

Transformer Diagnosis Based on Coupled Circuits Method Modelling

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Abstract—Diagnostic goal of transformers in service is to detect the winding or the core in fault. Transformers are valuable equipment which makes a major contribution to the supply security of a power system. Consequently, it is of great importance to minimize the frequency and duration of unwanted outages of power transformers. So, Frequency Response Analysis (FRA) is found to be a useful tool for reliable detection of incipient mechanical fault in a transformer, by finding winding or core defects. The authors propose as first part of this article, the coupled circuits method, because, it gives most possible exhaustive modelling of transformers. And as second part of this work, the application of FRA in low frequency in order to improve and simplify the response reading.

This study can be useful as a base data for the other transformers of the same categories intended for distribution grid.

Keywords—Diagnostic; Coupled Circuit Method; FRA; Transformer Faults.

I. INTRODUCTION

TRANSFORMERS are valuable equipment which makes a major contribution to the supply security of a power system. So the diagnostic methods are systematically being improved and extended due to growing requirements for reliability of power systems in terms of uninterrupted power supply and avoidance of blackouts. Hence, the detection of winding faults in transformers, during exploitation is an important aspect of power transformer failure prevention.

If a transformer is inflicted by a fault, it is necessary to take it out of service as soon as possible in order to minimize the expected damage. The cost associated with repairing a damaged transformer is very high. An unplanned outage of a power transformer can cause a very important socio-economical prejudice.

Consequently, it is of great importance to minimize the frequency and duration of unwanted outages of power transformers. The defects which lead to put the transformers in out of service have various natures; in our work we are interested in those of the electric type, which affect the

winding circuit. Because investigation shows that transformer failures are caused by internal winding short-circuit faults. One important reason for these faults is erosion of the winding and conductor insulation due to vibrations initiated by the electromechanical forces at service current and over currents.

In the majority of the cases, the transformers are put out of service by their protection systems, which react only if the transformer undergoes a serious incident, such as; transformer differential protection which contains a number of additional functions (matching to transformation ratio and vector group, restraint against inrush currents and over-excitation). Therefore it requires some fundamental consideration for configuration and selection of the setting values. Optimum design of the transformer protection ensures that any faults that may occur are cleared quickly and possible consequential damage is minimized.

II. TRANSFORMER FAULTS DETECTION

The partial internal winding short-circuit faults leads to over-current in windings that result terrible damages such as severe hot-spots, oil heating, winding deformation, damage to the clamping structure, core damage, and even explosion of transformer.

The ideas is to detect faults at there embryonic states. And, is conditioned neither by the transformer Plug off (disconnection) nor by its operation mode. So, Frequency Response Analysis (FRA) is found to be a useful tool for reliable detection of incipient mechanical fault in a transformer, by finding winding or core defects. It is a powerful and sensitive method to evaluate the mechanical integrity of core, windings and clamping structures within power transformers by measuring their electrical parameters in a wide frequency range. Thus, contribute to maximum supply security, and to avoid expensive unexpected outages.

The transformer high voltage side supplied by a low frequency voltage choc generates voltage impulsion at its secondary side. The measured signals gains and frequencies are compared to those of a healthy winding.

In the major works the FRA is tested by injecting a sinusoidal excitation voltage with a continuously increasing frequency [9,11]; the authors propose to inject a triangular excitation voltage for one appropriate frequency. The comparison of input and output signals generates response which can be compared to reference data. Deviations indicate geometrical and/or electrical changes within the transformer.

The FRA is a comparative method, i.e. an evaluation of the transformer condition is done by comparing an actual set of FRA results to reference results. Three methods are commonly used to assess the measured traces:

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1. FRA results will be compared to previous results of the same unit
2. FRA of one transformer will be compared to a type-equal one
3. FRA results of one phase will be compared to the results of the other phases of the same transformer

III. COUPLED CIRCUIT METHOD

The windings belong to the active part of a transformer, and their function is to carry current. The windings are arranged as cylindrical shells around the core limb Fig. 1. In several works, one considers that the electromagnetic coupling of a winding coil of a phase is perfect; consequently, they make an equality approximation between self and mutual inductance unit.

