Guillermo APONTE[1], Héctor CADAVID[2], Juan Carlos BURGOS[3], Eduardo GOMEZ[4]

Universidad del Valle (1,2,4), Universidad Carlos III (3)

A methodology for obtaining by measurements the transformer physical-circuital model parameters

***Abstract**. Modeling a transformer usually requires all its construction data, which is very difficult to obtain for the units in operation; for new transformers manufacturers are not usually willing to provide this information. This paper presents a procedure to obtain the parameters of the transformer physical-circuital model based on data obtained from external measurements, without need for design data. This was done by using different tests, some routine tests like losses and other special tests such as frequency response or FRA. It is also presented the application of the procedure to obtain the model of a 15-KVA 13200 / 244 V single-phase transformer, and its use to simulate the frequency response.*

***Streszczenie.** W artykule zaprezentowano procedurę określania parametrów modelu transformatora na podstawie pomiarowych danych eksperymentalnych. Przedstawiono przykłady testów rutynowych jak i specjalnych. Uzyskane wyniki sprawdzono na przykładzie transformatora 15-KVA 13200/244 V. (**Metodologia eksperymentalnego określania parametrów modelu transformatora**)*

Keywords: Transformer, diagnostic tests, equivalent circuit, parameters, frequency response analysis.
Słowa kluczowe: transformator, model transformatora, pomiary

Introduction

The model is "an approximation, representation, or idealization of aspects related to the structure, behavior, or operation of a real-world process, concept, or system" [1]. Transformer modeling is focused on from different perspectives, finding a wide panorama in the numerous and diverse research works carried out, which shows the complexity of the theme [2],[3],[4],[5],[6],[7],[8].

Transformer model parameters are usually obtained from the physical transformer characteristics, implying its dismantling or working in partnership with the manufacturer that has the design and construction information; this is quite difficult because manufacturers usually do not provide information on designs and materials used in the construction of their transformers.

Alternatives have been proposed to build the transformer model by using data from field tests [6], [7], [8], and [9], which makes it viable to obtain the model for installed transformers. This work shows a procedure to obtain the parameters for a physical extended circuital classic transformer model, where it is assumed that:
- The parameters are concentrated.
- The parameters are not frequency dependent.

Transformer Circuit Physical model

The transformer at low frequency

The operation principle of the transformer at low frequency (60-50 Hz) and without load is shown in Fig. 1, where an alternating voltage on the primary side creates a time-varying flow that magnetically concatenates the two windings.

$$e_1(t) = -N_1 \frac{d\phi(t)}{dt} \qquad e_2(t) = -N_2 \frac{d\phi(t)}{dt}$$

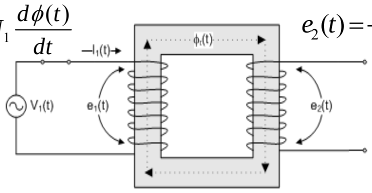

Fig. 1. Transformer without load.

When the transformer is without load, the time-varying flow is created by the current flowing through the primary winding, given that this current is very small, winding losses and leakage flux are neglected. Assuming that all the flux is concentrated in the magnetic core (R_{exc}-L_{exc}), the equivalent transformer circuit is shown in Fig. 2.

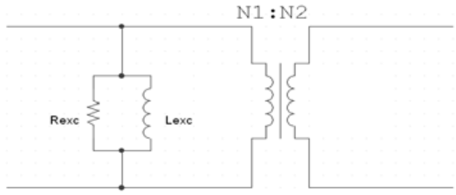

Fig. 2. The no-load transformer circuit (50-60 Hz).

If the secondary is short-circuited and a voltage is applied in the primary so that nominal currents I_1 and I_2 circulate, which are much higher than the magnetization; the effects of the windings (R_H, L_H, R_L, L_L) are now dominant in the circuit and the magnetizing branch is neglected, Fig. 3.

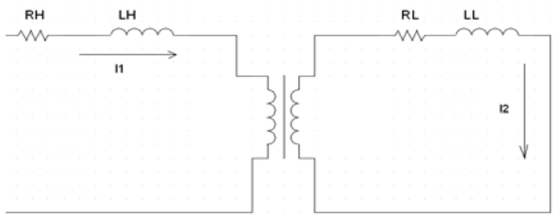

Fig. 3.The short-circuited transformer circuit (50-60 Hz).

For the transformer with normal load, the two previous conditions should be considered, leading to the equivalent circuit shown in Fig. 4.

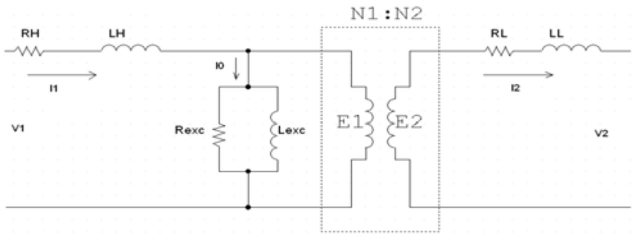

Fig. 4. The normal load transformer circuit (50-60 Hz).

