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Low and high frequency model of three phase transformer by frequency response analysis measurement

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Abstract: The behavior analysis of the transformer is usually achieved by the frequency response analysis (FRA), which is obtained by the application of a very low AC voltage in over a wide frequency range. This paper presents a low and high frequency modelling approach of a three-phase transformer. The developed model consists of a cascade of parallel RLC cells, whose parameters are identified using the frequency response analysis data measurements obtained on each transformer phase. Thus, the proposed model can simulate the frequency behavior of the transformer windings without reference to the geometries of the coils which makes it easily usable in the failure diagnosis field. Experimental results on a 300 VA laboratory transformer validate the proposed model.

Keywords: Three-phase transformer; Frequency response analysis; Model of RLC cells; Three-phase transformer model

PACS: 81.70.-q, 84.37.+q

1 Introduction

The transformer is an extremely important element in electrical systems. So its monitoring is necessary for the continuity of the power supply and stability of electrical networks. However, the currently used frequency response analysis (FRA) is a useful tool which can give an indication of different mechanical deformations that can appear in transformer windings [1–5]. Furthermore, applying the FRA idea to evaluate the transformer windings state is based on the fact that the winding displacement or deformation changes according to the geometrical properties of the windings, which are related to its capacitive and inductive parameters. Changes in these parameters therefore modify the winding frequency response, which can be observed by measuring its transfer function. In the FRA process the transformer can be modeled by a complex network of RLC elements that are composed of resistances, inductances and capacitances [6–9]. In the literature, several studies suggest techniques for shape analyzing of the FRA response in order for the detection and localization of various incipient faults in the transformer windings [1, 10–15].

Therefore, a low and high-frequency behavior study of transformer windings is necessary, which will allow us to develop an equivalent model to the three-phase transformer from FRA data measurements obtained in a wide frequency range reflecting the electric and electromagnetic behavior of transformer windings. However, since the proposed model by Wilder Herrera et al. in reference [16] is limited to the low frequency (10 Hz-10 kHz) for studying the magnetic behavior of a three-phase transformer. Then, it is noted that the high-frequency behavior impedance of the transformer is characterized by several resonance points due to inductive and capacitive effects of the windings. This leads us to a reflection on a high-frequency equivalent model to a three-phase transformer composed of a cascade of the parallel RLC cells, whose parameters are calculated as a function of the resonance points and the bandwidth of each peak of the FRA response. The proposed model in this paper can simulates qualitatively and/or quantitatively the transformer windings behavior in the low and high frequency. The obtained results are experimentally tested on a 300 VA laboratory transformer.

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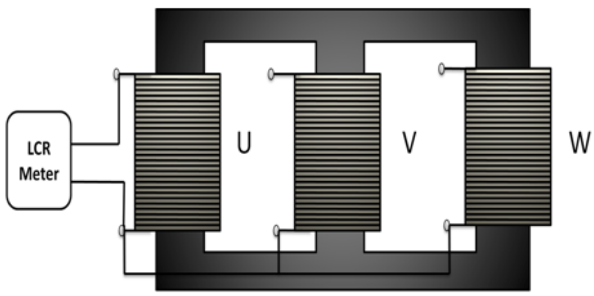

Figure 1: FRA test on three-phase transformer [15]

2 The proposed model

An inspection of the winding impedance behavior that is characterized by several resonant points induces a reflection on an electrical model indicating their behavior, so that the different impedance peaks will be reproduced in their respective frequencies. In this work, the procedure for calculating of the three-phase transformer parameters is presented. Next, the RLC cells model method was used to estimate the transfer function of the transformer windings in order to study its frequency behavior. Figure 1 shows the FRA test performed on the phase U to obtain ZmU as a function of frequency, and thus ZmV and ZmW have been found [16]. Hence, Figure 2 depicts the comparison between these measured impedances on each phase.

According to Figure 2, we can see that the measured impedances curves of two lateral phases (ZmU and ZmW) and that of the central phase (ZmV) are substantially same at high frequency. Whereas, it has been found at low frequency that the impedance amplitude of the first resonance of the central phase (ZmV) is greater than the other two with a shift to the left compared to the measured impedances in lateral phases (ZmU and Zm) as illustrated in Figure 2. This can be explained by the magnetic influence of the two lateral phases on the central phase.

