Calculation of Leakage Reactance in Transformers with Constructive Deformations in Low Voltage Foil-Windings

Guillermo Diaz, Enrique Mombello, *Senior Member IEEE*, Guillermo Guidi.

***Abstract*—Foil-winding transformers with high currents in low voltage winding normally have copper/aluminum bars as leads of the coils. A practical solution for locating bar leads without increasing the size of the active part is to flatten the coil in the leads zone causing a deformation. Abnormalities in the leakage reactance have been identified in this type of transformers. In order to take this effect into account, this work proposes a correction to the mathematical formulation for calculating the leakage reactance in transformers with deformations in the low voltage winding. Three methods for calculating the leakage reactance have been compared for four real case studies: the proposed formulation, the commonly used formulation and detailed simulations with the finite element method in 3D (FEM3D). The leakage reactance calculated with the proposed method has been found to have an improved accuracy compared with the one calculated using the formulation without correction in all case studies. The main contribution of this work is that the proposed correction in the formulation makes it possible to increase the accuracy in the calculation of leakage reactance, avoiding the need to resort to detailed simulations with FEM3D.**

***Index Terms*—Transformer, Leakage reactance, analytical methods, finite element method**

I. INTRODUCTION

Transformer impedance is undoubtedly one of the most important parameters in transformer design and it is of crucial importance for manufacturers that its final measured value is as close as possible to the value guaranteed to the purchaser. Due to the nature of the transformer manufacturing process, small deviations in the dimensions of materials such as conductors and barriers are unavoidable. As a consequence of this fact and the complexity of transformer magnetic modeling, it is very difficult to ensure that the measured impedance value exactly matches the guaranteed value. This is why international standardization organizations such as ANSI have defined the maximum permissible deviations of the measured impedance value from the guaranteed value. In accordance with ANSI IEEE C57.12.00 standard, the tolerance for transformers with impedances greater than 2.5 % is ± 7.5 % [1]. In the event that a transformer falls outside the tolerance specified by the standard, the purchaser may reject the unit or impose fines on the manufacturer, resulting in negative economic impacts for both parties.

As the rated power of the transformer increases, the resistive component of the impedance becomes less and less relevant, while the reactive component X becomes the predominant component of the impedance. Because the reactive component is associated with the leakage flux, this component is known in the literature as the *leakage reactance* [2]. Therefore, this work is focused on the leakage reactance only.

In the transformer design process it is necessary to evaluate hundreds or thousands of different geometric alternatives looking for those that meet all technical and constructive constraints at the lowest possible cost. Therefore, the calculation method must be as fast and reliable as possible [3]. Among the methods most frequently used by transformer manufacturers at the design stage are several analytical formulations [4], [5], [6] as well as the Rabins' method [7]. The geometric mean distance method [8] has also been recently proposed. At the final design stage, where detailed studies are required, the 3D finite element method is one of the preferred methods [9].

The manufacturers have relied for decades on the use of analytical formulations for the calculation of the parameters of the transformer thanks to its practicality and rapid evaluation. In spite of the above, it will be shown in this work that the naive use of this type of formulations can be risky in transformers whose coils have geometric deformations.

As will be seen in detail in Section II, these deformations are made when using bar leads, thus avoiding an increase in the size and therefore the cost of the transformer. Figure 1 shows a coil with a deformation in the leads area.

This work has been organized as follows: In Section II a discussion about the need to deform the low voltage coils is presented. Additionally, it is shown from several case studies that the value of the measured leakage reactance increases with respect to the expected value if the usual calculation procedure is used. Section III presents the analytical formulation of leakage reactance based on leakage areas (usual formulation). The geometric model of the deformed LV coil is also introduced and from this model an explanation of the increase in leakage reactance is given. In addition, formulas for the corrected calculation of leakage area are derived. Section IV describes the most important aspects of the detailed calculation of leakage reactance using FEM3D. Section V presents a summary of the results of leakage reactance calculation using the corrected formulation, the current formulation and FEM3D. Finally, Section VI gives the most relevant conclusions of the work. The most important contributions of this work are

Guillermo A. Diaz F. currently works as professor and researcher of the La Salle University in Bogota Colombia. e-mail: guandiaz@unisalle.edu.co (see http://www.unisalle.edu.co).

