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A novel methodology for transformer low-frequency model parameters identification

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ABSTRACT

This paper describes a novel methodology to estimate the parameters of a low-frequency model of a 3-phase transformer, by only using data from its frequency response. The described calculation procedure takes into account the magnetic coupling among different phases and allows their analysis separately, enabling the identification of a possible failure. This work describes the used core model, the procedure to obtain its parameters, and its application when interpreting the low frequency results of the Frequency Response Analysis (FRA) measurements.

1. Introduction

The Frequency Response Analysis (FRA) is a sensitive technique for evaluating the mechanical integrity of transformers by measuring either their electrical transfer function or impedance over a wide-frequency bandwidth [1]. Failure detection by using the FRA technique is mainly based on the graphical comparison of curves obtained when plotting the measured responses in different stages of the transformer life cycle. The frequency response of the transformer is obtained in a reference state, usually after manufacturing, when a healthy condition is supposed. Then the same transformer is measured in an evaluation state when a possible faulty condition is suspected. The variation between the reference and evaluation curves can point to a possible failure.

However, quantification and localization of damage cannot be assessed with the degree of accuracy needed for diagnosis and decision making. To solve this task several researchers propose methodologies to interpret the FRA curves [2–5]. Alternatively there are proposals which suggest using a transformer model to interpret the measured frequency response. Additionally international organizations have recommended the use of models to face this difficulty [6–9]. The transformer can be modeled as an electrical network of R, L, and C parameters [10–13] whose values can be calculated to match the same frequency response that the transformer presents. Considering this similarity, any change in the transformer's internal geometry, like winding displacement and/or deformation, will become a variation in the frequency response and hence, a change in the parameter's value. Therefore a possible failure can be detected, quantified and located by an inspection of the R, L, and C parameter variations between reference and evaluation states.

There are several works concerning transformer modeling for FRA interpretation distinguished by aspects like model structure and analyzed phenomena [14–17]. This contribution follows the methodology exposed in [18], and develops a transformer model that operates in the low-frequency bandwidth, obtained from the measured response curve data. The model allows the interpretation of response curve in the low frequency bandwidth which is usually 20–10 kHz.

Section 2 describes the transformer's magnetic core circuit. Section 3 describes the model structure. Sections 4 and 5 describe the mathematical procedure to calculate the parameters' value. Finally, Section 6 contains the experimental results obtained by applying the methodology to a power transformer.

2. Magnetic circuit

Transformers are made up of a magnetic circuit formed by laminated steel sheets on which the windings are wound. Power

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transformers are usually built core-type with three-limb. Each winding is wound on each magnetic core limb as shown in Fig. 1.

The FRA method consists in measuring the transformer's electrical equivalent impedance, over a wide-frequency bandwidth using a low voltage sinusoidal wave. The amplitude and phase of the measured impedance is plotted versus frequency. The transformer impedance can be measured in different conditions and through different accessible terminals, forming four types of test. In this paper only end-to-end open circuit test is treated.

In the end-to-end open circuit test, the signal is applied to one end of winding (Vin) and the transmitted signal is measured at the other end (Vout), with the other windings terminals in open circuit as shown in Fig. 2, for a star connected winding. In this configuration the transformer behavior on the low frequency bandwidth is determined mainly for the magnetic core. This influence is negligible at frequencies above 10 kHz, since the magnetic field penetration depth decreases with increasing frequency.

The equivalent core magnetic circuit is shown in Fig. 3, where Φ_U, Φ_V and Φ_W yield the three magnetic fluxes of the respective U, V and W phases; $\Re_U$, $\Re_V$ and $\Re_W$ represent the reluctance of three-phase magnetic circuits and N_UI_U, N_VI_V and N_WI_W yield the magneto-motive force present in every transformer winding.

There are two common features in the core geometry of all three-limb core-type transformers:

- The magnetic path longitude of the middle phase is lower than that of the lateral ones, making the middle leg reluctance ($\Re_V$) lower than that of the lateral ones ($\Re_U$ and $\Re_W$).
- The magnetic paths of the lateral phases are equal due to symmetry as are the associated reluctances $\Re_U$ and $\Re_W$.

