Computer modeling in the diagnostics of transformers' windings deformations

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The diagnostics of power transformers is very important in order to plan repairs and replacements of aged population of transformers operated in Poland and Europe. One of these methods is Frequency Response Analysis – FRA. It can detect any mechanical changes in active part of transformer, which may even lead to serious faults of units in service. As the method is based on comparison of measured curves, which are not always available from previous measurements the computer modeling was applied to create models of windings' response. The paper presents examples of models created for simple windings and also for real transformer with some deformations of windings simulated.

1. Introduction

The average age of power transformers operated in Poland and other European countries is constantly growing. At present over half of them are operated over 25 years. In addition there are not sufficient possibilities of producing new units in short period of time. Therefore it is very important to recognize transformers' technical condition. One of diagnostic methods used for this purpose is Frequency Response Analysis – FRA. The method, already applied in industry, is based on the correlation of the geometry of windings and their transfer function, usually in the range from 10 Hz to 2 MHz. The FRA method is used for detection of deformations in windings – radial buckling, axial displacement or inter-winding short-circuits and others. These deformations result from electrodynamic forces coming from short circuits, transient overvoltages, ageing of solid insulation in transformer and also during transportation of units. Slightly damaged winding doesn't lead directly to catastrophic fault of transformer, as it can be still operated for longer time, e.g. to next overvoltage, which could breakdown the weakened insulation and generate fault of unit [1].

2. Assessment of FRA results

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

$$\mathrm{FRA[dB]} = 20\log\frac{U_{out}}{U_{in}} \qquad (1)$$

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. The typical FRA curves measured on the power transformer are shown on the Fig. 1. The assessment is currently based mainly on visual comparison of curves recorded between three phases of unit, between sister units or for measurements taken earlier for the same unit. The last option is giving the full information on changes in transformer's active part, however it is not possible to obtain FRA "fingerprints" for transformers produced 20-25 years ago. Therefore additional direction in development of FRA method is computer modeling of transformer response.

The comparison can be also performed with automated computer algorithms, there are two of them applied in industrial practice (Chinese Standard DL/T911-2004 and NCEPRI method). These algorithms are based on calculating differences between two curves in given frequency ranges, responsible for various phenomena in transformer, but cannot be used without additional help of experienced specialist.

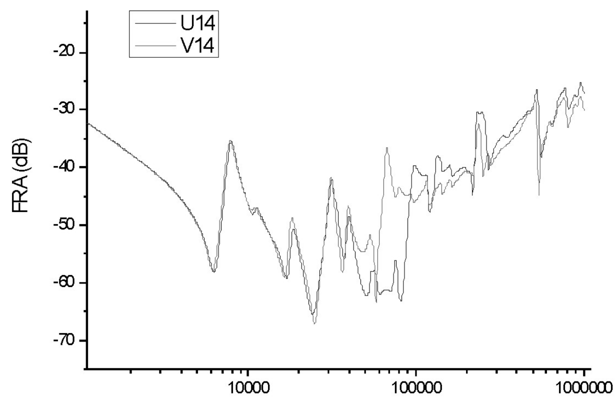


Fig. 1. Example of differences in FRA measurements

The identified frequency ranges are related to core magnetism influence, obvious or slight deformations and set-up of connections and leads [2].

3. Modeling of FRA response

In industrial practice there are often cases of transformers which are difficult to be assessed due to lack of earlier "fingerprints". Usually it is difficult to find sister unit of the same construction operated in the same working conditions with the same history of service. The comparison between phases is not always very reliable as there are always differences between middle phase and side phases as there is different magnetic flux distribution. Additionally in some transformers there are differences between phases which are known to be typical for given type, e.g. related to leads set-up in the tank or position of bushing versus windings. In such cases the best option seems to be creation of computer model of "healthy" winding and simulation of various defects or even creation of a tool analyzing and comparing response of phases and model and giving possible causes for observed differences.

