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A Novel Approach of Power Transformer Diagnostic Using 3D FEM Parametrical Model

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***Abstract*—**This paper deals with a novel approach of power transformers diagnostics. This approach identifies the exact location and the range of a fault in the transformer and helps to reduce operation costs related to handling of the faulty transformer, its disassembly and repair. The advantage of the approach is a possibility to simulate healthy transformer and also all faults, which can occur in transformer during its operation without its disassembling, which is very expensive in practice. The approach is based on creating frequency dependent impedance of the transformer by sweep frequency response analysis measurements and by 3D FE parametrical modeling of the fault in the transformer. The parameters of the 3D FE model are the position and the range of the axial short circuit. Then, by comparing the frequency dependent impedances of the parametrical models with the measured ones, the location and the range of the fault is identified. The approach was tested on a real transformer and showed high coincidence between the real fault and the simulated one.

***Keywords*—**Fault, finite element method, parametrical model of transformer, sweep frequency response analysis, transformer.

I. INTRODUCTION

CURRENTLY a lot of distribution system operators are trying to reduce operation costs. Usually, economization are reached using extend maintenance period and at the same time a number of diagnostic measurements is increased, thereby at the same time an emphasis is on a quality of these diagnostic measurements.

In general, periodic diagnostic measurements are measurements of a resistivity, an insulation resistance, moisture, a tan delta, a sweep frequency response analysis (SFRA), a gas analysis and also lower frequency diagnostic measurements such as a partial discharge, a furan analysis, a breakdown voltage, etc. [1], [2]. Diagnostic measurements can be off-line and on-line [3].

Most of the diagnostic measurements provide only a determination of a fault state and they do not yield the exact determination of the fault or the range of this fault [4], [5]. In other words, the measurements only determine a kind of the fault (short-circuit, shift winding, etc.), but not the fault location in the transformer (for example: tertiary winding or phase A, etc.). This has an influence on the decision making of the distribution system operators.

In many cases, the decision of the distribution system operators has many times financial consequences. To make optimal decision (e.g. to put out of the operation or keep a transformer in the grid) the operator tries to gather as many information about the transformer as possible. The decision on the decommissioning can be correct if and only if the real state of the transformer is known.

In cases, where the standard diagnostic measurements offer insufficient information about the real state of the fault transformer, the operator tries to employ more sophisticated methods. By using more sophisticated methods an expensive premature transport and the disassembly can be avoided.

Consequently, the sophisticated methods try to analyze the state of the transformer more exactly, e.g. by the matching of real diagnostic measurement data, such as SFRA (described in [5], [11]) with data obtained from a mathematical model of the transformer:

- equivalent circuit [6], [7],
- hybrid winding model [8],
- transfer function [9],
- Finite Element Method (FEM) [10]
- etc..

However, the analytical approach has a lower accuracy and a short computational time. On the other hand the FEM approach has a longer computational time but reaches higher accuracy due to a small sectioning [9] or a fine meshing.

This paper deals with a novel approach to the power transformer diagnostics, which is based on a 3D FE parametrical model, which simulate the real diagnostic measurement and uses off line diagnostic data of SFRA in order to determine the exact location and a range of the fault. In the article, the focus is put on the axial short circuit on the transformer winding. This is reached by creating 3D FEM parametric model of the transformer and solver its harmonic electromagnetic field distribution. Then, from the electromagnetic field, all parameters of the transformer equivalent circuit are calculated. They are subsequently used to determine the total impedance of the transformer as a function of the frequency. The total impedance is then compared with the measured data of the real transformer (TO294-22kV) at certain frequencies. If the data do not coincide, the parametric 3D FE model is adjusted until the calculated and the measured impedances are identical.

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II. DESCRIPTION OF THE APPROACH

In this section, the working principle of the approach is described. It can be demonstrated by a flowchart in Fig. 1.

The procedure is programmed in Linux script, which uses also Opera comi files. The program has two parts. The first part takes care of the interaction between a user and the program. The second part (the computational part) is a modeling and a determination of the healthy as well as faulty transformer parameters.