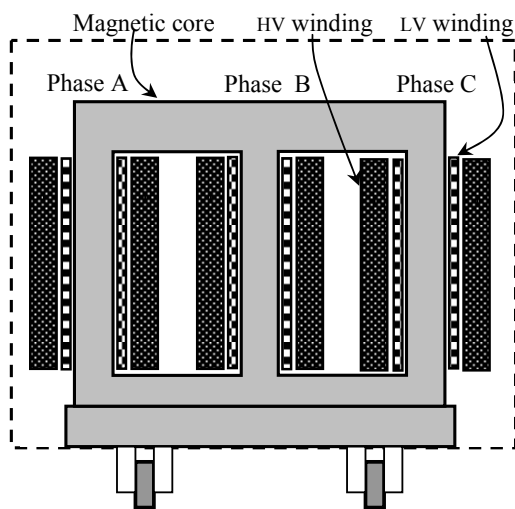


Fig. 1 Transformer architecture

Spectral analysis method is based on a very complete modelling of the transformers by taking in account electromagnetic and electrostatic fields (Fig. 2).

The analysis and the detection of faults are based on reference data and harmonics signature. Therefore, the transformer is divided into several portions of windings (coils); one has to consider then, several circuits in interactions [6]. Each element in defect found its own harmonic signature; this means, the reading and analysis defects became more complex; generally require artificial intelligence, such as the neuron networks or fuzzy logic [5].

The elements which make the study more complex are the condensers, which are the consequence of the electrostatic field. Their effect is much highlighted in high frequency, for this reason the authors propose to reduce their effect, while working not into high but rather low frequency (in our case 5 Hertz) consequently the model is reduced to the Fig. 2 (b).

The temporal and space variations of all the laws of electricity obey to Maxwell's equations [4], e.g. the electromagnetic waves.

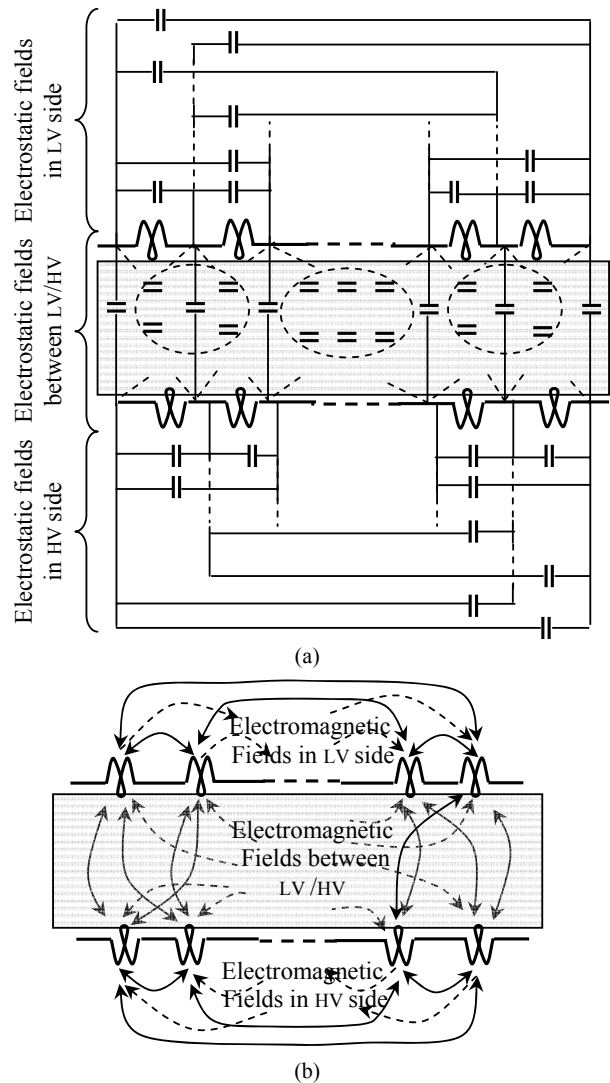


Fig. 2 Internal interactions of coils in the transformers
(a) electrostatic interactions (b) electromagnetic interactions

The effects of skin and proximity [3] are the consequences of fields induced in a coil by itself or by the nearest coils Fig. 3. This effect can be expressed in the form of self and mutual inductances [1].

