POWER TRANSFORMERS EVALUATION USING A DIGITAL MODEL OBTAINED FROM TERMINAL IMPEDANCE MEASUREMENTS

L. M. de A. Coutinho[1]
H. J. A. Martins[2]
G. M. V. Zambrano and A. C. Ferreira[3]
[1]Petrobras Distribuidora
[2]Electric Power Research Center, CEPEL
[3]Federal University of Rio de Janeiro, UFRJ
*email: leonardoufrj@gmail.com

Abstract: This work shows a developed method that estimates the parameters of an electrical equivalent circuit of the power transformer from its tests of terminal impedance. Using the developed method is possible to adjust an electrical equivalent circuit that reproduces the measurements reflecting the real conditions in which the equipment is operating. So it can be performed a sensitivity analysis in electrical calculated parameters by checking the correlations involving changes in the core, windings and connections with the regions of the terminal impedance curves.

1 INTRODUCTION

Power transformers are important and complex equipment that compose the electrical system and due these characteristics need more and more refined evaluation and diagnosis methods. One emerged method for evaluating the integrity of these equipment is the frequency response analysis, where each power transformer has its own fingerprint, associated with its natural's resonances and anti-resonances. This method is effective for diagnosing windings movements, which can evolve into a defect, while other methods were not as effective in this case.

The test frequency response that this work refers is the terminal Impedance test, where the relationship between the modules implemented and measured signal (voltage and current) and phase difference between the measured signal and applied in the measurement of input impedances of the windings of a transformer.

The terminal Impedance test is conducted measuring the impedance of power transformer windings by injecting a voltage signal at one end of the winding and measuring the corresponding current signal. While measuring winding terminal impedance the others normally remain opened.

In general the signal applied is a voltage, subject to a transformer winding, while the measuring equipment (bridge circuit) measures a current through the other end of winding. The applied voltage may be considered at its angle in the reference and the current is measured with magnitude and lag angle. The frequency ranges from 20 Hz to 10 MHz, through at least about 200 measurement points throughout this frequency range. The measuring points should be well distributed for each decade of frequency, detecting influences of high and low voltage windings, the core and connections.

Usually the number of measurements to be performed depends on the number of windings, for example, for a three-phase transformer, are held at least six measurements, one for each winding.

This kind of test has been extensively explored in literature, but there is some difficulty in evaluation quantitatively the results obtained. Based on this fact, this paper search to develop a way to estimate the electrical parameters of the equipment, such as resistance, capacitance and inductance, supporting a transformer modelling, aiming their use for diagnosis and prognosis purposes. In this case, the transformer model electrical parameters were adjusted with the same order of magnitude of those of a real transformer, so it is possible to simulate some behaviours of the equipment with some changes in the parameters.

2 EQUIVALENT CIRCUIT

The evaluation of power transformers studied in this work is based on identification of natural's resonances and anti-resonances of the equipment. It intends to correlate with the winding deformation; short-circuits and other common defects, due to these tests are sensitive to changes occurring in the electrical parameters of windings, core, electrical insulation, internal connections to tank and bushings. To better understand the changes in these parameters, and considering its constructive aspects, the transformer can be modelled as a set of capacitances and inductances.

The windings are energized with different voltages due to nominal ratio of the transformer, while the core and the tank are grounded, causing the capacitive effect between the windings, tank and core. This network of capacitances and inductances inherent in the windings change along the transformer geometry, causing several resonance frequencies characteristics of each equipment tested in the frequency domain. These network elements can be studied mathematically to simplify this geometrically complex circuit in a lumped equivalent circuit.

This form of modelling is equivalent to the transformer with its coils distributed in various PIs (π), composed with a series capacitance (Cs), the capacitance between two turns or coils, the inductance (L) and resistance (R). The capacitance between windings and tank or between windings, defined as Geometric capacitance (Cg), to represent the couplings between adjacent structures. The π model used is shown in Figure 1.

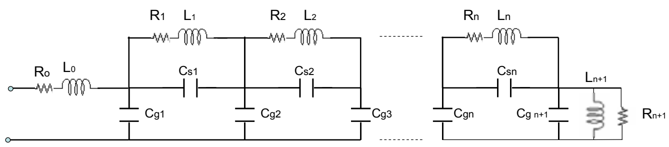

Figure 1 – Equivalent circuit of a monophase power transformer

The copper losses in this model are represented by resistors in series with inductances. The core is modelled as a resistance in parallel with an inductance, called resistance and inductance of magnetization.

Using an equivalent circuit that models approximately the transformer behaviour it is possible simulate and compare with those observed in real equipment, supporting the diagnosis of possible defects.