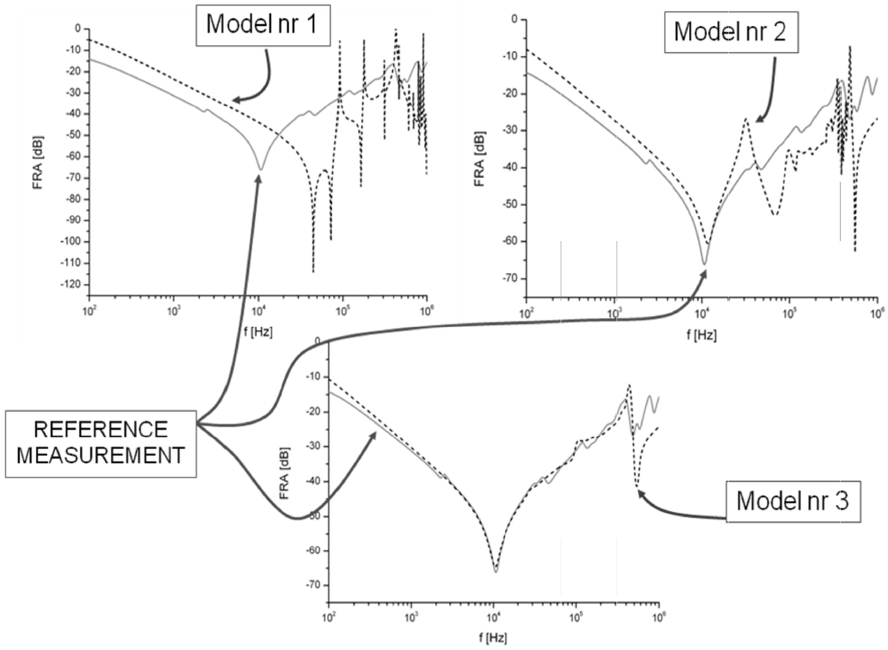


Fig. 2. Examples of models of single winding compared to reference measurement

Some examples of models' responses compared to measured data are given on Fig. 2. These were calculated for the small single winding of 15/0.4 low power transformer. The computer model, rather simple at the beginning of experiment, had new elements been added at subsequent stages, resulting in good conformity to real measurements at the end. It was necessary to take into consideration not only basic series and parallel RLC elements but also couplings, leakage currents and other factors not constant in the frequency range. There is also the problem with obtaining actual sizes of all simulated elements and their exact material properties, as these values are used for model generation. It is not possible to open every transformer to measure internal sizes, so the modeling is based on information given in technical documentation of transformer, not always containing all details as they are. All these elements create the circuit model through which the same FRA signal is transferred as for real object giving more or less similar result.

At the current stage of modeling it is not possible yet to create complete models giving exactly the same response as this of modeled transformers. However these are still developed and can simulate some basic faults. Models of winding's FRA response consist of basic RLC elements and additional couplings. The total number of elements directly influences the accuracy of model. The model used for presented simulations was based on 156 RLC elements and over 300 additional couplings. These were put as a net of series and parallel capacitances, series inductances, magnetic couplings and series and parallel resistances [3]. The second presented model was created for the winding used for previous controlled deformations tests for 15/0.4 kV, 16 MVA transformer [1]. The winding was taken out of tank and some basic deformations were carried out with FRA measurements taken at all stages. It allowed to identify the basic ranges and types of changes in registered curves related to given type and size of deformation. Such experiment will be repeated in the next couple of months in laboratory conditions (previous one was in field conditions before scraping the transformer) and will possible give even more detailed relations. All tests were performed for winding without tank and oil. Therefore also model is based on calculations considering these facts. Such model cannot be considered as a tool providing the response of complete transformer and was used only for these tests, as it was the easiest way to compare real measurements before and after deformation with different approaches of model. Also the geometry of winding wasn't typical as there was no tap changer mounted, leaving regulation winding open, but still having influence on parallel parameters of model [2].

The first stage of modeling was to prepare model of the 'healthy' winding – before introducing controlled deformations. There were several approaches undertaken, each of them containing additional elements, leading to modeled curve similar in shape to the real one (Fig. 3). However, all of these parameters are always just a simplification of real phenomena and properties, therefore there will be always some errors in model generation and further interpretation of results. Such errors may be comparable or even higher than differences between healthy and slightly damaged phase, therefore it will be not always possible to use computer modeling for automated analysis of the FRA results.

In the above example the curves look similar, having number, position and type of resonances comparable, however using any automated tool for assessment would generate obvious deformation results.

The next approach was generated for the winding after conducting deformation. The deformation was big in scale, not possible to occur in the real transformer, but as the model used for the experiment was simple, consisting of only ten circuit levels it was necessary to introduce deformation giving clear differences possible to simulate in one of ten circuit levels. Changes of RLC parameters in the model were considered according to real deformation size and new parameters for model were obtained. After model recalculation the new simulation had been created (Fig. 4b).