The transformer at mid frequencies

If the transformer is analyzed at medium frequency, the capacitances between windings (C_{HL}) and from these to earth (C_H and C_L) became important, as well as the series winding capacitances or internal capacitances Fig. 5.

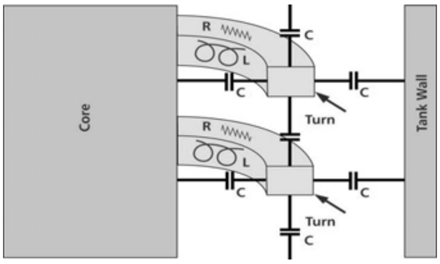

Fig. 5. Internal winding capacitances.

The transformer circuit is modified at high frequency by the effect of the capacitances mentioned, along with the capacitance associated with the magnetic core sheets or excitement capacitance (C_{exc}). The circuit transformer for medium frequencies will be the shown in Fig. 6 which is known as the frequency extended classic physical-circuital transformer model [9], [10], [11].

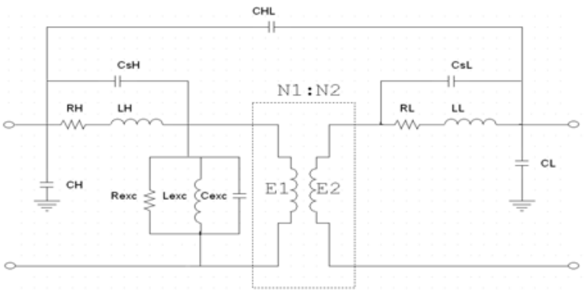

Fig. 6. The frequency extended classic physical-circuital transformer model.

For high frequencies, the circuit components of Fig. 6 should be considered distributed parameters and also frequency dependent.

Procedure for obtaining the model parameters

The parameters for the model in Fig. 8 model can be obtained by external measurements [9], [12], using the results of the following tests:

The no-load test

In this test, a voltage of 60 Hz AC is applied over one transformer side (usually the high voltage side), while the other end is in open circuit. Neglecting the winding losses and assuming no leakage flux, Fig. 7 shows the equivalent no-load transformer circuit at low frequency, where I_0 is the total current, Im the current necessary to generate the core magnetic flow, and Ife the current due to the losses in the magnetic material.

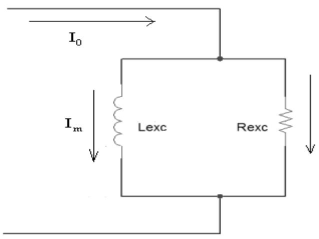

Fig. 7. The no-load current (50-60 Hz).

From the values of voltage V, current I_0, and active losses W, measured in the test, resistance (R_{exc}) and excitation inductance (L_{exc}) values are determined. The R_{exc} resistance is found from the active loses:

$$R_{exc} = \frac{V^2}{W} \tag{1}$$

Having R_{exc}, the I_{fe} current can be obtained and the magnetizing current I_m can be calculated:

$$I^2{}_m = I_o{}^2 - \left(\frac{V}{R_{exc}}\right)^2 \tag{1}$$

Knowing the magnetization current I_m, the excitation inductance (L_{exc}) can be calculated:

$$L_{exc} = \frac{V}{2\pi f * \sqrt{I_0{}^2 - \left(\frac{V}{R_{ex}}\right)^2}} \tag{2}$$

Open circuit test in mid frequencies

The C_{exc} magnetizing capacitance begins to take effect at frequencies above the nominal (Fig. 8), reaching the condition of resonance with the excitation inductance L_{exc}, at a frequency value denominated as F_{n_Open}.

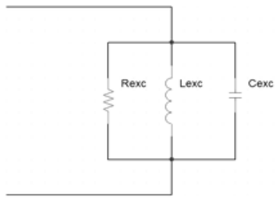

Fig. 8. Branch magnetization at mid frequency.

The resonance frequency (F_{n_open}) can be found from the open circuit frequency response test (Fig. 12), and with this value C_{exc} can be calculated:

$$C_{exc} = \frac{1}{(2\pi * f_{n\_\text{open}})^2 * L_{exc}} \tag{3}$$

Winding resistance test

In this test a DC voltage is applied to one transformer winding and the current is measured, with the other windings open. With the current, the winding resistance values can be calculated (r_{DC}).

$$r_{DC} = \frac{V_{DC}}{I} \tag{4}$$

The transformer ratio test

The transformation ratio test gives the turns ratio between high-voltage and low-voltage windings. This “a” relationship is used to refer to the parameter values from one winding to another.