3 METHODOLOGY

The method used in this report to calculate the power transformer's equivalent circuit was the Gradient Descent, allowing the optimization of objective functions related to impedance amplitude and angle in function of frequency, in the high and low voltage windings. By optimizing these four objective functions it was possible to determine the electrical equivalent circuit that reproduces the measured curves in the frequency domain, with a sufficient approximation degree.

This method has the advantage of estimating equivalent electrical parameters for the main components of the transformer (core, high and low voltage windings, connections), resulting in a circuit that responds to real measurements, and from this circuit it is possible to reconstruct the terminal impedance measurements curves. Thus it is possible to analyze quantitatively by changes in electrical parameters of equivalent circuit the effect of variations in each component of transformer and check the influence on their estimated curves as well as associate a type of defect.

This developed methodology firstly try to estimate the parameters of equivalent electric power transformer (circuit synthesis) and, through these parameters, estimate its equivalent terminal impedance curve by Gradient Descendent, based on comparison the data from terminal impedance measurements of high and low voltage windings of the transformer to be modelled.

To use the Gradient Descendent method to calculate the electrical parameters of a transformer four objective functions need to be minimized. It was used data from terminal impedance for both high and low voltage windings together with the phase measurements for both windings, considering a frequency range previously defined. The four objective functions are described in the equations below.

$$F_{|z_h|} = \frac{1}{N_{|z_h|}} \sum_{1}^{n\omega} \varepsilon_{|z_h|}^{2} \qquad (1)$$

$$F_{|\theta_h|} = \frac{1}{N_{|\theta_h|}} \sum_{1}^{n\omega} \varepsilon_{|\theta_h|}^{2} \qquad (2)$$

$$F_{|\theta_x|} = \frac{1}{N_{|\theta_x|}} \sum_{1}^{n\omega} \varepsilon_{|\theta_x|}^{2} \qquad (3)$$

Where Zh and Zx are amplitude of high and low voltage windings impedance respectively. “θ_h” and “θ_x” are phase angles measured in high and low voltage windings of the same test impedance terminal. “N” is the number of frequencies considered and “□” is the error, which can be defined by the following equations:

$$\varepsilon_{|z|}(j\omega) = |Z(j\omega)| - |\tilde{Z}(j\omega)| \qquad (4)$$

$$\varepsilon_{|\theta|}(j\omega) = |\theta(j\omega)| - |\tilde{\theta}(j\omega)| \qquad (5)$$

To apply Gradient Descendent method is necessary to transform these four objective functions into a single function, which is the weighted sum of four previously described. This multi-objective function is defined in the following equation.

$$F = \gamma_1 \cdot F_{|Z_h|} + \gamma_2 \cdot F_{|Z_x|} + \gamma_3 \cdot F_{|\theta_h|} + \gamma_4 \cdot F_{|\theta_x|} \qquad (6)$$

An iterative process was used to minimize the gradient value, because at the minimum, the gradient function value is null or has a too small numeric value. The goal is to use an iterative reduction of gradient value, expecting a converging value close to zero, or equal to a predetermined tolerance. The calculation in the next iteration is modified proportionally to the change in gradient of the objective function.

The methodology follows a sequence from the initial values, with the calculation of the errors and objective functions values, producing results that are inserted in new calculations, according to the flowchart in Figure 2.

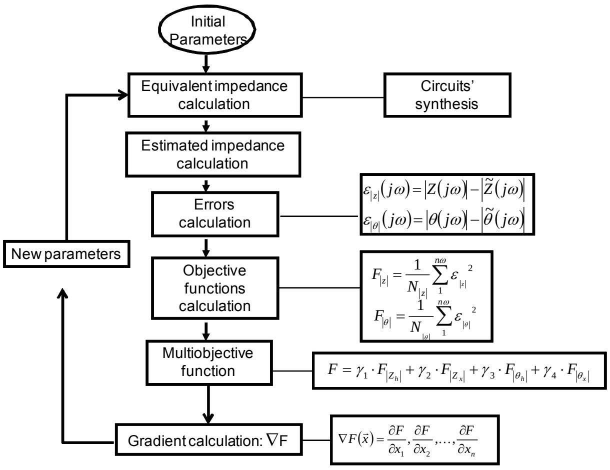

Figure 2 – Methodology flowchart

4.0 - EFFECT OF INTERNAL DEFECTS IN TRANSFORMER TERMINAL IMPEDANCE

Using the electrical equivalent circuit of the power transformer, changes can be made in one or more components, and plotting frequency response curves, the effects can be verified, allowing a sensitivity analysis. It is possible to obtain a correlation between each frequency range of the curves and changes in transformer components like core, windings, connections, etc. Knowing the correlation between equipment parameters changes and the corresponding effects it is possible to determine the kind of defect and possible location.