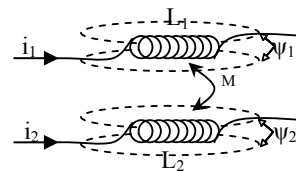


Fig. 3 Effect of self inductances and mutual

Then magnetic flux ψ_1 created by coil 1 has as expression (1):

$$\psi_1 = L_1 i_1 + M i_2 \quad (1)$$

Where, L_1 and M are respectively, self and mutual inductance. If a coil in addition to its own field, is surrounded by one or

more other coils [10] Fig. 2(b), in this case they interact through inductances known as mutual ($M_{k,j}=M_{i,k}$). This interaction can be put in equation thanks to several theories such as the finite element method, fuzzy logic, etc....[2,8] we choose in our study the coupled circuits method [7], which has as an advantage, the possibility of an analytical development,

as it is shown bellow. Moreover, it gives most possible exhaustive modelling of transformers.

Electro-magnetic fluxes of all coils in primary and secondary side of transformer ψ vs. current relationship are given by (2).

$$\begin{bmatrix} \psi_1^p \\ \psi_2^p \\ \vdots \\ \psi_N^p \\ \psi_1^s \\ \psi_2^s \\ \vdots \\ \psi_M^s \end{bmatrix} = \begin{bmatrix} L_0^p & M_{1-2}^p & \cdot & \cdot & M_{1-N}^p & M_{1-1}^{p-s} & M_{1-2}^{p-s} & \cdot & \cdot & M_{1-M}^{p-s} \\ M_{1-2}^p & L_0^p & \cdot & \cdot & M_{2-N}^p & M_{2-1}^{p-s} & M_{2-2}^{p-s} & \cdot & \cdot & M_{2-M}^{p-s} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ M_{1-N}^p & M_{2-N}^p & \cdot & \cdot & L_0^p & M_{N-1}^{p-s} & M_{N-2}^{p-s} & \cdot & \cdot & M_{N-M}^{p-s} \\ M_{1-1}^{p-s} & M_{1-2}^{p-s} & \cdot & \cdot & M_{1-N}^{p-s} & L_0^s & M_{1-2}^s & \cdot & \cdot & M_{1-M}^s \\ M_{1-2}^{p-s} & M_{2-2}^{p-s} & \cdot & \cdot & M_{2-N}^{p-s} & M_{1-2}^s & L_0^s & \cdot & \cdot & M_{2-M}^s \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ M_{1-M}^{p-s} & M_{2-M}^{p-s} & \cdot & \cdot & M_{N-M}^{p-s} & M_{1-M}^s & M_{2-M}^s & \cdot & \cdot & L_0^s \end{bmatrix} \begin{bmatrix} I^p \\ I^p \\ \vdots \\ I^p \\ I^s \\ I^s \\ \vdots \\ I^s \end{bmatrix} \quad (2)$$

The field generated by the first coil of the primary winding and the first coil of the secondary winding is respectively:

$$\left. \begin{aligned} \psi_1^p &= L_1^p \cdot I^p + \sum_{n=1}^N M_{1-n}^p \cdot I^p + \sum_{m=1}^M M_{1-m}^{p-s} \cdot I^s \\ \psi_1^s &= L_1^s \cdot I^s + \sum_{n=1}^N M_{1-n}^{p-s} \cdot I^p + \sum_{m=1}^M M_{1-m}^s \cdot I^s \end{aligned} \right\} \quad (3)$$

