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RLC-MODELS FOR COMPUTER MODELING OF TRANSFORMERS' WINDINGS FREQUENCY RESPONSE

The diagnostics of power transformers is a very fast developing branch, due to increasing average age of assets and changes in asset management strategies, nowadays companies introduce asset management based on technical condition. One of important methods used for diagnostics of a transformer's active part is Frequency Response Analysis (FRA). It allows determination of mechanical condition of windings, their displacements, deformations and electric faults, as well as some problems with internal leads and connections, core and bushings. For the aim of windings impedance modeling the RLC models are applied. The idea of lumped parameters models was presented in [6]. The new universal model basing on circuit solution is developed in this paper. Lumped parameters used are calculated with finite element method and Maxwell package. The examples of models created for simple windings were compared to real measurements.

1. INTRODUCTION

The FRA method is based on the analysis of transfer function of windings. The winding can be described by a set of local capacitances, self and mutual inductances and resistances. Every change in winding geometry leads to change of these parameters, therefore the transfer function's shape is also changed. The analysis of FRA results is based on comparison of data presented usually as sine signal damping along frequency spectrum in logarithmic scale. This can be compared to results recorded for given transformer in time intervals, between phases, between twin or sister units or with help of computer models. The first method is optimal, but for most of old transformers there is no fingerprint data available.

The next two approaches are usually applied in industrial practice, however they are quite uncertain and may lead to misinterpretations. Each transformer can have differences in FRA curve compared between phases or, if compared to other units, due to constructional differences [2]. Helpful results can be obtained from controlled deformations, but this method cannot be applied in mass scale and generalized [3].

All above lead to introduction of computer models, which may be useful for interpreting changes in FRA charts. Models are usually based on real physical

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dimensions and properties of transformers. However, it is still difficult to construct models having frequency response identical to real units and allowing to simulate various defects with similar effect on the FRA curve as real deformation in winding. There are various methods used for transformer modeling, based on lumped or distributed parameters models, FEM methods etc. [1,4,5,6].

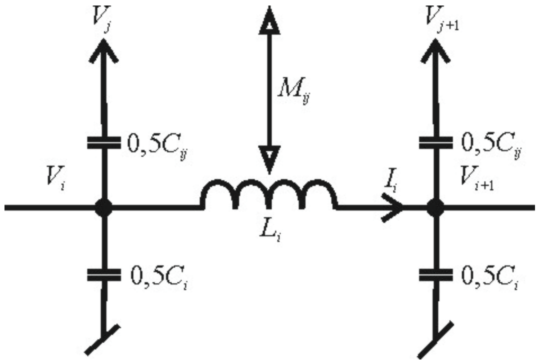

Fig. 1. RLC model of a single turn

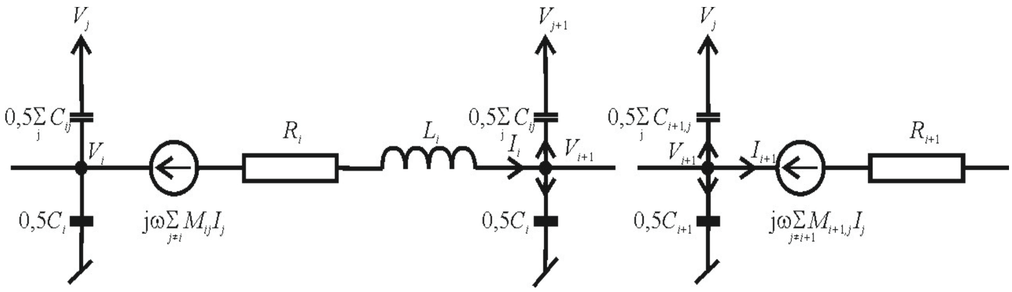

Fig. 2. Network model and interconnection of two turns

2. FRA MEASUREMENTS

At this stage of FRA development results of measurements are given as damping of windings to sine signal in frequency range, according to formula:

$$FRA[\mathrm{dB}] = 20\log\left|K_{\mathrm{u}}(f)\right| = 20\log\frac{\left|U_{\mathrm{out}}\right|}{\left|U_{\mathrm{in}}\right|} \qquad (1)$$

where: U_{in} – voltage signal applied to winding, U_{out} – voltage signal measured.

The measurement can be taken either on two ends of the winding (with secondary winding open or shortened and grounded) or between windings of the same phase.