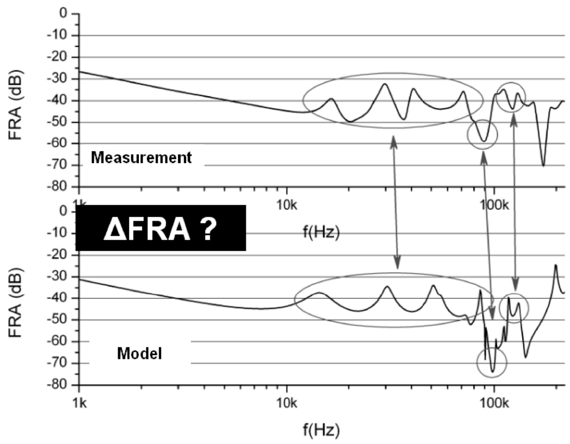
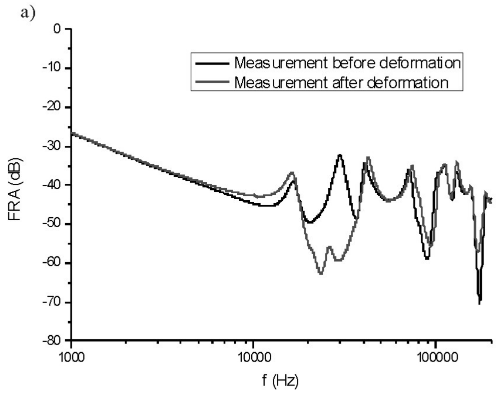


Fig. 3. The comparison of measurement and modeling of 16 MVA winding

a)



b)

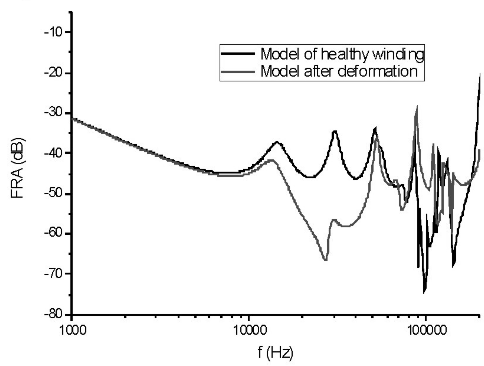


Fig. 4. The comparison of measurements (a) before and after deformation and simulations, (b) corresponding to them

At first it seemed that such slight change in the model wouldn't give noticeable and correct response, but results showed that the model worked, giving changes similar to real measurements on deformed winding. It can be seen that character of changes for simulation of deformation in model is similar to real measurements before and after deformation. Both frequency ranges and amplitude shifts occur in similar areas. Of course differences between models and real winding's response are still too large and in the normal conditions it would be identified as rough deformation, but this example shows that it is possible to obtain models giving response similar to real objects after simulating deformations [4].

The Fig. 4a presents real measurement before and after deformation. The most important differences between curves can be observed in the frequency range from 10 kHz to 100 kHz. This range is related to changes in windings geometry. In the Fig. 4b corresponding model is presented. It can be seen that in the mentioned range changes of FRA curve are similar in size, position and type to measured ones. In higher frequencies differences are bigger, as it is not possible to simulate the whole frequency range with one model. In addition there are many factors influencing this part of FRA curves, which cannot be easily identified, generalized and modeled in a simple way.

4. 3D FEM-model for analysis of electromagnetic field

The described model shows the possibility of modeling the electromagnetic field of the transformer windings using finite elements. For this aim the COMSOL Multiphysics 3.5A package was used. The analyzed model is shown in Fig. 5.