And, the field generated by the primary and the secondary winding is respectively:

$$\left. \begin{aligned} \psi^p &= \sum_{n=1}^N \psi_n^p \\ &= \left(\sum_{n=1}^N L_n^p + \sum_{n=1}^N \sum_{m=1}^M M_{n-m}^p \right) \cdot I^p + \sum_{n=1}^N \sum_{m=1}^M M_{n-m}^{p-s} \cdot I^s \\ \psi^s &= \sum_{m=1}^M \psi_m^s \\ &= \sum_{m=1}^M \sum_{n=1}^N M_{m-n}^{p-s} \cdot I^p + \left(\sum_{m=1}^M L_m^s + \sum_{m=1}^M \sum_{n=1}^M M_{m-n}^s \right) \cdot I^s \end{aligned} \right\} \quad (4)$$

One defines self inductances of the primary and secondary winding as follows

$$\left. \begin{aligned} L^p &= \sum_{n=1}^N L_n^p + \sum_{n=1}^N \sum_{m=1}^M M_{n-m}^p \\ L^s &= \sum_{m=1}^M L_m^s + \sum_{m=1}^M \sum_{n=1}^M M_{m-n}^s \end{aligned} \right\} \quad (5)$$

On the other hand, the total mutual inductance between the primary and the secondary winding is:

$$M^{p-s} = \sum_{m=1}^M \sum_{n=1}^N M_{m-n}^{p-s} \quad (6)$$

So, the relation (2) can be simplified to (7):

$$\begin{bmatrix} \psi^p \\ \psi^s \end{bmatrix} = \begin{bmatrix} L^p & M^{p-s} \\ M^{p-s} & L^s \end{bmatrix} \begin{bmatrix} I^p \\ I^s \end{bmatrix} \quad (7)$$

An inductance depends on the form and dimensions of its coil. In our case it is circular axisymmetric ($2.r^p$ the primary diameter winding, $2.r^s$ the secondary diameter winding, & $2.r_w$ the wire diameter). Relations (8) respectively define the self inductance of the primary and secondary.

$$\left. \begin{aligned} L_0^p &= \mu \cdot r^p \cdot \left[\ln\left(\frac{8 \cdot r^p}{r_w^p}\right) - \frac{7}{4} \right] \\ L_0^s &= \mu \cdot r^s \cdot \left[\ln\left(\frac{8 \cdot r^s}{r_w^s}\right) - \frac{7}{4} \right] \end{aligned} \right\} \quad (8)$$

With regard to the mutual, we separate them into two:

- between the coils of the same winding fig.4, e.g the relation (9) for the primary winding,

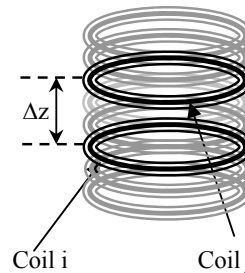


Fig. 4 The mutual between the coils of the same winding

$$M_{i-j}^p = \frac{\mu \cdot 2 \cdot r^p}{k_p} \cdot [(1 - k_p^2) \cdot IE_1(k_p) - IE_2(k_p)] \quad (9)$$

$$\text{Where, } k_p = \frac{2 \cdot r^p}{\sqrt{(2 \cdot r^p)^2 + \Lambda z^2}}$$

- And the other between the primary and the secondary winding of the same phase Fig. 5 (10) (the windings are taken coaxial).

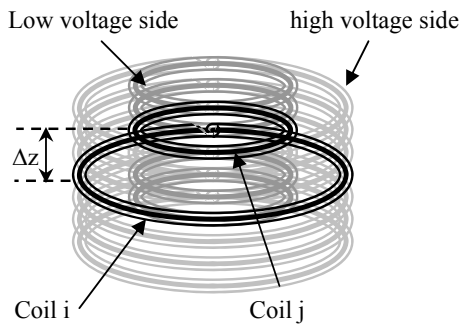


Fig. 5 The mutual between HV& LV winding coils of the same phase

$$M_{i-j}^{p-s} = \frac{\mu \cdot 2 \cdot \sqrt{r^p \cdot r^s}}{k_{ps}} \cdot [(1 - k_{ps}^2) \cdot IE_1(k_{ps}) - IE_2(k_{ps})] \quad (10)$$

$$\text{Where; } k_{ps} = \frac{2 \cdot \sqrt{r^p \cdot r^s}}{\sqrt{4 \cdot (r^p + r^s)^2 + \Lambda z^2}};$$

$$\text{And; } \Lambda z = |i - j| \cdot r_w$$

IE_1 and IE_2 are the integral elliptic of the first and second kind respectively.