3. LUMPED PARAMETER MODEL

Assumed RLC - model of a single turn is shown in Fig.1. It consists of self inductances L_i, capacitances C_i and resistances R_i, as well as mutual inductances M_{ij} and capacitances C_{ij}. The adopted model is characterized by the fact, that it includes the mutual inductances and capacitances between all turns of the winding.

Voltage difference on the branch i is given by

$$V_i - V_{i+1} = I_i \cdot R_i + \mathrm{j}\omega \sum_j M_{ij} I_j, \text{ where } M_{ii} = L_i. \tag{2}$$

The first voltage $V_\mathrm{i} = V_\mathrm{in}$ is known. So, we have the number of unknown voltages equal number of branches N_g. Sum of the currents in node i+1 is

$$\begin{aligned} I_i = I_{i+1} &+ \frac{\mathrm{j}\omega}{2}\left(C_i + C_{i+1}\right) \cdot V_{i+1} + \\ &+ \frac{\mathrm{j}\omega}{2} \sum_{j \neq i} C_{i,j} \cdot \left(V_{i+1} - V_{j+1}\right) + C_{i+1,j} \cdot \left(V_{i+1} - V_j\right). \end{aligned} \tag{3}$$

Number of current equations is N_g, while the number of unknown currents equals $N_\mathrm{g} + 1$. The current in the last branch $I_\mathrm{out} = V_\mathrm{out}/R_0$ ($V_\mathrm{out} = V_{N\mathrm{g}+1}$), where R_0 means the resistance of measuring instrument. Considering (2) and (3) we obtain the system of $2 \cdot N_\mathrm{g}$ equations to solve, whose matrix owns the following form:

$$[\boldsymbol{A}]\begin{Bmatrix} \boldsymbol{V} \\ \boldsymbol{I} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{A}_\mathrm{VV} & \boldsymbol{A}_\mathrm{VI} \\ \boldsymbol{A}_\mathrm{IV} & \boldsymbol{A}_\mathrm{II} \end{bmatrix} \begin{Bmatrix} \boldsymbol{V} \\ \boldsymbol{I} \end{Bmatrix} = 0, \tag{4}$$

where the terms of the matrix $\boldsymbol{A}$ are given by following equations:

$$\boldsymbol{A}_\mathrm{VV} = \left.\underbrace{\begin{bmatrix} 1 & -1 & \ldots & 0 & 0 \\ 0 & 1 & \ldots & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & -1 & 0 \\ 0 & 0 & \ldots & 1 & -1 \end{bmatrix}}_{N_\mathrm{g}+1}\right\} N_\mathrm{g}, \tag{5}$$

$$\boldsymbol{A}_\mathrm{VI} = \left.\underbrace{\begin{bmatrix} -R_1 - \mathrm{j}\omega L_{11} & -\mathrm{j}\omega M_{12} & .. & -\mathrm{j}\omega M_{1,N_\mathrm{g}} & 0 \\ -\mathrm{j}\omega M_{21} & -R_2 - \mathrm{j}\omega L_{22} & .. & \ldots & 0 \\ \ldots & \ldots & .. & \ldots & \ldots \\ -\mathrm{j}\omega M_{N_\mathrm{g}-1,1} & -\mathrm{j}\omega M_{N_\mathrm{g}-1,2} & .. & -\mathrm{j}\omega M_{N_\mathrm{g}-1,N_\mathrm{g}} & 0 \\ -\mathrm{j}\omega M_{N_\mathrm{g},1} & -\mathrm{j}\omega M_{N_\mathrm{g},2} & .. & -R_{N_\mathrm{g}} - \mathrm{j}\omega L_{N_\mathrm{g},N_\mathrm{g}} & 0 \end{bmatrix}}_{N_\mathrm{g}+1}\right\} N_\mathrm{g} \tag{6}$$

$$\boldsymbol{A}_{\mathrm{IV}}=\frac{\mathrm{j}\omega}{2}\underbrace{\begin{bmatrix} 0 & C_1+C_2+C_{12} & -(C_{12}+C_{23}) & \ldots -(C_{1,N_g}+C_{2,N_g+1}) \\ -C_{31} & -C_{21} & C_2+C_3+C_{23} & \ldots -(C_{2,N_g}+C_{3,N_g+1}) \\ -C_{41} & -C_{31}-C_{42} & -C_{32} & \ldots -(C_{3,N_g}+C_{4,N_g+1}) \\ \ldots & \ldots & \ldots & \ldots \quad \ldots \\ -C_{N_g+1,1}-C_{N_g,1} & -C_{N_g+1,2}-C_{N_g,2} & -C_{N_g+1,3}\ldots & -C_{N_g,N_g-1} \end{bmatrix}}_{N_g+1}\Bigg\}N_g \tag{7}$$