E. Mombello and Guillermo Guidi currently work as professors and researchers of the CONICET - Universidad Nacional de San Juan, San Juan, Argentina.

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the following: *a)* A reasonable explanation is provided to justify the increase in the leakage reactance for this type of transformers. *b)* A correction to the current formulation is proposed which makes it possible to increase the accuracy of the calculation of leakage reactance in transformers with deformations in LV windings.

II. DESCRIPTION OF PROBLEM

Transformer manufacturers have found great potential in the use of foil conductor in low voltage windings due to its low cost and easy handling in the manufacturing process. However, a disadvantage of foil conductor is that large copper bars must be used as winding leads, which may have large cross-sections in order to guarantee current densities similar to those of the winding conductors. Figure 1 shows a picture of a deformed LV coil with bar leads while Figure 3 shows a schematic top view of one phase of a transformer.

The deformation in the LV coil is performed mainly due to economic considerations. The purpose of LV coil deformation is to ensure that the distance between the outer corners of the outer bars is approximately equal to the thickness of the main duct ($w_e \approx w_g$ see Figure 3). Figure 3 shows how the deformation of the LV coil allows the outer bar to be located by keeping its corners within the outer diameter of the LV coil, thus avoiding the need to increase the internal radius of the HV coil.

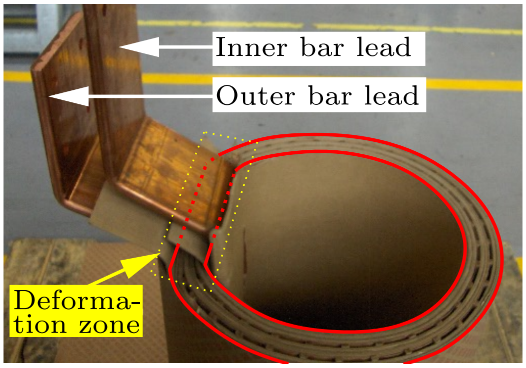

Fig. 1. Foil winding with deformation in the bar lead zone

Table I shows the results of leakage reactance calculated by the current formulation X_c (see (1)) [10] and the estimated values from measurements denoted by X_m[1] of four real case studies with foil-conductor LV windings and bar leads. Detailed test information for each case study is presented in Table III of Section VIII.

Table I also shows the relative errors between the measured and calculated values. The relative error was calculated as follows: $\varepsilon_{m.c} = (X_c - X_m)/X_m$. Accordingly, $\varepsilon_{m.c} < 0$ means that the calculated value is below the measured value. As can be seen, in the first case study the relative error between the measured value and the calculated value was -7.53%. It should be noted that for this case study the relative error of leakage reactance is very close to the maximum tolerance specified by ANSI IEEE C57.12.00. Similarly, in case study 2, the relative error between the measured value and the calculated value was -6.15%. In case studies 3 and 4 the measured values of leakage reactance are also higher than those calculated, although to a lesser extent if compared with the first two case studies. It is important to emphasize that the current formulation for calculating X_c provides sufficiently accurate and reliable results in transformers with circular coils and reasonably uniform ampere-turn distributions.

TABLE I
MEASURED AND CALCULATED DATA OF LEAKAGE REACTANCE IN FOIL TRANSFORMERS WITH BAR LEADS

Variable (unit)	Case Study 1	Case Study 2	Case Study 3	Case Study 4
X_c (%)	5.16	4.73	6.03	7.31
X_m (%)	5.58	5.04	6.09	7.36
$\varepsilon_{m.c}$ (%)	-7.53	-6.15	-0.99	-0.68

The specific problem that has been detected is that in general, *transformers with LV coils with bar leads show measured values of leakage reactance higher or considerably higher than the values calculated with the current formulation*. This situation produces uncertainty for the manufacturers, since as shown in Table I, the deviation can be highly variable, so it is not trivial to anticipate how much the final reactance will increase with respect to the calculated value.

III. ANALYTICAL FORMULATION OF LEAKAGE REACTANCE

Despite the great progress made in recent decades in numerical methods such as the FEM and the boundary element method (BEM) [12], analytical solutions are still of great value to the industry due to their practicality and rapid evaluation [3]. The analytical formulation for calculating the leakage reactance for circular coils will be presented in this section and then this formula will be corrected to include the effect LV winding deformation.