Relations (8, 9, 10) allow an exact parameterization, which depends on the position, in addition to the coils shape.

IV. SIMULATION MODEL

We tested several form of choc voltages: sinusoidal, square, triangular, down saw tooth, up saw tooth, and this last which was retained, considering the clearness of its harmonic responses, at the internal transformer defects:

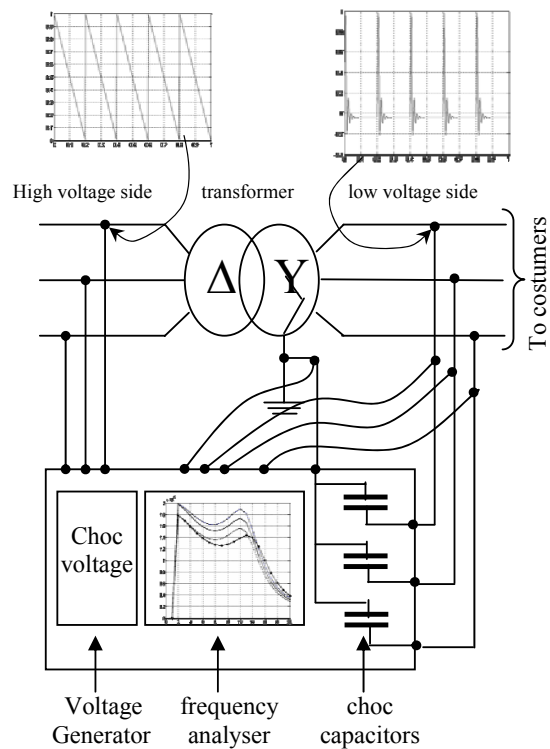


Fig. 6 Proposed model

To analyze the health of our transformer one excites it by the preset choc wave under low frequency. Consequently, one eliminates the capacitive effect inside the transformer and diagnoses can be done with the transformer in service. Since, in this case the equivalent impedance of the consumers will have only an attenuator effect. Thus the electrical equation can be summarized as follow:

$$\left. \begin{aligned} u^p &= d\psi^p / dt + R^p i^p \\ u^s &= -d\psi^s / dt - R^s i^s \\ u^s &= \frac{1}{C} \int i^c dt \end{aligned} \right\} \quad (11)$$

One makes the difference between the instantaneous parameters by the capital letters and the RMS values by the small letters.

V. SIMULATION RESULTS AND DISCUSSION:

During simulation the authors compare the frequency analysis of the healthy state "star plot" with the fault cases.

Defects considered for different percentage of coils in short circuit, compared to the total number of winding:

- defects of the primary winding Fig. 7(a)
- defects of the secondary winding Fig. 7(b)
- defects of the core Fig. 7(c)

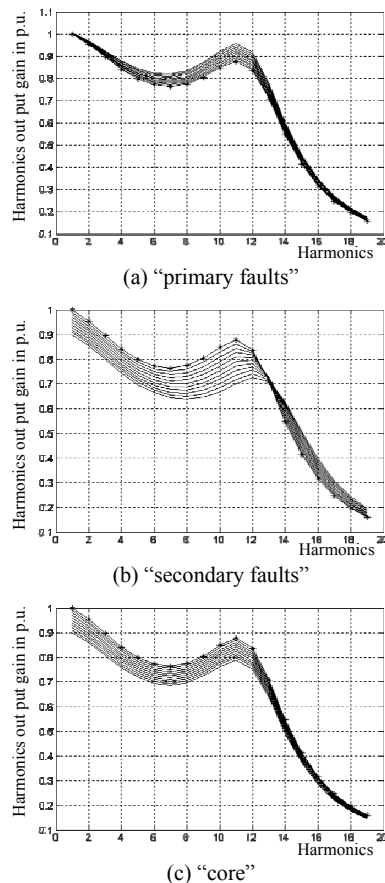


Fig. 7 Frequency analyser for different number of coils in fault

In low frequency as it's the case in this work, harmonics angles are not significant in faults identification.