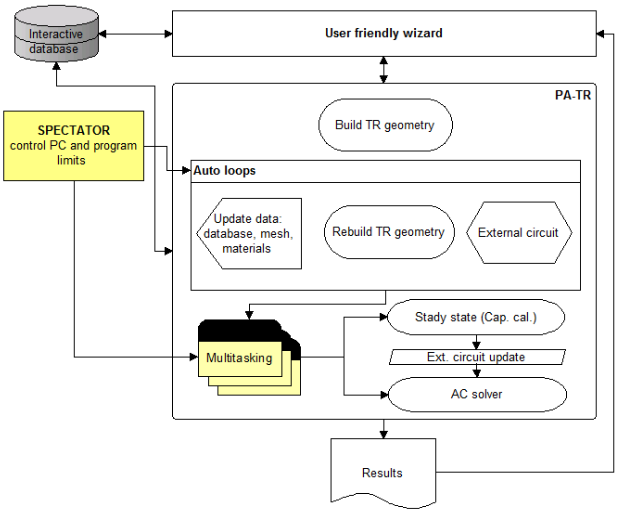

Fig. 1 The working principle of the proposed approach

A. User Friendly Wizard

The interaction of the user with the program and the database is done through the user friendly wizard. At the beginning the user may define a completely new transformer to make a combination of parts of existing transformers or to select an existing transformer.

The data needed for the transformer definition are entered through the wizard to the interactive database in case of the newly defined transformer, or the data are taken from the database in case of the existing transformer or a combination of parts of the existing transformers.

Further, the user defines the type of the fault that should be identified as for example a radial or an axial short circuit and a shift of the winding.

B. Interactive Database

As mentioned in the previous subsection, all data defined by the user are stored in the interactive database. The interactive database is used by PA-TR module and its submodules. This database consists of data as geometry dimensions, material properties, types and ranges of faults, which needs to be investigated.

This database contains also data created by the computational part as external circuits, data from all simulations which have already been done on the existing healthy and faulty transformers.

C. Spectator

The computational part executes several tasks in order to identify parameters which are needed for the next computations (intermediate step) or the final comparison with the measurements. This part is controlled by the hybrid program structure SPECTATOR, which opens multitasking strands to execute tasks, with the assistance of Linux scripts. This causes that the calculation is running autonomously and user independent. SPECTATOR manages hardware resources in a way that maximizes a server performance and shortens the computation time.

D. Building of the TR Geometry

The computational part utilizes number of the transformer geometry modification. Therefore, it is convenient to build "clean" geometry first, see Fig. 2, where is the transformer geometry without a definition of material properties. The geometry corresponds to the healthy transformer with all important elements, such as regions of windings, a core, insulations, oil, etc.

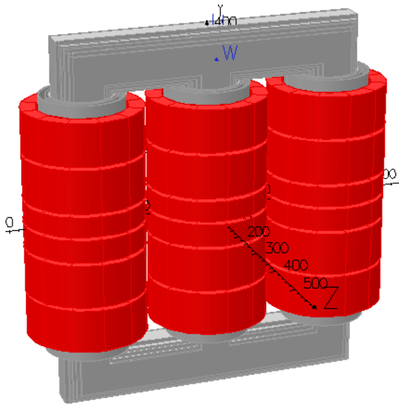

Fig. 2 "Clean" model of the analyzed transformer TO294-22kV

To build the "clean" geometry, SPECTATOR calls the Build TR geometry. This is the first task in open thread provided by SPECTATOR.

E. Auto Loops

The main task of Auto loops is to calculate the impedance at different frequencies, which corresponds to the impedance obtained by SFRA measurements. Towards this end, for the healthy or the faulty transformer, the following is carried out:

1) prepare models for no-load and short circuit simulations,
- remove redundant geometry parts (insulation regions),
- assign material properties,
- assign current sources,
- assign boundary conditions,

2) prepare models for mutual capacities calculations,
- assign material properties,
- assign voltage potentials,
- assign boundary conditions,

3) created an external circuit for FE harmonic analysis,
- created an external circuit representing SFRA no-load and

short circuit measurements,

- assign resistances and mutual capacities,
- defined voltages and frequencies of measurement,

4) prepare models for the harmonic FE simulations,

- change types of windings,
- assign circuit element names of windings,
- load the external circuit.