Analysis of these tests on a wide frequency range will provide a simple electrical equivalent model to the three-phase transformer. This model is constituted of a cascade of parallel RLC cells reflecting the behavior of the transformer in low and high frequency. In addition, the three phases of the transformer can be represented by the three impedances Z_U, Z_V and Z_W as in Figure 3. In where Z_U, Z_V and Z_W are impedances reflecting the physical behavior of the phases U, V and W respectively. The impedances Z_U, Z_V and Z_W are obtained using the expressions (1)-(3) from the measured impedances ZmU , ZmV and ZmW [16].

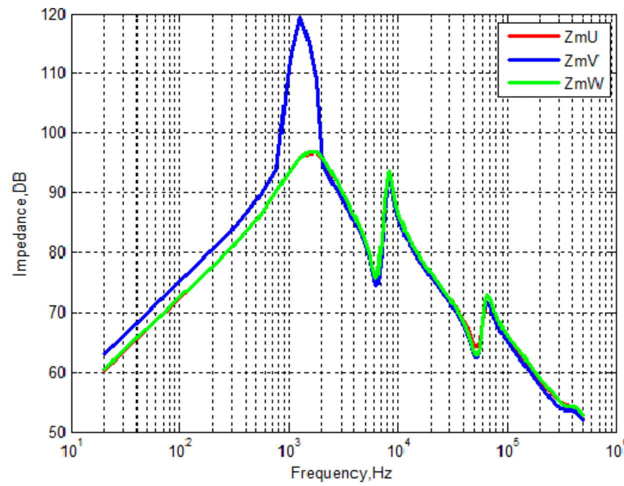

Figure 2: Comparison between the measured impedance on the central phase and those of the lateral phases

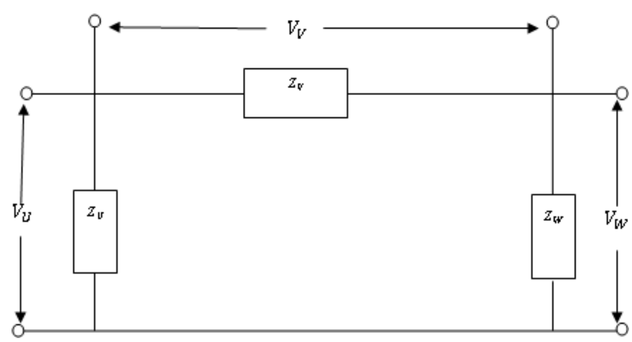

Figure 3: Three-phase transformer model with impedances Z_U, Z_V and Z_W

$$Z_U(\omega_i) = \frac{ZmU_i^2 + ZmV_i^2 + ZmW_i^2}{2.(ZmU_i - ZmV_i - ZmW_i)} - \frac{ZmU_i.ZmV_i + ZmU_i.ZmW_i + ZmV_i.ZmW_i}{(ZmU_i - ZmV_i - ZmW_i)} \quad (1)$$

$$Z_V(\omega_i) = \frac{ZmU_i^2 + ZmV_i^2 + ZmW_i^2}{2.(ZmV_i - ZmU_i - ZmW_i)} - \frac{ZmU_i.ZmV_i + ZmU_i.ZmW_i + ZmV_i.ZmW_i}{(ZmV_i - ZmU_i - ZmW_i)} \quad (2)$$

$$Z_W(\omega_i) = \frac{ZmU_i^2 + ZmV_i^2 + ZmW_i^2}{2.(ZmW_i - ZmV_i - ZmU_i)} - \frac{ZmU_i.ZmV_i + ZmU_i.ZmW_i + ZmV_i.ZmW_i}{(ZmW_i - ZmV_i - ZmU_i)} \quad (3)$$

The series model of parallel RLC cells is based on FRA data measurement performed on a transformer winding (Figure 2). However, the parallel RLC circuits that make up

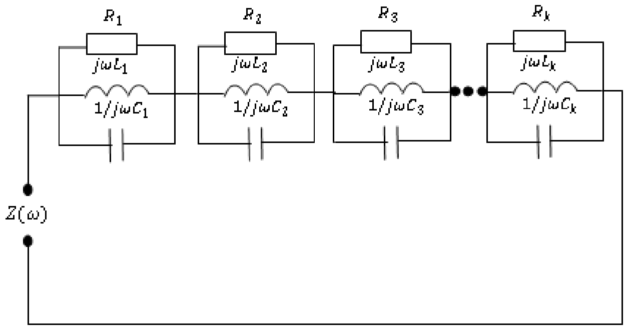

Figure 4: Series model of parallel RLC cells [16, 17]