If frequency analyser spectrum gain is above the reference data the faults are located at the primary side Fig. 7(a). But if they are under the reference data, for low frequency, and above, for high frequency the faults are located in the secondary side Fig. 7(b). If the gain frequency is under reference data for all recorded frequency the faults are located in the core Fig. 7(c). The number of coils in fault can be estimate by deviation quantity of the gain compared to the reference one

VI. CONCLUSION

We estimate, that the diagnostic goal of transformers in service, is to detect the winding or the core in fault, but it is not necessary to encumber the module of treatment, by other

equations (then other circuits) for the exact localization of the defect point, which can be dealt with in the second phase of maintenance. Thus diagnostic is used in order to take a decision of assumption about the degree and urgency of the defect.

This study can be useful as a bases data for the other transformers intended for distribution grid. Considering that they have a same category (rate power, voltages & frequency) and sizes (windings and core dimensions).

The coupled circuits method proved as a powerful proceeding of modelling, and the results given by FRA in low frequency provide a simple and direct analysis of eventual internal defects.

REFERENCES

- [1] S. Babic, S. Salon, C. Akyel, "The Mutual Inductance of Two Thin Coaxial Disk Coils in Air", IEEE Transactions on Magnetics, vol. 40, n° 2, March 2004, pp. 822-825.
- [2] V.P. Bui, Y. Le Floch, G. Miller and J-L. Coulomb, "A New Three-Dimensional (3D) Scalar Finite Element Method to Compute T0", IEEE Transactions on Magnetics, vol. 42, n° 4, April 2006, pp. 1035-1038.
- [3] F. Groh, D. Beck, W. Hafla, A. Buchau and W. Mr. Rucker, "Calculating Exciting Fields Using the Fast Multi-pole Method and Integral year Transformation to the Coil Surfaces", IEEE Transactions on Magnetic, vol. 41, n° 5, May 2005, pp. 1384-1387.
- [4] S. Bouissou, F. Piriou, "Comparison Between Two Formulation in Terms of Potential for the Coupling of Magnetic and Electric Circuit Equations", IEE Proceeding in Science, Measurement and Technology, vol. 141, n° 6, November 1994, pp. 486-490.
- [5] Y. Le Floch, G. Miller, C. Guerin, P. Labie, X. Brunotte and D. Boudaud, "Coupled Problem Computation of 3D Multiply Connected Magnetic Circuits and Electric Circuits", IEEE Transactions on Magnetics, vol. 39, n° 3, May 2003, pp. 1725-1728.
- [6] C.W. Trowbridge, J.K. Sykulski, "Nap Key Developments in Computational Electromagnetic and Their Attribution", IEEE Transactions on Magnetic, vol. 42, n° 4, April 2006, pp. 503-508.
- [7] V. Doirat, G. Berthiau, J. Fouladgar and A. Lefèvre, "EC. Modelling by Coupled Circuits Method Considering the Skin and Proximity Effects", the 11th International Workshop on Electromagnetic Non-destructive Evaluation (ENDE'06), Japan, June, 2006.
- [8] J. Gyselink, R.V. Sabariego and P. Dular, "Time-Domain Homogenization of Windings in Two-Dimensional Finite Models Element", the 12th biennial Conference on Electromagnetic Field Computation (CEFC'06), Miami, Florida, the USA, April 30th-May 3rd 2006.
- [9] Marek Florkowski et al "Transformer winding defects identification based on a high frequency method" 2007 Meas. Sci. Technol. N° 18 2827-2835.
- [10] Mr. Arturi, Mr. Ubaldini, Eddy current loss and coil inductance evaluation in dc machines by a PC-based f.e code, IEEE Transactions on Magnetic vol.27 n°5, 1991 pp. 4129-4132.
- [11] Meshal Al-Shaher; Mohamed Saied "Recognition and Location of Transformer Winding Faults Using the Input Impedance" Electric Power Components and Systems, Volume 35, n° 7 July 2007, pages 785 – 802.