For the calculation of the no-load and the short circuit parameters, insulation parts and oil regions are redundant; therefore, they are removed from the model. The material properties are assigned to the ferromagnetic core (BH curve) and coils (permeability). Current sources are assigned to the coils (according to the kind of the simulation). The boundary conditions are assigned to outer background surfaces (the tangential magnetic boundary condition).

For the calculation of the mutual capacities, the all transformer regions are important; therefore, no regions are removed from the "clean" geometry. The material properties are assigned to the oil, the insulation and the coil regions. The voltage potentials are assigned to the coils and the TR frame (according to the kind of the simulation). The boundary conditions are assigned to the outer background surfaces (zero voltage potential).

In the points 1) and 2), the models are prepared to identify the equivalent circuit parameters see (Fig. 3).

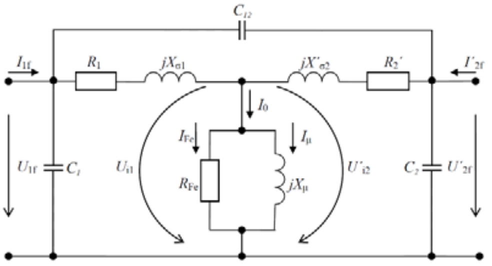

Fig. 3 The simplified equivalent circuit of transformer including parasitic capacitances

The external circuit (see Fig. 4) for the harmonic analysis is created according to the type of the connection (Y,Z,D) and spatial distribution of the TR parts (coils and core).

The external circuit is edited according to the type of the simulation (no-load, short circuit, type of measurement connection), that means that some elements are left out (see Figs. 4-6).

In the external circuit the voltage sources represent harmonic voltage sources with defined amplitude and frequency. Resistance elements represent the phase resistance of windings and capacities represent the mutual capacities between different combinations of coils, core and tank, where Cx(x∈ (1; 2; 3; 4; 5; 6; 11; 22; 33)) are the capacities between the coils and the ground, CSPx (x ∈ (1; 2; 3)) are the capacities between the primary and the secondary windings and CSx (x ∈ (1; 2; 3)) are the capacities between the different phases of the primary windings on one TR leg. Wx elements are coupled to the coils of the 3D FE model.

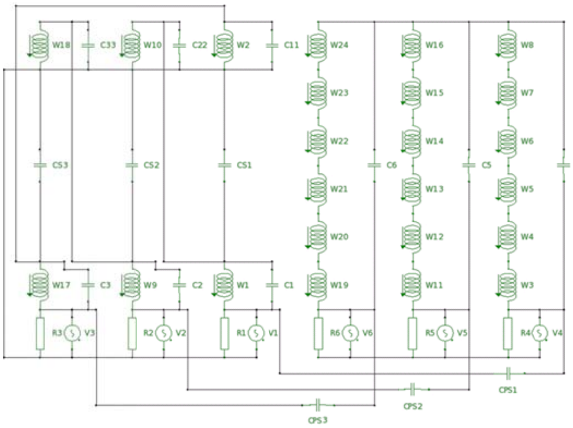

Fig. 4 The external circuit coupled with 3D transformer model

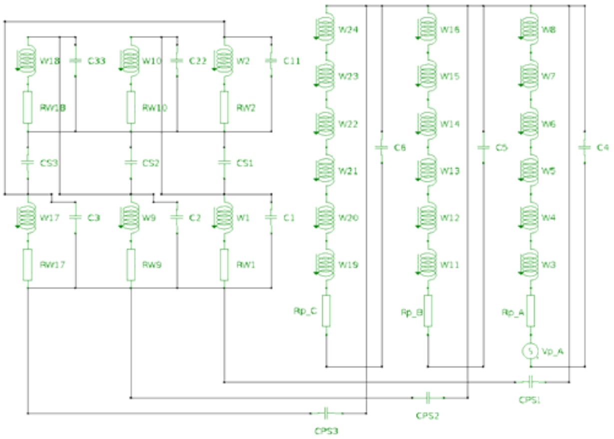

Fig. 5 The external circuit for the harmonic analysis (A-N short circuit SFRA measurement for healthy TR)

The values of the external circuit elements are taken from results of points 1) and 2).