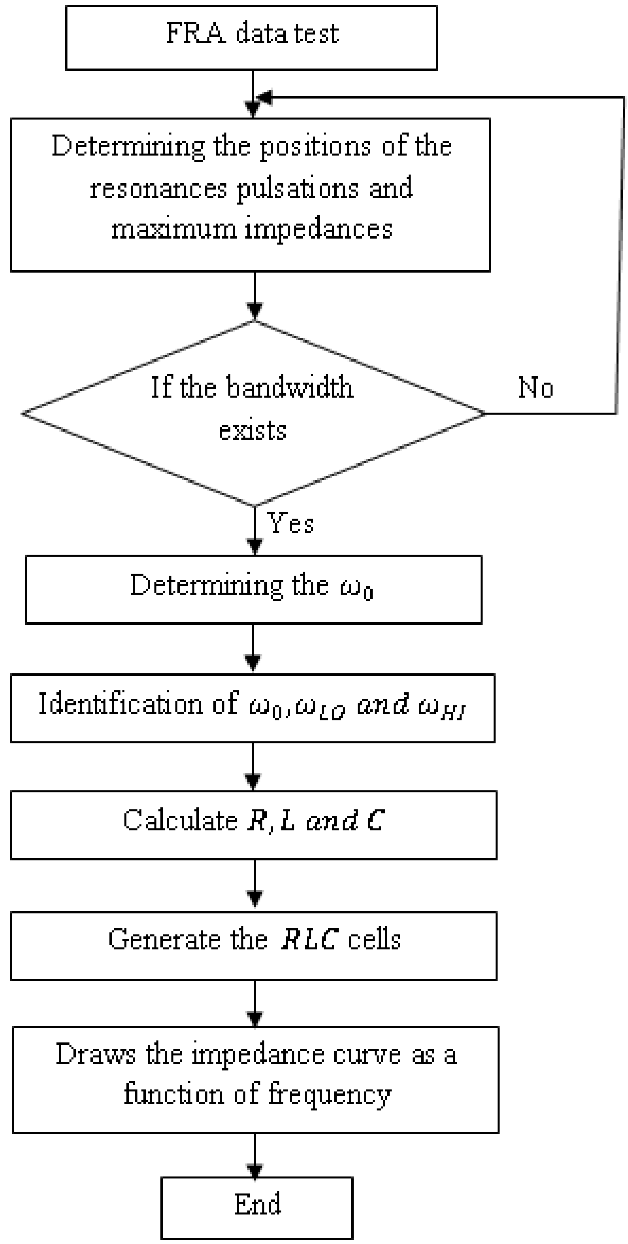

Figure 5: Flowchart of the proposed model

the model are determined from the resonance peaks corresponding to the different cutoff frequencies of the winding response in the frequency regime. These cells, thus obtained are arranged as a function of the number of resonance points of the frequency response impedance in order to obtain the equivalent model to the winding as in Figure 4. In the cascade model of parallel RLC cells, each cell is composed by RLC elements in parallel, in which the number of cells connected in series depends on the number of measured resonance points in FRA test. Therefore, Figure 4 shows k RLC cells in series, where, each cell is composed of a resistance R_k, a capacitance C_k and an inductance L_k in parallel, with k = 1, 2, 3… In addition, the determination of equivalent circuit parameters is performed according to the flowchart of Figure 5 [17].

3 Synthesis of the proposed model

The proposed model is synthesized using the frequency response measured on each phase according to references [15, 16]. On the other hand, the equivalent circuit construction is deducted for each phase, and it consists of a cascade of parallel RLC cells whose parameters are identified according to the flowchart of Figure 5 [17, 18].

The cells consist of three basic passive electrical elements, inductance representing the storage magnetic field, capacitance representing the electric field storage and resistance representing the dielectric losses [17–19]. Otherwise, obtaining the electrical parameters; R, L and C of each cell was made from the measured frequency response for which there were several peaks throughout the frequency bandwidth. Thus, Figure 6 shows the equivalent model of the three-phase transformer.