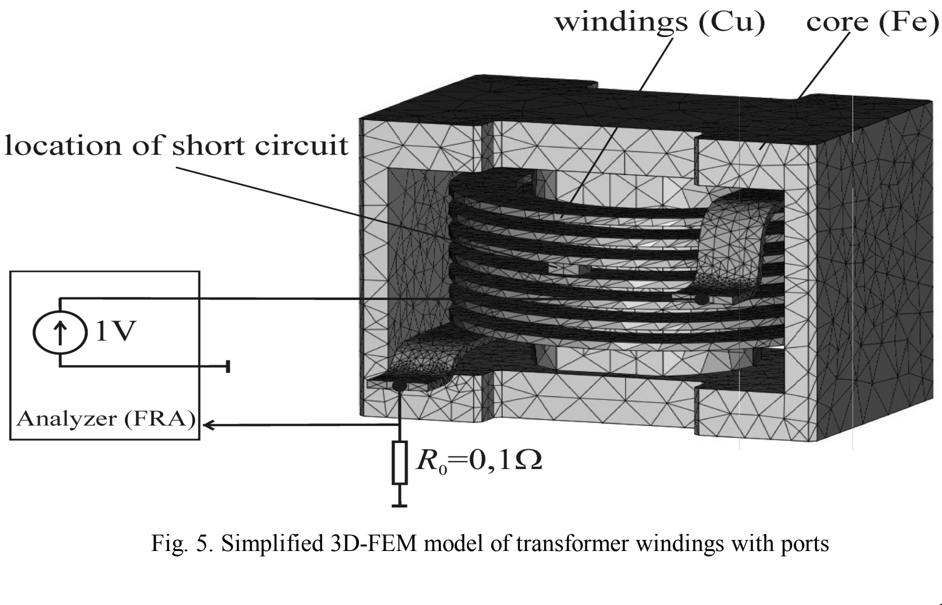


Fig. 5. Simplified 3D-FEM model of transformer windings with ports

The modeling was done by discretization of the analyzed area on 91k tetrahedral finite elements, using a quadratic approximation within the elements. Number of degrees of freedom in analyzed model exceeded 800k, and the size of problem to be solved ranged from 6 to 8 GB of computer memory. Analysis time for a single frequency value exceeded 20 minutes (with CPU I7 / 2.67 MHz, 9GB RAM, Windows 7 64bit).

For description of 3D electromagnetic field A-V formulation was chosen, because of its convenience for solving of models with forced voltage supply. The shape of these equations is as follows:

$$(j\omega\gamma - \omega^2\varepsilon_0\varepsilon_r)\mathrm{div}\mathbf{A} + (\gamma + j\omega\varepsilon_0\varepsilon_r)\mathrm{divgrad}V = 0$$

$$(j\omega\gamma - \omega^2\varepsilon_0\varepsilon_r)\mathbf{A} + \mathbf{rot}\times\left(\frac{1}{\mu_{0\mu_r}}\mathrm{rot}\times\mathbf{A}\right) + (\gamma + j\omega\varepsilon_0\varepsilon_r)\mathrm{grad}V = 0 \tag{2}$$

while the material parameters were following:

- windings: $\mu_r = 1$, $\varepsilon_r = 1$, $\gamma = 5.998_{10}7$ [S/m],
- core (steel sheets): $\mu_r = 1000$, $\varepsilon_r = 1$, $\gamma = 10$ [S/m],
- air: $\mu_r = 1$, $\varepsilon_r = 1$, $\gamma = 1$ [S/m].

Assumption of non-zero value of γ for the air was dictated by the need to improve the convergence of the solution. Fig. 6 shows the distribution of current density on the surface of the windings in the presence of a short circuit at a frequency of $f = 1000$ Hz. The brighter color shows a significant amount of current in the short turn.

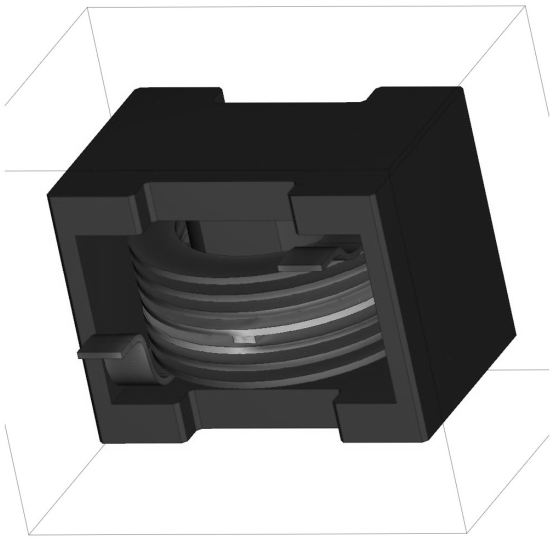


Fig. 6. Current density in short turns of the winding

The results obtained from simulation for the frequency range 50 Hz – 100 kHz were used to provide similar characteristics as those obtained by the analyzer FRA. Due to the scale of the assumed model and a small number of coil turns, measuring resistance R_0 was reduced to a value having neglible impact on the current in the circuit, i.e. 0.1 Ω. Acquired amplitude and phase characteristics are shown in the drawings below. Darker characteristics correspond to the state without a short circuit.