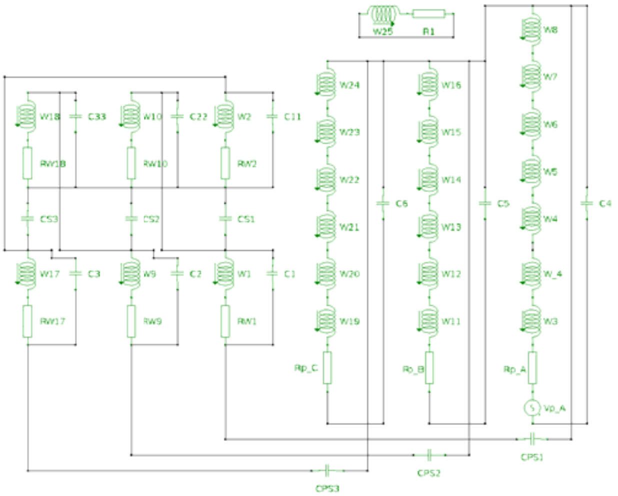

Fig. 6 The external circuit for the harmonic analysis (A-N no-load SFRA measurement for faulty TR)

For the calculation the transformer impedance, the types of windings must be changed from Biot-Savart current sources (used in the magnetostatic simulation) to the circuit element, which is then available for the external circuit. When the winding in 3D FE model is defined as the external circuit element, then this winding can be represented in the model as a volume or as a filament. The filament is set of individual elements stacked in a row, if the gaps between the elements are disregarded, then the elements form an infinitely thin fiber. The filamentary representation of the winding is chosen; because, it does not need to be meshed and so a shorter computational time is needed to solve the 3D FE model.

F. Healthy and Faulty Transformer Models

The healthy transformer models are prepared as described in previous subsection and it is shown in Fig. 7.

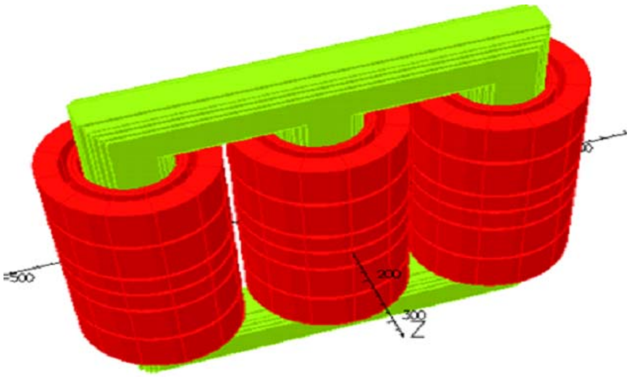

Fig. 7 Model of the healthy transformer TO294-22kV

The faulty transformer models are prepared as the healthy transformer model, but some parts of the model are changed to represent certain types of a fault. In this case, it is parametrized axial short circuit, where the parameters present the position and the range of the short circuit (see Fig. 8).

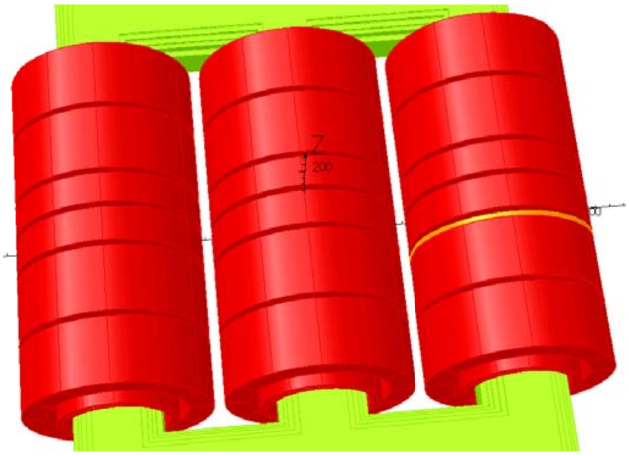

Fig. 8 Model of the faulty transformer TO294-22kV with axial short circuit (orange)

When the axial short circuit is created, the original coil is divided to four parts (see Fig. 9):

- the short circuit layer,
- the part of the original coil in the same layer as the short circuit layer,
- the rest of the original coil,
- the space between the short circuit and the original coil (determined by insulation spacers between coil turns).