The physical behaviors of the transformer coils as in Figure 7 were obtained for each phase using equations (1)-(3). Where the magnetic behavior can be observed at low frequency about 20 Hz-5 kHz, an increase of the central phase impedance (Z_U) compared to those of the lateral phases (Z_V and Z_W) can be explained by the influence of these two windings on the central winding. However, Z_U and Z_W impedance curves are almost confused, with a slight difference due to the male manufacturing of the transformer coils. On the other hand, the procedure for diagnosing transformer failures in the FRA domain is usually based on the comparison between two FRA traces in the frequency regime, one corresponding to the transformer in the healthy state and the other of the transformer in a state of possible failures. Consequently, in order to use this model for the detection and localization of

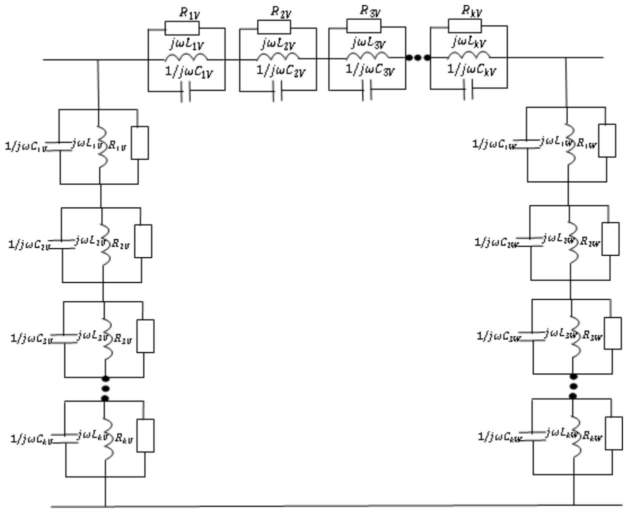

Figure 6: Proposed model of three phases of the transformer

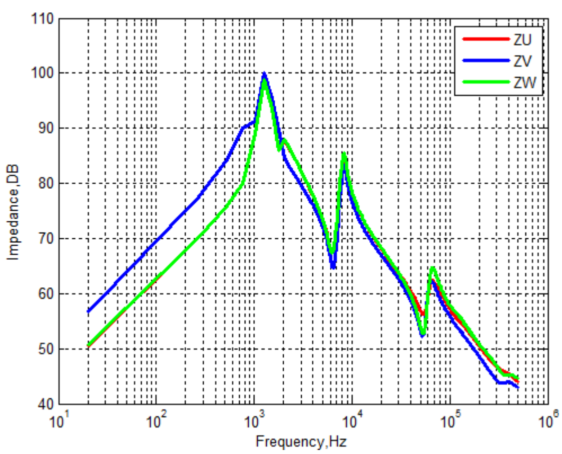

Figure 7: Comparison between the impedances Z_U, Z_V and Z_W of the phases U, V and W

the three-phase transformer faults, two measurements of the frequency response on a healthy and defective transformer are necessary. However, each FRA measure must be modeled separately to determine the model parameters using the algorithm explained above (flowchart of Figure 5). However, the changes analysis of both parameters models of the healthy and defective transformer can give an indication of the type and the point of the defects. In addition, the percentage changes between both models parameters can be calculated [20–22] to find a correlation between the proposed model parameters and the fault type.

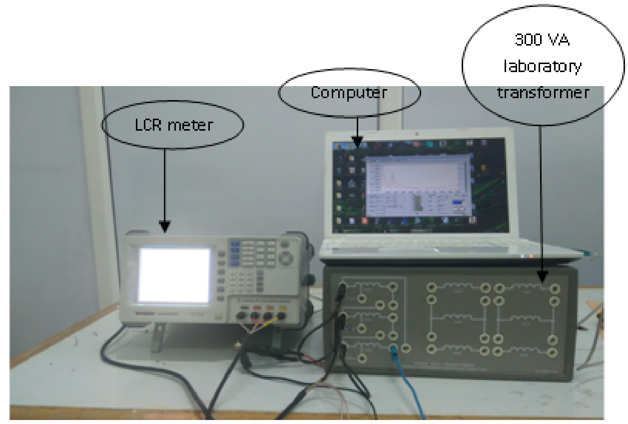

Figure 8: Test bench

4 Experimental validation of the proposed model

The proposed model was experimentally validated on a 300 VA laboratory transformer. So that, the measurement was done automatically using the following equipment: Precision LCR meter DC, 20 Hz-5 MHz as in Figure 8.

The equivalent circuit of the three-phase transformer depicts in Figure 6, whose parameters are identified using FRA data measurements. The results obtained from the measurements on the three-transformer are compared to those estimated using the RLC cells method and shown in Figure 9(a), (b) and (c).