These two effects can be synthesized by (1), where the k parameter depends on the transformer geometry.

$$\Re_U = \Re_W = \frac{\Re_V}{k} \quad \text{where} \quad 0 < k \leqslant 1 \tag{1}$$

The different values among lateral and central reluctances cause the curves representing the frequency responses to differ when the lateral and central windings are measured. When a lateral phase is excited by the voltage applied during the end-to-end open circuit measurement, the curve reproduces two resonance peaks corresponding to both the asymmetric magnetic paths (C_1 and C_2 in Fig. 4) of the magnetic flux. On the other hand, the curve obtained for the central phase reproduces a unique resonance peak, corresponding to two symmetric magnetic paths (C_3 and C_4 in Fig. 4) of the same reluctance.

Three-limb core-type transformer presents an asymmetry between the magnetic paths corresponding to each transformer phase. In the case of transformer with other types of geometry such as shell-type or five-limb core-type transformers, the magnetic paths are practically symmetrical and therefore the frequency response from all phases tends to exhibit a curve characterized by only one resonance peak in the low frequency bandwidth.

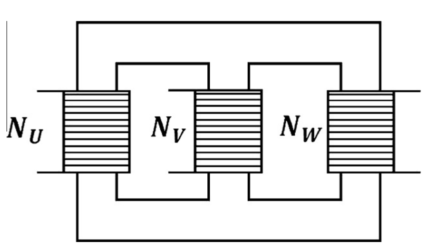

Fig. 1. Three-phase three-limb core-type transformer.

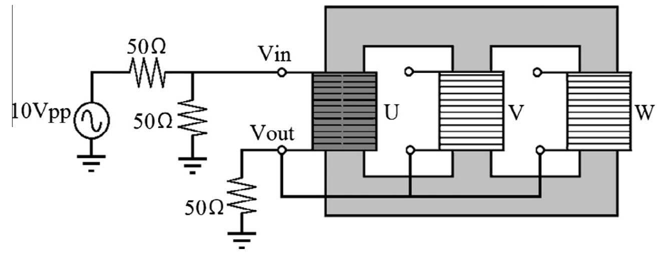

Fig. 2. End-to-end open circuit test in the U phase for a star connected winding.

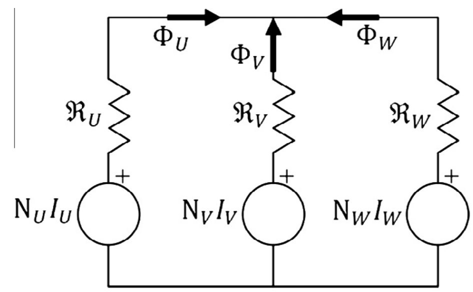

Fig. 3. Transformer magnetic circuit.

3. Low-frequency model

In this paper, the low-frequency bandwidth is defined as the range where the second resonance in the end-to-end open circuit measurement of a lateral phase (or the first in the central phase) is included. The electric equivalent core model is presented in Fig. 5 and is derived from the transformer magnetic circuit (Fig. 3) by applying the Duality Principle and adding the parasitic capacitances and resistances in each transformer phase.

Parameters L_U, L_V and L_W represent the magnetization characteristics of the respective phases U, V and W as expressed in (2) where $\Re_U$, $\Re_V$ and $\Re_W$ are the magnetic reluctances shown in (1) and N_U, N_V and N_W are the number of turns on each winding. Variations in L_U, L_V and L_W parameters can indicate faults associated with the magnetic core, residual magnetization or turn-to-turn short circuit, among other.

$$L_U = \frac{N_U^2}{\Re_U} \quad L_V = \frac{N_V^2}{\Re_V} \quad L_W = \frac{N_W^2}{\Re_W} \tag{2}$$

The active power losses of the magnetic core for each phase can be represented by adding the three resistive parameters $\Re_U$, $\Re_V$ and $\Re_W$ that comply with the relationship illustrated in (3) where V_U, V_V and V_W are the test voltages and $P0_U$, $P0_V$ and $P0_W$ are the core power losses. Variations in R_U, R_V and R_W parameters can indicate problems associated with the magnetic core.

$$R_U = \frac{V_U^2}{P0_U} \quad R_V = \frac{V_V^2}{P0_V} \quad R_W = \frac{V_W^2}{P0_W} \tag{3}$$

Finally, the low-frequency model (Fig. 5) is completed by adding the C parameters representing the winding capacitance of each phase. Variations in C_U, C_V and C_W parameters can indicate problems such as overall movement of windings.

As soon as the model obtained represents the physical phenomena reproduced in the frequency response, it can be used to interpret the measurements and assess possible failures. For example, in a three-limb core-type transformers showing healthy condi-