$$\boldsymbol{A}_{\mathrm{II}}=\underbrace{\begin{bmatrix} -1 & 1 & \ldots & 0 & 0 \\ 0 & -1 & \ldots & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & 1 & 0 \\ 0 & 0 & \ldots & -1 & 1 \end{bmatrix}}_{N_g+1}\Bigg\}N_g \tag{8}$$

and the vector

$$\begin{Bmatrix} \boldsymbol{V} \\ \boldsymbol{I} \end{Bmatrix}=\begin{bmatrix} V_{\mathrm{in}} & V_2 & \ldots & V_{N_g} & V_{\mathrm{out}} & I_{\mathrm{in}} & I_2 & \ldots & I_{N_g} & I_{\mathrm{out}} \end{bmatrix}^{\mathrm{T}} \tag{9}$$

The matrix $\boldsymbol{A}$ is dense populated, so its solution for the whole winding takes considerable time of computation.

4. OBTAINING OF LUMPED PARAMETERS

The parameters RLC of the turns are obtained from two-dimensional field model analysis of the winding. The model consists of single, unconnected wires, excited by known voltage or current.

To provide the own and mutual capacitances the electrostatic model is solved:

$$\nabla\cdot\left(\varepsilon_{\mathrm{r}}\varepsilon_0\nabla\Phi(r,z)\right)=-\rho\,. \tag{10}$$

For own and mutual inductances and resistances the eddy current model described by

$$\nabla\times\frac{1}{\mu}(\nabla\times\boldsymbol{A})+\mathrm{j}\omega\gamma\boldsymbol{A}=\boldsymbol{J}_s\,. \tag{11}$$

The solutions were carried out utilizing ANSYS Maxwell package, which owns the possibility to determine the necessary matrices, namely inductance matrix from magnetic energy:

$$W_{AV}=\frac{1}{4}\int\boldsymbol{B}_i\cdot\boldsymbol{H}_j^*\mathrm{d}V,\quad L_{ij}=\frac{4W_{AV}}{I_{Peak}^2}=\int\boldsymbol{B}_i\cdot\boldsymbol{H}_j\mathrm{d}\Omega\,, \tag{12}$$

capacitance matrix from electric energy:

$$W_{ij}=\frac{1}{2}\int_{\Omega}\boldsymbol{D}_i\cdot\boldsymbol{E}_j\,\mathrm{d}\Omega,\ C_{ij}=\frac{2W_{ij}}{V^2}=\int_{\Omega}\boldsymbol{D}_i\cdot\boldsymbol{E}_j\,\mathrm{d}\Omega\,, \tag{13}$$

and the resistances from power dissipation:

$$P=\frac{1}{2\gamma}\int\boldsymbol{J}\cdot\boldsymbol{J}^*\mathrm{d}\Omega,\ R=\frac{2P}{I_{Peak}^2}=\frac{\int\boldsymbol{J}\cdot\boldsymbol{J}^*\mathrm{d}\Omega}{\gamma I_{Peak}^2}=\int\boldsymbol{J}\cdot\boldsymbol{J}^*\mathrm{d}\Omega\,. \tag{14}$$

5. SIMULATION RESULTS AND COMPARISON TO FRA

The results provided by the described lumped parameter model were compared to these obtained with transmission line method, described in [7]. The simulation results with both methods yields very similar results until frequency of 1Mhz. For higher frequencies there is visible the signal delay associated with the length of the transmission path, which corresponds to the coil winding.

The simulation results were compared to measurements done using Omicron FRAnalyser. The comparison for the winding consisting of 18 turns is shown in Fig. 3 and similar comparison for 60 turns is shown in Fig. 4.