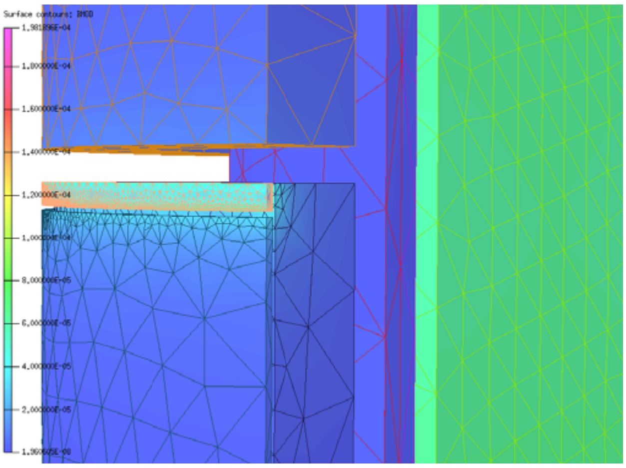

Fig. 9 Distribution of magnetic flux density for the faulty transformer

Then, the external circuit is changed correspondingly (see Fig. 6), where R1 represents the resistance of the short circuit turns, W25 is coupled to the short circuit layer and the original W4 is divided to W4 (with the decreased number of turns) and W_4 (the rest of the original coil). Also the resistance of phase A is decreased.

G. Computing Solvers

As mentioned above, SPECTATOR opens the multitasking strand to solve prepared models, where a static and a harmonic (AC) solvers are used. The static solvers calculate capacities from the models prepared in point 2), the magnetizing and the leakage inductances from the models prepared in point 1) and the harmonic solver uses the external circuit prepared in point 3) to calculate the impedance of the transformer.

H. Handling of Results

When any of FE simulations are completed, then SPECTATOR sends these data to the database, to preserve them, and they are available via user friendly wizard to the user.

III. MATHEMATICAL BACKGROUND OF THE TRANSFORMER PARAMETER CALCULATION

The mathematical background of the transformer parameter calculation is presented in the following subsections. It describes the calculation of the parameters from the magnetic field, electric field and the time varying electromagnetic field distributions.

A. No Load Parameters Calculations

In the magnetostatic simulation, the values of the phase magnetizing currents at certain time instant are used [1]. They are calculated from effective value of the magnetizing current amplitude at the selected time instant. This effective value can be measured or calculated as for example according to the following equation [12]:

$$I_{\mu} = I_N \frac{q_B m_{Fe}}{S_N} \tag{1}$$

where I_N is the nominal current (guaranteed by the manufacturer), q_B is the coefficient of the apparent power losses obtained from $q_B = f(B)$, m_{Fe} is the mass of the transformer core and S_N is the value of apparent power (guaranteed by the manufacturer).

The magnetizing inductance is calculated as follows:

$$L_{\mu} = \frac{|\Psi_A| + |\Psi_B| + |\Psi_C|}{|i_A| + |i_B| + |i_C|} \tag{2}$$

where *I* represents the instantaneous values of the currents, *Ψ* are the flux linkages of each phase. Equation (2) is valid at any time instance (see in [1]).

In normal conditions, the magnetizing inductance depends on the magnetizing current at frequencies 50 or 60 Hz, based on the country of use. But, diagnostic equipments measure impedances in a broad frequency range up to kHz. Therefore, in this model, B-H curve has to be included not only for the common operational frequency but also for higher frequencies range.