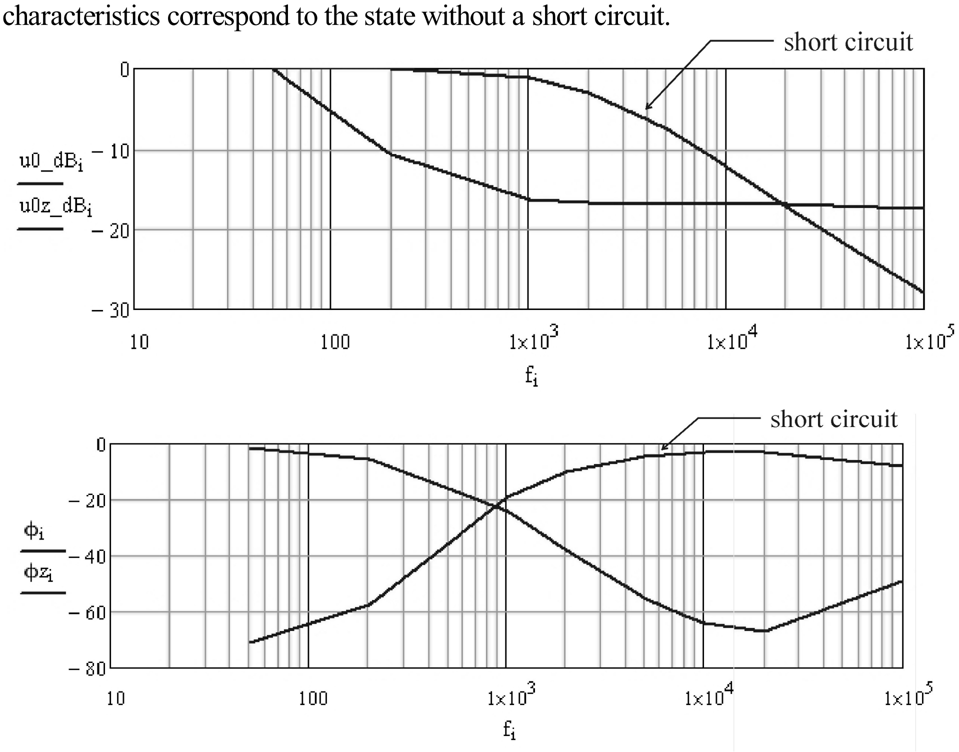


Fig. 7. Frequency characteristics of output voltage in presence of short circuit

It should be noted that due to large dimension of finite elements in relation to the skin depth for the copper, the results are reliable only until the frequency of f = 20 kHz.

5. Summary

The FRA method is an important diagnostic tool for detection of mechanical deformations of windings. The way of taking measurements, connection set-ups and properties of devices used for recording FRA curves are being standardized (e.g. IEC group PT 60076-18). There is still problem with full analysis of results and identification of existing faults in windings, their scale or exact position. One of tools, which may be used for analysis of results are computer models of FRA response. After obtaining simulated curves similar to real measurements, based on parameters of modeled windings or transformer, it will be possible to simulate various types and sizes of deformations and check their influence on the shape of recorded curve. For preparing the models it is necessary to consider many details of construction and parameters of windings, however examples presented in the paper show, that it is possible to create models having response similar to real measurements. In addition, these models were based on rather simple approaches, having the winding divided into ten level circuit. Preparing more complex model will lead to more detailed models. It is planned to perform deformation measurements on recently obtained transformer in laboratory conditions and prepare computer models allowing to simulate created deformations.

References

[1] "Mechanical-Condition Assessment of Transformer Windings Using Frequency Response Analysis (FRA)", Report of CIGRE Working Group A2.26, (2008).

[2] Banaszak Sz. "Conformity of Models and Measurements of Windings Deformations in Frequency Response Analysis Method", New Electrical and Electronic Technologies and Their Industrial Implementation, Przeglad Elektrotechniczny 7'2010, pp. 278-280.

[3] Banaszak Sz., Szrot M.: „Pomiary odpowiedzi częstotliwościowej uzwojeń transformatora w warunkach kontrolowanej deformacji", IX Sympozjum Inżynieria Wysokich Napięć IW-2008, Będlewo, czerwiec 2008, Przegląd Elektrotechniczny 10/2008, pp. 128-131.

[4] Banaszak Sz.: „Modelowanie odpowiedzi częstotliwościowej uzwojeń transformatora", IX Sympozjum Inżynieria Wysokich Napięć IW-2008, Będlewo, VI.2008, Przegląd Elektrotechniczny 10/2008, pp. 124-127.