnetic core. The self- and the mutual inductances are then determined, taking into account the contribution of the ferromagnetic core, by computing an integral of the vector magnetic potential $\vec{A}_c(\vec{r})$ over the path of a conductor.

The inductance contribution of the conducting ring in air is more conveniently calculated from the energy expression [3]. Figure 1 shows the obtained inductance matrix of the test transformer.

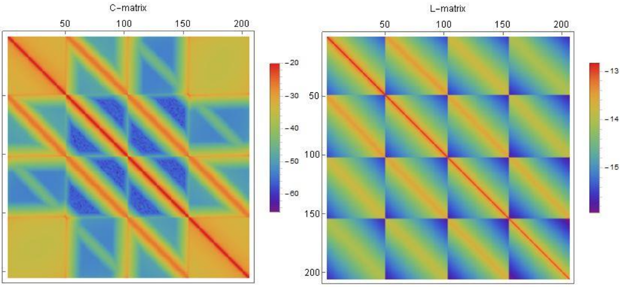


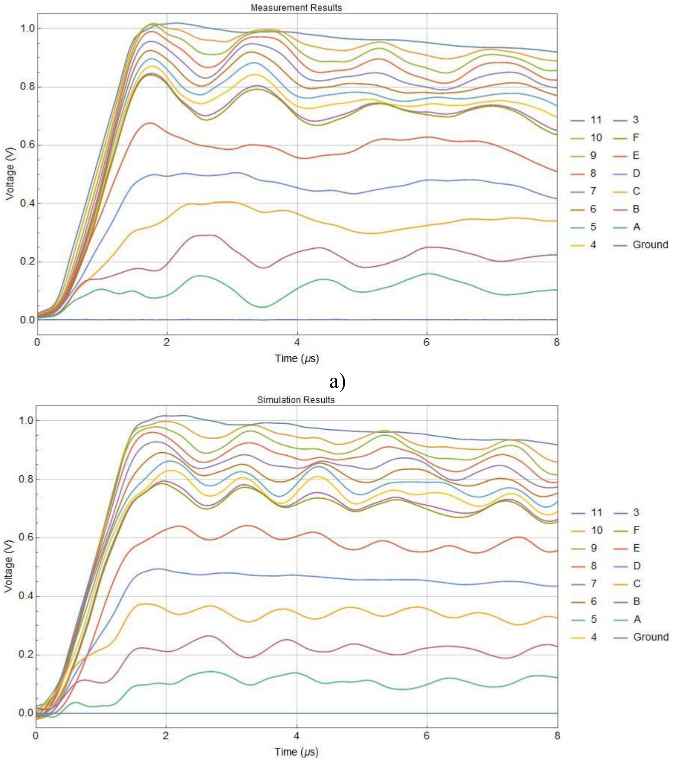
Fig. 1. Calculated C and L matrices for the ABB RESIBLOC® transformer.

### C. *Resistance calculation*

The winding's resistance is frequency dependent. It is calculated with the vector magnetic potential formulation and integral equations approach. The frequency and amplitude set are previously determined from the known input wave form. The system of equations is then solved for unknown surface current densities on rectangular elements for each frequency. The point matching technique is applied and both skin and proximity effects are taken into account. Finally, resistances of each of the conductors are calculated from Joule losses in conductor. Further details will follow in the full paper.

## III. MEASUREMENT AND SIMULATION RESULTS

ABB RESIBLOC® dry-type transformer with additional tap connections that allow voltage measurement along the winding is used to verify the presented approach. The measurement results of the lightning-impulse test are shown in Figure 2a.



a)

b)

Fig. 2. Measured (a) and simulated (b) voltage at different winding positions during the lightning-impulse test for the ABB RESIBLOC® dry-type transformer.

### A. Simulation method

The numerical method used for simulation results takes into account all capacitive and inductive couplings between every single turn of the winding. Therefore, L and C matrices are fully populated. A given input signal is transformed to frequency domain and the resistance matrix is calculated for every dominating frequency. After obtaining RLC matrices, a system of ordinary differential circuit equations is solved for every frequency point using *Wolfram Mathematica* and the method presented in [1]. Results are transformed back to time-domain and shown in Figure 2b.