In Figure 3, it is shown how a variation in core inductance affects the region of low frequencies around the first resonance of the graph. In this case where the core inductance was reduced by 50%, as expected, the first part of de curve is shifted to the right and there was an increase in resonance frequency because this frequency is inversely proportional to the inductance value, as the following equation:

$$\omega = \frac{1}{\sqrt{LC}} \quad (7)$$

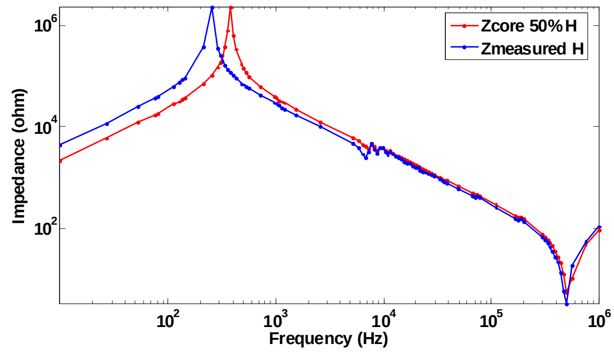

Figure 3 - Terminal impedance amplitude behaviour with core inductance reduced by 50%

With the aim of studying the effect of core resistance, its original value was varied, but the changes become only visible when its value was changed to 15% of its original one. Figure 4 shows the results of core resistance variation.

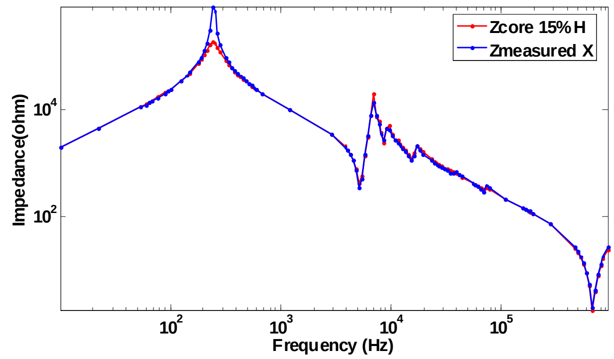

Figure 4 – Terminal impedance amplitude behaviour with core resistance in 15%

To understand the effect of winding connections in the terminal impedance a 60% reduction in the inductance was made. Changes in high frequency region are noted, as shown in Figure 5.

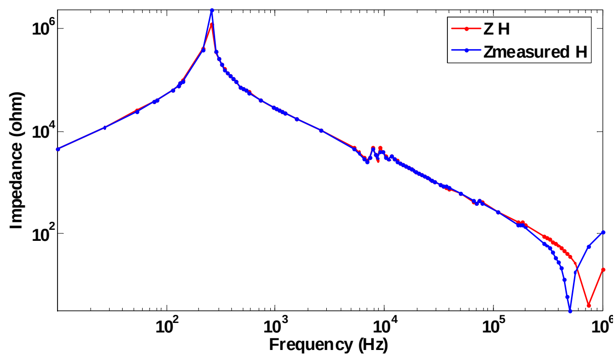

Figure 5 – Terminal impedance module with the inductance of connections reduced by 60%

As previously observed, the high frequency region, around the latest anti-resonance, is responsible for changes in winding connections, test equipment connections and bushing effects. As expected, a reduction in inductance causes an increase in anti-resonance frequency, since this frequency is inversely proportional to inductance, as in following equation:

$$\omega = \frac{1}{\sqrt{L(C_S + C_g)}} \quad (8)$$

To obtain a sensitivity analysis of transformer winding displacement, a variation in geometric capacitance value was made in one of high voltage PI, near the transformer core. The capacitance in this region was increased nine times, causing visible modifications, as showed in Figure 6.

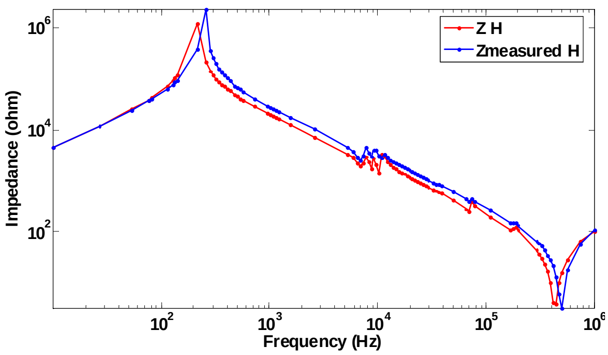

Figure 6 – Geometric capacitance increasing of a coil

Even if the variation of this capacitance has been made in high voltage winding, although not showed, this effect is reflected to the low voltage winding, there is also a shift in the curve of low voltage winding impedance terminal.