A. Analytical Formulation for Circular Coils

Del Vecchio et al. [10] derive the formula for calculating the per unit leakage reactance of transformers with two circular windings very clearly. According to Del Vecchio's formulation, the leakage reactance can be calculated as follows

$$X_c = \frac{(2\pi)^2 \mu_0 f S_b}{(V_b/N)^2 (h+s)} \cdot \left(\begin{array}{c} \frac{r_{m1}w_1}{3} + \frac{r_{m2}w_2}{3} \\ + w_g r_{mg} + \frac{w_1^2}{12} - \frac{w_2^2}{12} \end{array} \right) \quad (1)$$

The notation X_c refers to leakage reactance calculated by the *current* formulation. In this equation r_{m1}, r_{mg} and r_{m2} are the mean radii of LV, the main duct and the HV winding respectively; w_1, w_2 and w_g are the radial thicknesses of the windings and of the main duct respectively; h is the average height of LV and HV coils. Additionally, S_b is the apparent power per leg (single-phase) while V_b, N and f are the base phase voltage, the number of turns of the reference winding and the operating frequency respectively. For the purposes of

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[1] The measured value leakage reactance was determined in all units from the measurements of the short-circuit voltage and the load losses. For more information about transformer tests see [11].

this article the LV winding is assumed to be the reference winding.

The derivation of (1) assumes uniform ampere-turn distribution and takes into account the curvature of the magnetic flux lines by means of the correction factor s, which can be calculated as [10]

$$s = 0.32 \cdot (r_4 - r_0) \tag{2}$$

where r_0 is the core radius and r_4 is the external radius of the HV winding. All geometrical variables of (1) have been defined to be consistent with the dimensions in Figure 2.

The leakage area is defined as the cross-sectional area (top view) of the corresponding cylinder, either that of the LV winding $A_1 = \pi(r_2^2 - r_1^2)$, that of the main duct $A_g = \pi(r_3^2 - r_2^2)$, or that of the HV winding $A_2 = \pi(r_4^2 - r_3^2)$. The leakage area can alternatively be expressed as a function of the mean radius and the thickness as $A_i = 2\pi r_{mi} w_i$ for $i = \{1, g, 2\}$. Equation (3) can be obtained by rewriting (1) using this last notation.

$$X_c = \frac{2\pi\mu_0 f S_b}{\left(V_b/N\right)^2 (h+s)} \cdot \left\{ \begin{array}{l} A_g + \frac{A_1}{3} + \frac{A_2}{3} \\ + \frac{\pi w_1^2}{6} - \frac{\pi w_2^2}{6} \end{array} \right\} \tag{3}$$

It is extremely important to note in (3) that the leakage area of the main duct A_g is the most important term of leakage reactance. As can be seen, this term has the smallest denominator (the unit), so a small change in this area can produce significant changes in the leakage reactance. The aim is to keep the thickness of main duct as small as possible due to cost savings, there are other restrictions such as cooling, insulation and the required impedance value itself, which can cause the leakage area of the main duct to be significant compared to that of the windings.

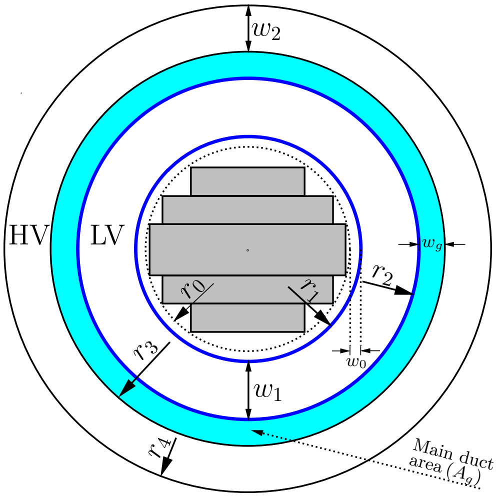

Fig. 2. Schematic diagram of one phase of the transformer with circular LV and HV windings