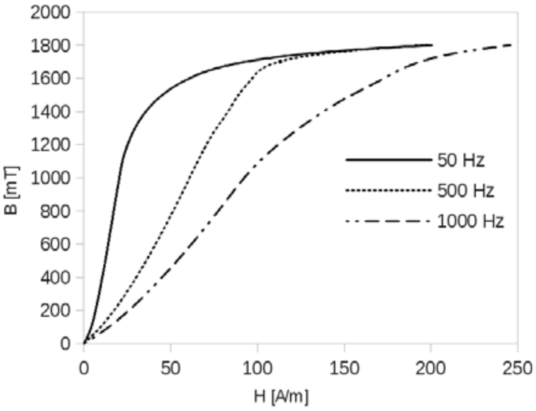

Fig. 10 BH curve for three frequency measured by BROCKHAUS MPG SST 150

The frequency dependent B-H curve (see Fig. 10) is used for the simulation of SFRA measurements to calculate the impedance for 50 Hz and for 1 kHz.

B. Short Circuit Parameters Calculations

The leakage inductance can be calculated either by using the energy of the magnetic field (3) or by multiplying the magnetic vector potential and the current density (4). According to [1], the leakage inductances can be calculated for 3D as follows:

$$L_{\sigma} = \frac{2\int_V \vec{B}\vec{H}\,dV}{i^2} \tag{3}$$

$$L_{\sigma} = \frac{\int_V \vec{A}\vec{J}\,dV}{i^2} \tag{4}$$

where *i* is the instantaneous value of the current in the coil, $\vec{B}$ is a vector of the magnetic flux density, $\vec{H}$ is the vector of a magnetic intensity, $\vec{A}$ is the magnetic vector potential, $\vec{J}$ is the vector of the current density, *dV* is the elementary volume. The first approach can be used if the B-H characteristics of the material is linear (magnetic energy is equal to the magnetic coenergy).

The calculation of the phase resistance R is carried out based on the following equation:

$$R = \rho \frac{2\pi l_{avg} N}{\pi r^2 - \pi\left(r - \sqrt{\frac{2}{\omega\mu\gamma}}\right)^2} \tag{5}$$

where *N* is the number of one phase turns, l_{avg} is the average length of one turn, *r* is the average coil radius, *μ* is the permeability of vacuum, *ω* is the angular speed and *γ* is the specific electrical conductivity of the wire material, *ρ* is the specific resistivity of wire material. This equation takes into account skin effect.

C. Transformer Capacities Calculations

The transformer capacities are obtained by means of the energy of the electrostatic field:

$$C = \frac{2\int_V \vec{E}\vec{D}\,dV}{U^2} \tag{6}$$

where *U* is the electrical potential difference used in the transformer (usually between terminal voltage and ground), $\vec{E}$ is the vector of the electrical field intensity, $\vec{D}$ is the vector of the electric flux density, *dV* is the elementary volume.

D. Impedance of Transformer

The impedance of the transformer is calculated from the harmonic analysis, when the harmonic voltage $\dot{U}$ (voltage on terminals) is divided by current $\dot{I}$ (current in the loop of the voltage source).

$$\dot{Z} = \frac{\dot{U}}{\dot{I}} \tag{7}$$

The impedance is frequency dependent and corresponds to the impedance obtained by SFRA measurement (see Fig. 12).

IV. SIMULATION RESULTS AND EXPERIMENTAL VERIFICATION

The proposed approach is applied to the real power transformer with nameplate: TO294-22kV, Yzn1, 100 kVA, 22/0.4 kV, 50 Hz (see Fig. 11).

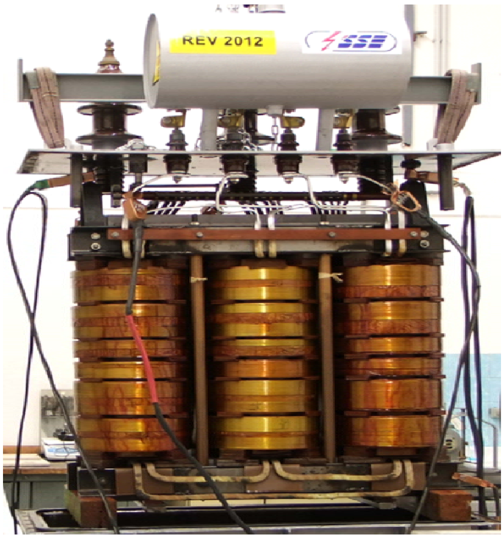

Fig. 11The analyzed transformer TO294-22kV

The healthy transformer equivalent circuit was identified by the no-load, the short-circuit and the capacitance measurements. The frequency dependent impedances (for the healthy and the faulty transformer) were measured by the SFRA. Where the faulty transformer was artificially created by introducing the four turns axial short-circuit on A-phase. In the Fig. 7 the 3D FE model of the healthy transformer can be seen and Fig. 8 shows the faulty transformer. The distribution of electromagnetic field density in a vicinity of the coil with the short circuit is shown in Fig. 9.