It is also noted that in the high-voltage terminal impedance curve, where it was made a change in geometric capacitance value, there is also a magnitude variation in the whole curve.

Although not showed, it is important to note, the copper losses, which are the inherent resistance of windings were modeled as a lumped parameter, a resistor in series with an inductor. The variation of these resistances does not cause any displacement of impedance terminal curve, just modifications in amplitude of resonant peaks.

4 REMARKS AND CONCLUSIONS

From the developed model, it is possible to change electrical parameters, to perform simulations in order to understand the effect these parameters cause in the frequency response. These simulations intended to recreate practical defects, simulating real situations, normally found in a power transformer during its operation.

Modelling of power transformers windings by lumped or distributed parameters is well known in literature, where these parameters are estimated using data from the internal geometry of equipment, such as distance between its components, characteristics of its materials and its variation with frequency. In the methodology studied in this work it is possible to estimate the parameters of a lumped pis (π) transformer model, from the terminal impedance test.

The great advantage of this method is the possibility of modelling other windings simultaneously, noting the effects of a winding relative to other, enabling more accurate results by checking the interaction between windings.

The calculated electrical equivalent circuit parameters have the same order of magnitude of a real transformer, making it possible to reproduce the behaviour of a power transformer in the frequency domain due to changes in main components. By varying the equivalent circuit is possible to associate the region of low frequencies to core changes, defects of inductive origin. In the region of medium frequencies dominate the effects in windings and in the high frequencies one, are mainly influenced by changes in connections (cables and even measuring circuits) of the transformer, as shown in Figure 7.

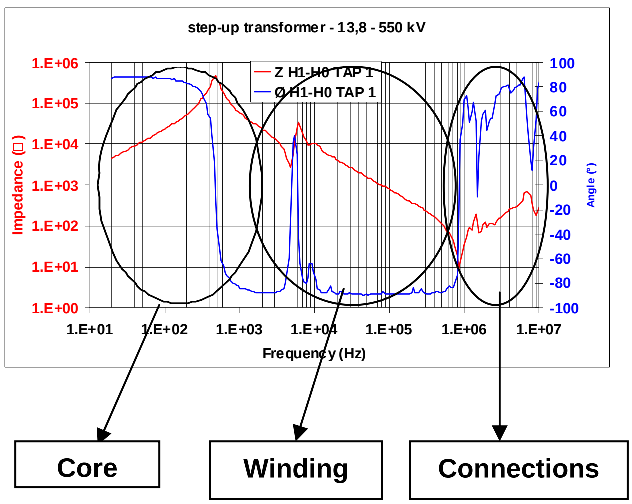

Figure 7 – Main frequency ranges for diagnostic purposes

According to the defect simulations, longitudinal parameters as inductance, series capacitance, and resistance affect the terminal impedance curve vertically, causing amplification or attenuation to the corresponding pole values. The transverse parameters such as geometric capacitance modify directly the position of resonance frequencies, not influencing so much the amplitude terminal impedance curve.

This methodology will help to validate the relationship between the parameters of power transformers and main types of defects, as well as implementation of defects of mechanical or electrical characteristics. Help to perform analysis of defects or faults from changes in equivalent circuit, or application of defects in different locations of transformer, allowing a sensitivity analysis according to change of its electrical parameters.

5 REFERENCES

[1] L. M. de A. Coutinho, “Power transformer modelling using frequency domain techniques”; M.Sc. Dissertation, Coppe/UFRJ, Rio de Janeiro, RJ, Brazil, 2010 (in Portuguese)

[2] G. M. V. Zambrano, “Identification of parameters of power transformer equivalent circuit”; D.Sc. Thesis, Coppe/UFRJ, Rio de Janeiro, RJ, Brazil, 2009 (in Portuguese)

[3] H. J. A. Martins, “Diagnostic of power transformers using frequency domain techniques”; D.Sc. Thesis, Coppe/UFRJ, Rio de Janeiro, RJ, Brasil, 2007 (in Portuguese)

[4] K. Karsai, D. Kerenji, L. Kiss, “Large Power Transformer” (Studies in Electrical and Electronic Engineering, Vol 25), Elsevier Company, New York, 1987

[5] L. F. Blume, A. Boyajian, G. Camilli, T.C. Lennox, S. Minecci, V. M. Montsinger, “Transformer Engineering”, 1a. Edition, John Wiley & Sons, Inc., New York, 1938.