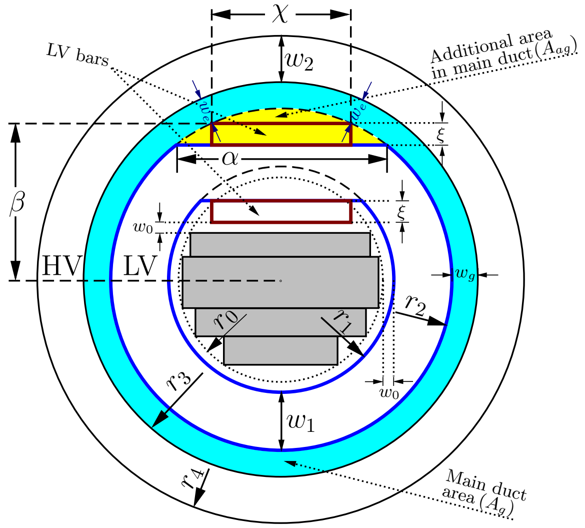

Fig. 3. Schematic diagram of one phase of the transformer with a deformed LV winding

B. Analytical Formulation for Coils with Deformation

Figure 3 shows schematically a phase of a transformer with a deformed LV windings and bar leads. Figure 3 shows that the deformation of the LV coil originates an additional area in the main duct, which did not exist in the case of circular windings of Figure 2. This additional leakage area will be called A_{ag} and added to the area of the main duct to obtain a better approximation of leakage reactance. Consequently, (3) will be corrected to consider the deformation of LV as follows

$$X_a = \frac{2\pi\mu_0 f S_b}{\left(V_b/N\right)^2 (h+s)} \cdot \left\{ \begin{array}{l} (A_g + A_{ag}) + \frac{A_1}{3} + \frac{A_2}{3} \\ + \frac{\pi w_1^2}{6} - \frac{\pi w_2^2}{6} \end{array} \right\} \tag{4}$$

In this case, X_a refers to the leakage reactance calculated with the *corrected* formulation. Note that the effect of the current flowing in axial direction through the external bar has been ignored in the formulation of X_a. This can be justified by the fact that the magnetomotive force contribution of the outer bar is $1/N$ times that of the winding and on the other hand the direction of the field produced by the current flowing through the bar is mostly orthogonal to that of the main duct.

In order to calculate X_a it is necessary to find an expression to determine the additional leakage area A_{ag}. The first step will be to determine an expression for the length of the flat part α. Using the Pythagoras' theorem the following expression can be found

$$\alpha = 2\sqrt{r_2^2 - (\beta - \xi)^2} \tag{5}$$

where ξ is the thickness of the bar. From the equation of the circumference, the distance β can be calculated as follows

$$\beta = \sqrt{r_2^2 - (\chi/2)^2} \tag{6}$$

where χ is the width of the bar. Finally, to determine the additional leakage area A_{ag}, the exact formula of the general circular segment area is used [13]. Hence the additional leakage area can be calculated as follows

$$A_{ag} = r_2^2 \cos^{-1}\left(\frac{\beta - \xi}{r_2}\right) + \frac{\alpha}{2}(\xi - \beta) \tag{7}$$

It should be noted that the leakage area of the LV winding A_1 is also affected by the deformation. However, it can be

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considered that this variation is not significant and to account for this effect would complicate the formulation unnecessarily. On the other hand, only one third of this area is used to calculate the leakage reactance. Therefore, it will be assumed that the leakage area of the LV winding remains unchanged when deformation is present.

It should also be noted that Figure 3 shows that the core has fewer stacks on the side of the bars than on the opposite side. This asymmetry of the core has the purpose of preserving the minimum clearance between the internal bar and the core (w_0) while avoiding the increase of the internal duct between the core and the LV winding. The magnetic flux density is to be calculated using the effective cross section of this asymmetrical core.

IV. DETAILED CALCULATION OF LEAKAGE REACTANCE USING FEM3D

The purpose of performing detailed FEM3D calculations is to be able to compare the results of the corrected formulation with a model free of the effects inherent to measurements such as imperfect equipment calibration, voltage drop in the short circuit bars during the test and possible effects of strong magnetic fields on the measuring devices.

The FEM3D model has been implemented so as to represent as accurately as possible the geometry of the transformer and especially the deformation of the LV winding. Some of the most relevant features of the FEM3D model used are listed below.