Leakage reactance test (short circuit)

In this test, a frequency sinusoidal voltage is applied to a transformer winding (usually high voltage), while the other winding is short-circuited, as shown in Fig. 9. The currents must be equal to or close to the nominal values.

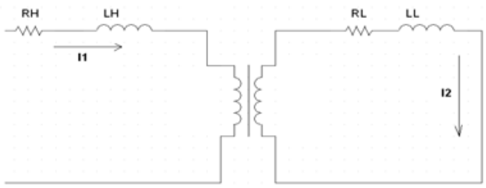

Fig. 9. The transformer under short-circuit condition.

The core effect is negligible because the excitation voltage is nearly zero. When measuring the resistance of a winding, the other winding resistance will be present, but both values are referred to the measurement side, i.e. the high voltage side in Fig. 10.

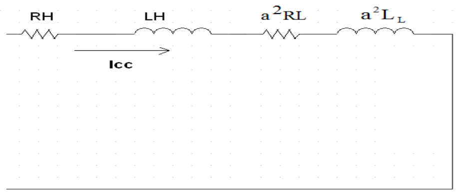

Fig. 10. Transformer short-circuit condition referred to the high voltage side.

With the total current I and the measured active W_{cc} loss values, the total AC resistance can be calculated (R_{H_AC} in the high voltage case):

(5)
$$R_{H\_AC} = \frac{W_{cc}}{I^2}$$

But the R_{H_AC} resistance seen from the high voltage side involves the resistance of both windings:

(6)
$$R_{H\_AC} = R_H + a^2 RL$$

It can be assumed that the relationship between the values of DC resistance in ($r_{L\text{-}DC}$ and $r_{H\text{-}DC}$) is approximately equal to the AC resistance ratio (R_H and R_L) [13], [14]:

(7)
$$\frac{R_L}{R_H} = \frac{r_{L\_DC}}{r_{H\_DC}}$$

From (7) and (8), the value of R_H can be found:

(9)
$$R_H = \frac{R_{H\_AC}}{1 + \left[a^2 * \left(\frac{r_{L\_DC}}{r_{H\_DC}}\right)\right]}$$

With R_H, it can be found R_L (Eq.7).

The equivalent inductance L_{Heq} can be calculated using Eq. (10).

(8)
$$V = Z * I = \sqrt{(R_{H\_AC})^2 + (2 * \pi * f * L_{Heq})^2} * I$$

The equivalent inductance L_{Heq}, involves the low side and high side windings:

(9)
$$L_{Heq} = L_H + a^2 L_L$$

Assuming for the inductances the same relationship that for DC resistances [13], [14]:

(10)
$$\frac{r_{L\_DC}}{r_{H\_DC}} = \frac{L_L}{L_H}$$

From (11) and (12), the high voltage winding inductance L_H, can be calculated (Eq 13):

(11)
$$L_H = \frac{L_{Heq}}{1 + \left[a^2 * \left(\frac{r_{L\_DC}}{r_{H\_DC}}\right)\right]}$$

Once L_H is obtained, it can be found L_L Eq. (11).

Transformer test short-circuited in high frequency

When the transformer is in short-circuit condition and the frequency increases, the value associated with the windings series capacitive reactance decreases while their inductive reactance increase, until they reach resonance condition. When the short circuit is at the low voltage side the C_{SL} effect is canceled, only impacting on the C_{SH} capacitance (Fig. 11). The reverse condition occurs if the short circuit is at the high voltage side.

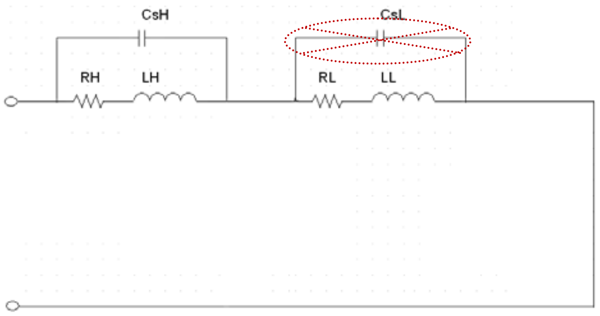

Fig. 11. Equivalent circuit short-circuited in high frequency

The short-circuit resonance frequency, F_{n_short}, can be found in the transformer frequency response curves (Figures 14 and 15). Given that L_H and L_L are known, the C_{SH} and C_{SL} values can be calculated by using Eqs. 14 and 15, respectively.

(12)
$$C_{sH} = \frac{1}{(2\pi * f_{H\_short})^2 * L_H}$$

(13)
$$C_{sL} = \frac{1}{(2\pi * f_{L\_short})^2 * L_L}$$

The Capacitance test

With this test, the transformer total capacitances C_H, C_L, and C_{HL} are measured directly.