The measured value of the magnetizing reactance was 213.97 Ω and the calculated value of the no-load simulation was 185.84 Ω, which represents the deviation -13.14%. The deviation of the measured and calculated values can be explained by the fact that the simulation does not take the third harmonic in the magnetizing current into account and that the magnetizing current was calculated by (1), which values can slightly differ from the realty.

The measured value of the leakage reactance was 205.96 Ω and the calculated value from the simulation was 209.1 Ω. The deviation between the measured and calculated values is only 1.5%, which is attributed to measurement errors.

Comparison of the calculated and the measured values of transformer mutual capacities are shown in Table I.

TABLE I
COMPARISON OF MEASURED AND CALCULATED TRANSFORMER CAPACITIES (HV-HIGH VOLTAGE SIDE, LV-LOW VOLTAGE SIDE, T-TANK OF THE TRANSFORMER)

Measurement	C_{mea} [F]	C_{FEM} [F]	Error [%]
(HV-LV) 22-0,4	9.55E-10	8.17E-10	14.45
(HV-LV+T) 22-0,4+T	1.27E-09	1.19E-09	6.30
(HV-T) 22-T	1.34E-09	1.20E-09	10.45
(HV-LV) 0,4-22	9.56E-10	8.17E-10	14.54
(HV-LV+T) 0.4-22+T	2.46E-09	2.57E-09	-4.47
(LV-T) 0.4-T	1.94E-09	1.87E-09	3.61
(LV+HV-T) 0.4+22-T	1.82E-09	1.88E-09	-3.30
(LV-LV)	-	5.29E-08	-

It can be seen from the table that the error in the measurements of the capacities for the HV is quite large, which may occur due the variation of the insulating material thickness and the material permittivity between the HV and LV windings.

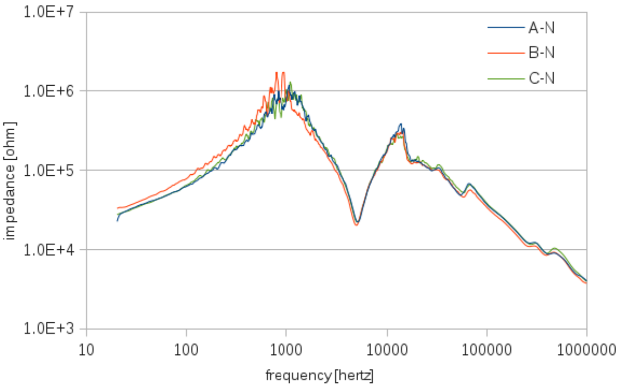

Fig. 12 The SFRA measured values of the transformer impedance versus the frequency for the healthy transformer

The measured values of the transformer impedance versus the frequency for the healthy transformer obtained from the no-load measurement are shown in Fig. 12. The corresponding values, but for the faulty transformer with the axial short circuit on A-phase are in the Fig. 13. Comparing the both figures, the impedance of A-phase of the faulty transformer is clearly different from the corresponding curve of the healthy transformer.

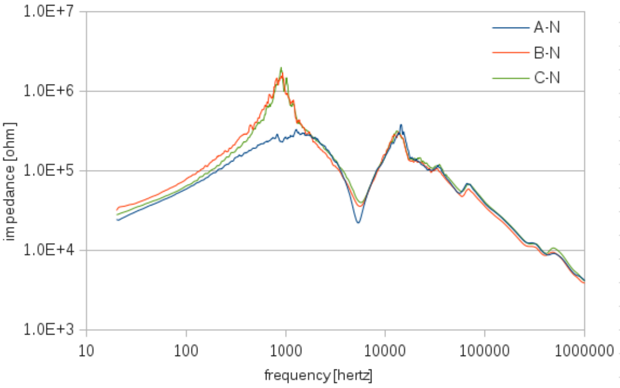

Fig. 13 The SFRA measured values of the transformer impedance versus the frequency for the faulty transformer

The simulation was carried out for the frequencies 50 Hz and 1 kHz. The 1 kHz frequency was selected based on the SFRA measurement. At this frequency, a large difference in the healthy and the faulty impedance is visible. The comparison of the healthy and the faulty transformer impedances is in the Table II.