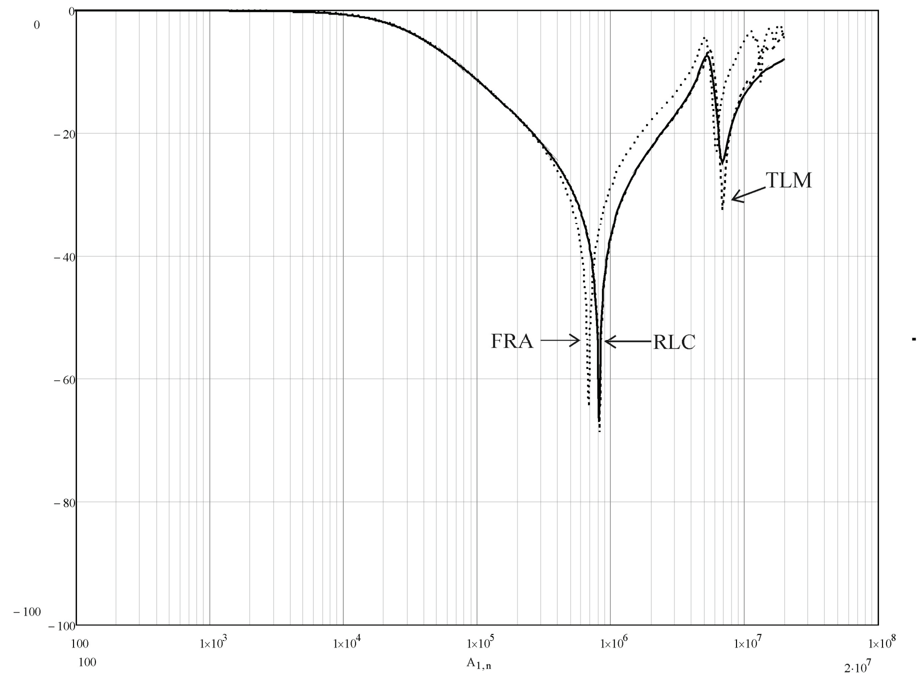

Fig. 3. The amplitude of the signal (1) obtained using lumped parameter model (RLC) compared to transmission line method (TLM) and measurement (FRA) . Winding with 18 turns

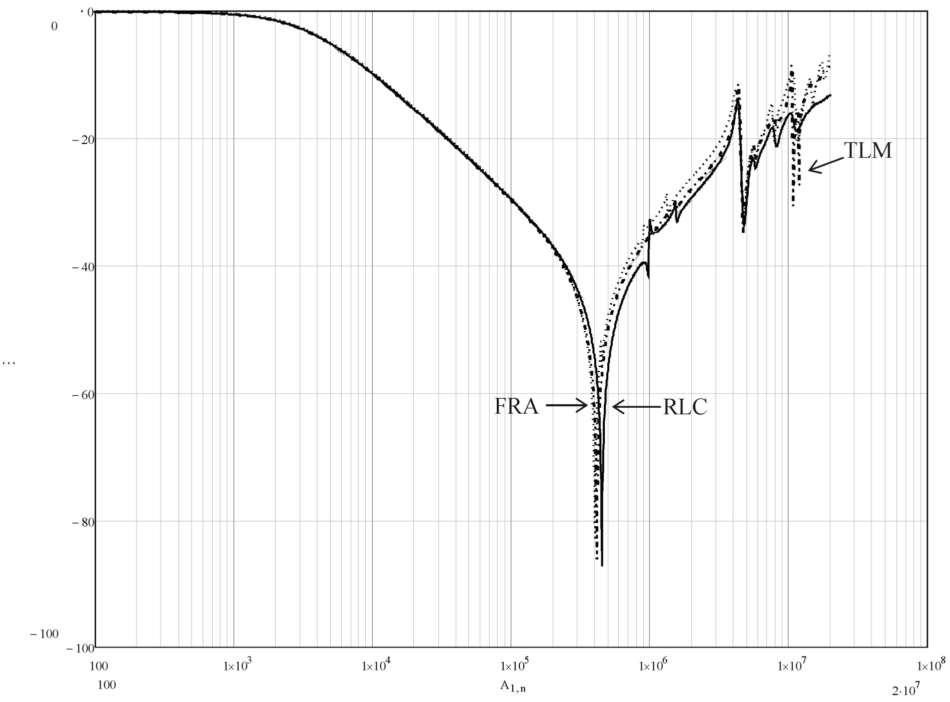

Fig. 4. The amplitude of the signal (1) obtained using lumped parameter model (RLC) compared to transmission line method (TLM) and measurement (FRA). Winding with 60 turns

6. FUTURE WORK

The described method can be applied to the analysis of transformers with a large number of turns. The determination of the resistances, capacitances, inductances and mutual inductances can be done using the finite element method, however long computational time should be taken into account. In many cases, the circular-cylindrical symmetry allowing for 2D analysis can be used. Presented models allows for simulation of some deformations of the windings so long, as the cylindrical symmetry will not be lost. For other deformations it will need the full 3D analysis.

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