The SFRA test

The seep frequency response test, or SFRA, provides information about the impedance or admittance transformer over a wide frequency range. It is a tool for evaluating the transformers mechanical condition and it can be used to identify the high side and low side winding resonant frequencies [15], [16], [17] y [18].

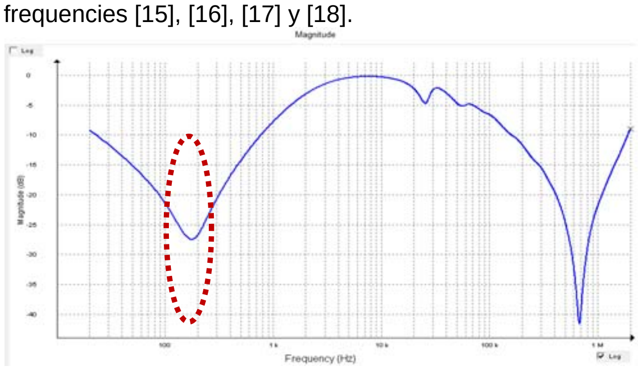

Fig. 12. Open circuit resonant frequency (F_{L_open}).

Although the SFRA test can be performed with different connection configurations [15]19], for finding the resonant frequencies, it can be used the SFRA curves obtained from the high side under open circuit condition and from the low side under short-circuit condition. The Fig. 12 shows the frequency response obtained at the high side winding with the low side under open circuit condition, where the first resonant point corresponds to the open circuit resonance frequency F_{L_open} [20], [21].

Fig. 13 shows the frequency response obtained at the high side winding with the low side under short-circuit condition, where the resonant point corresponds to the short circuit resonance frequency F_{L_short} [20], [21].

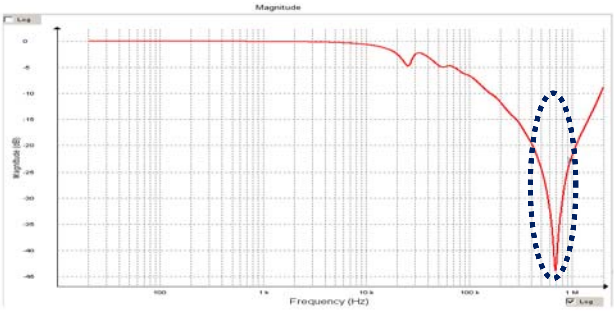

Fig. 13. Short circuit resonant frequency (F_{L_short}).

Model case

The procedure mentioned above was applied to find the model for a single-phase transformer 13200/244 V, 15 KVA. Once all the circuit model parameters were obtained (Fig. 6), the model was implemented in the Matlab simulation tool. Fig. 14, shows the measured and the modeled frequency response curves, it can be observed that at low and medium frequencies the measured and the modeled curves have a good approximation.

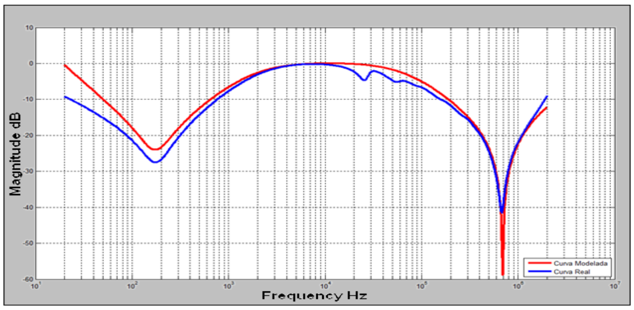

Fig. 14. FRA curve in open circuit, modeled and simulated

Conclusions

A simple procedure was developed to obtain the transformer physical circuit model parameters, based on external measurements.

This model can be used to obtain the transformer frequency response, showing acceptable performance when comparing the modeled and the measured curves in the range of low and medium frequencies.

The transformer physical-circuital model permits establishing a direct relationship between its parameters and the transformer physical elements, which can be used to associate the SFRA curve variations with real transformer changes.

Although the model most be adjusted, it can become a useful tool for supporting transformer diagnostic work, particularly for use in SFRA application.

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***Authors**: Prof. Guillermo Aponte M.,*
E-mail: guillermo.aponte@correounivalle.edu.co,
Prof. Héctor Cadavid Ramírez
E-mail: hector.cadavid@correounivalle.edu.co
Student Ph.D, Eduardo Gómez Luna,
E-mail: eduardo.gomez@correounivalle.edu.co
Universidad del Valle, Cali-Colombia, Calle 13 #100-00.
Prof. Juan Carlos Burgos.,. jcburgos@ing.uc3m.es
University Carlos III, Madrid-España. Avenida de la Universidad 30, 28911-Leganés