The model parameters were identified for each transformer phase using the RLC cells method explained in Figure 5.These parameters are shown in Table 1. However, the magnetic effect appears on the model parameters in low frequency range between 20 Hz and 1 kHz, in which the magnetic influence of the two lateral phases on the central phase can appear on the resistance and inductance values of the first peak. Besides, the inductance and resistance values of the central phase are greater than those of the lateral phases which are nearly equal ($L_V > L_U \approx L_W$ and $R_V > R_U \approx R_W$) at low frequency. Otherwise, at high frequency, these parameter values (R and L) are close with certain difference due to the male manufacturing of the transformer coils. On the other hand, the electric effect of the transformer windings is represented by the capacitances that appear in the high frequency. In which we can see from Table 1 that the capacitance of the central phase is greater than that of the lateral phases ($C_V > C_U \approx C_W$). In contrast all capacitances of each phase are almost equal at low frequency ($C_U \approx C_V \approx C_W$). Consequently, the diagnostic capability of transformer core defects can be done

Table 1: Parameter values of the proposed model for each phase U, V and W

Parameter Values	Phase U			Phase V			Phase W		
	$R_U\,(\Omega)$	$L_U\,(H)$	C_U (F)	$R_V\,(\Omega)$	$L_V\,(H)$	$C_V\,(F)$	$R_W\,(\Omega)$	$L_W\,(H)$	$C_W\,(F)$
Peak 1	87949,9	4,3199	$3{,}603\times10^{-9}$	100115,4	4,91749	$3{,}464\times10^{-9}$	87952,6	4,3201	$3{,}602\times10^{-9}$
Peak 2	18652,2	0,0648	$5{,}662\times10^{-9}$	14594,5	0,0507	$7{,}236\times10^{-9}$	18741,8	0,06512	$5{,}635\times10^{-9}$
Peak 3	1305,9	0,0012	$4{,}988\times10^{-9}$	1310,6	0,00096	$6{,}227\times10^{-9}$	1430,6	0,00108	$5{,}255\times10^{-9}$

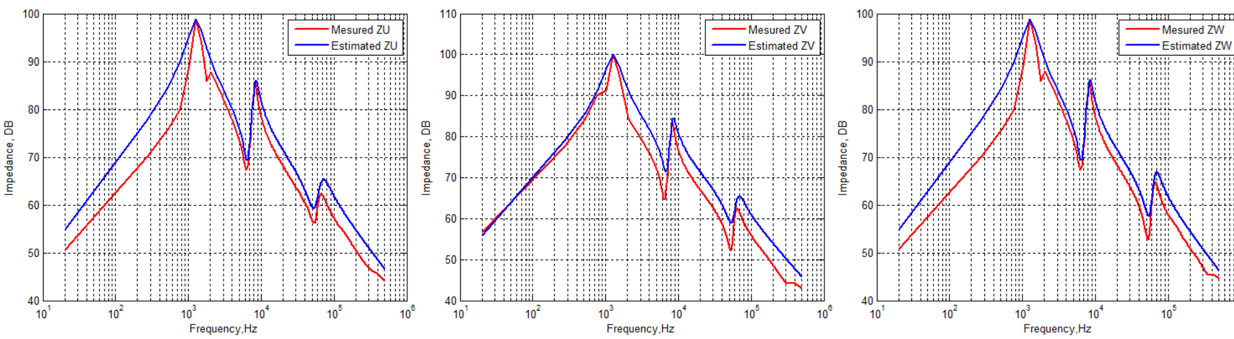

Figure 9: Comparison of the measured impedances on each phase of transformer to those estimated by the cascade RLC model (a): phase U, (b): phase V and (c): phase W

at the low frequency, so the deformation and/or displacement of the transformer windings can be analyzed at high frequency using the proposed model from their impact on inductive and capacitive properties. The parameters of the proposed equivalent model to a three-phase transformer are very sensitive to the geometrical changes of the transformer windings. Therefore, the existence of a minor mechanical deformations or a wrong manufacturing of the windings cause a misalignment on the model parameters.

5 Conclusion

In this paper, a modeling approach to three-phase transformer has been performed on the basis of simple low-power tests. The proposed model in this study consists of a series of parallel RLC cells, where these parameters are identified as a function of the resonance points and the bandwidth of the FRA response obtained on each transformer phase. In addition to that, the magnetic and electric behavior of the transformer coils was analyzed on the basis of the FRA response obtained on each phase and the parameters of the proposed model. Finally, this model was experimentally validated on a 300 VA laboratory transformer.

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