### B. Results

As one can see in Figure 2, the suggested numerical simulation procedure gives satisfactory results. The main oscillation of the winding has a frequency of 560 kHz according to the measurements and 567 kHz obtained using the simulation, resulting in 2% difference.

Comparison with measurements was done for the entire winding over time. The main focus is on determining the voltage peak of the first layer of the winding, between input lead-out “11” and lead-out “F”. Obtaining the deepest voltage dips along the winding shows the nonlinear voltage distribution thus enabling the insulation stresses evaluation for the winding. Figure 3 shows measured and simulated voltage distributions for the entire winding at the time of 4.2 µs.

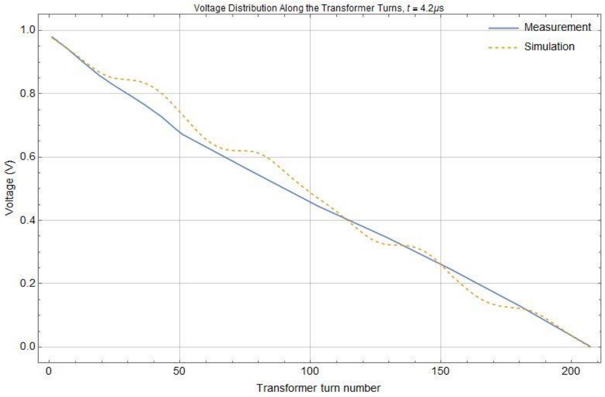


Fig. 3. Voltage distribution over the winding of the ABB RESIBLOC® dry-type transformer at the time of 4.2 µs.

The obtained measured and simulated results for the three deepest voltage dips for the first layer are shown in Table I. Both the value of the voltage dip and the time at which it occurred can be simulated with an acceptable accuracy.

TABLE I
MEASURED AND SIMULATED THREE DEEPEST VOLTAGE DIPS FOR THE FIRST LAYER OF ABB RESIBLOC® DRY-TYPE TRANSFORMER

| No. | Method | Voltage (V) | Time (µs) | Voltage difference | Time difference |
|---|---|---|---|---|---|
| 1 | Meas. | 0.317 | 2.56 | | |
| | Simul. | 0.298 | 2.59 | -6% | 1% |
| 2 | Meas. | 0.309 | 4.27 | | |
| | Simul. | 0.285 | 3.80 | -8% | -11% |
| 3 | Meas. | 0.284 | 8.03 | | |
| | Simul. | 0.270 | 7.84 | -5% | -2% |

### C. Conclusion

It has been demonstrated that the presented method for obtaining the RLC parameters of the transformer winding using the self-developed solvers can be effectively used as a fast way of simulating the high-frequency behavior of power and distribution transformers. The presented comparison of the obtained numerical results against the measurements revealed a good agreement.

## REFERENCES

[1] J. Smajic, T. Steinmetz, M. Rüegg, Z. Tanasic, R. Obrist, J. Tepper, B. Weber, M. Carlen, “Simulation and Measurement of Lightning-Impulse Voltage Distributions Over Transformer Windings,” *IEEE Trans. Magn.*, vol. 50, no. 2, 7013604, Feb. 2014.

[2] O. Chubar, C. Benabderrahmane, O. Marcouille, F. Marteau, F.J. Chavanne, P. Elleaume, "Application of Finite Volume Integral Approach to Computing of 3D Magnetic Fields Created by Distributed Iron-dominated Electromagnet Structures," *Proceedings of EPAC 2004*, Lucerne, Switzerland, pp. 1675-1677, 2004.

[3] T. Župan, Ž. Štih, B. Trkulja, "Fast and Precise Method for Inductance Calculation of Coaxial Circular Coils with Rectangular Cross Section using the One-Dimensional Integration of Elementary Functions Applicable to Superconducting Magnets", *IEEE Trans. App. Supercond.*, vol. 24, no. 2, 4901309, Apr. 2014.