TABLE II
COMPARISON OF MEASURED (SFRA) AND CALCULATED TRANSFORMER IMPEDANCES

Measurement	f [Hz]	Z_{SFRA} [Ω]	Z_{FEM}[Ω]	Error [%]
A-N (healthy)	50	43306.2	43086.7	0.507
B-N (healthy)	50	50616.4	55751.6	-10.145
C-N (healthy)	50	43121.9	43156.4	-0.080
A-N (short cir.)	50	38882.5	40983.3	-5.403
B-N (short cir.)	50	48995.0	48830.5	0.336
C-N (short cir.)	50	42379.5	45034.1	-6.264
A-N (healthy)	1000	827564.3	821375.4	0.748
B-N (healthy)	1000	762717.4	740407.1	2.925
C-N (healthy)	1000	1032641.1	824320.7	20.174
A-N (short cir.)	1000	265790.5	287649.6	-8.224
B-N (short cir.)	1000	912111.8	798441.4	12.462
C-N (short cir.)	1000	1243408.1	951030.0	23.514

The table contains the values of the transformer impedances for various combinations of phase connections. These values are calculated and measured between one phase (A, B, C) and the neutral point of the transformer (N). The maximal error is between 10% (50 Hz) and 20% (1 kHz). The same analysis was carried out for the faulty transformer. Also there is very good coincidence between measured and simulated values. The error is between 6% (50 Hz) and 23% (1 kHz).

This is caused by the filamentary definition of the windings in the FE harmonic simulations. Such defined winding has a line current defined on the infinitely thin fibers rather than a volume current in the winding. So, it may occur that some mesh elements are not connected to the filaments and therefore these elements are not sources of the line current. This causes slight deformation of the magnetic field and the difference in the measured and the calculated impedances.

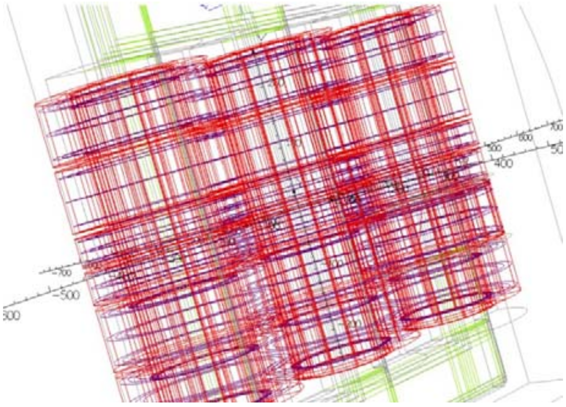

Fig. 14 The filamentary winding of the analyzed transformer

When comparing the results with the filamentary and the volume winging the relative error was reduced by 11.25%. But, the computational time has increased by factor 8 in case of the volume winding.

V. CONCLUSION

The proposed diagnostic approach uses the 3D FE parametrical model and SFRA measurements of the transformer to identify the range and the location of faults caused by an electrical short circuit without disassembling of the transformer. The key parameters of the approach are the parameters of the equivalent circuit and the impedance of the faulty transformer as the function of frequency. The measured and the calculated parameters of the parametrical model are compared until the most resembling model is identified. The results of the comparison show that the identified model of the faulty transformer corresponds to the real faulty transformer. The parameters and all models of the analyzed transformer are stored in the interactive database and are available via user friendly wizard to the used for future purposes as an analysis of different faults of transformers of the same type. The proposed parametrical 3D model is universal and very quickly can be used for other different three phase transformers. Further, this approach can also identify radial short circuits and winging shifts.

Our future work will be focused on an effective replacement of the filamentary windings by the volume mesh windings.

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