The deformation of the LV coil was represented in detail as shown in Figure 3. The inner and outer LV bars have been modeled with their respective currents. The internal cooling ducts of both windings have been modeled. The magnetic gap of the taps was modeled in the HV winding. Core asymmetry was considered in the model. The leakage reactance was calculated from the energy stored in the magnetostatic field [14]. The implemented model is parametric, which made it possible to represent each case study by changing the value of the geometrical and electrical variables corresponding to each one. The software used to perform the simulations was Ansys Maxwell 18.1.0 on a 2.8 GHz Core i7 desktop computer with 32 GB of RAM. The maximum adaptive error specified for the simulations was 0.1 %. In Figure 4 shows three views of the implemented model. The dimensions of the model of Figure 4 belongs to the case study 1.

As shown in Figure 4, two cross sections have been implemented, one in the flat zone and the other in the circular zone, both outside the core window. These sections allow a visualization of the behavior of the magnetic field in these critical areas in greater detail. Figure 5 shows the field distribution for each section of case study 1. It can clearly be seen that the main duct in the area of the deformation (Sec. A) is considerably larger than the main duct of the circular zone (Sec. B). On the other hand, an increase in the leakage area of the LV winding can also be observed, which could be attributed to the current flowing through the LV bar leads.

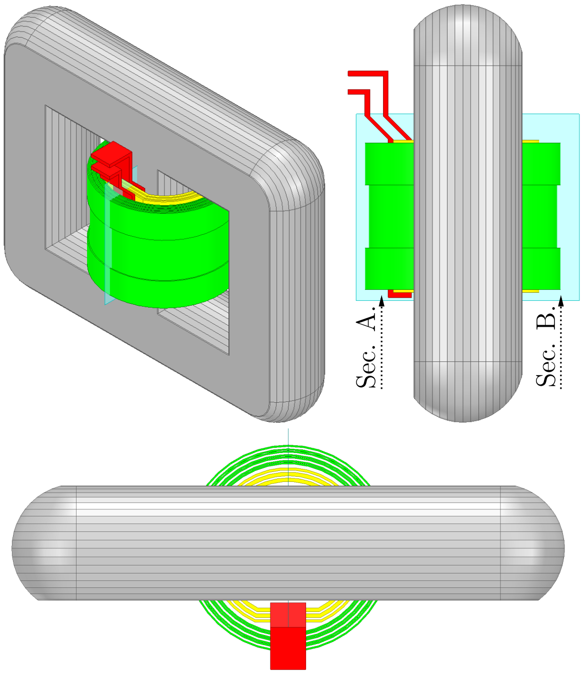
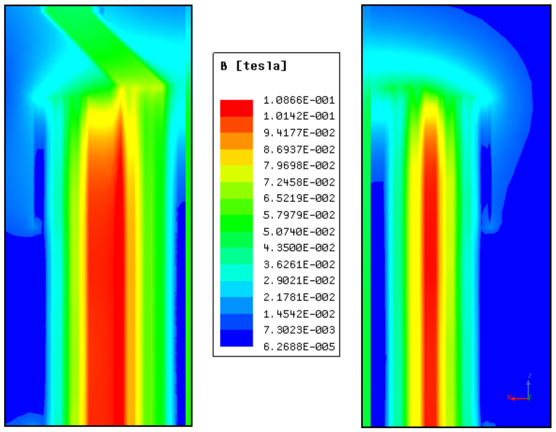


Fig. 4. Different views of the 3D model of the case study 1



Sec. A. Sec. B.

Fig. 5. Field distribution in the flat zone (Sec. A) and in the circular zone (Sec. B) for case study 1

V. VALIDATION AND RESULTS

This section will present the results found by applying the calculation methods presented in the previous sections of this paper. A comparison of the performance of these results against the measured values in real transformers are also shown. Table II presents a summary of the constructive information for all case studies whose parameters were already described in Section III-A. The results presented in this section are: the calculated leakage areas of the main duct and the additional leakage area due to deformation, the leakage reactances calculated with the current formulation X_c, with the corrected formulation X_a and with FEM3D X_{3D}, and finally relative errors between the measured value X_m and X_c, X_a, and X_{3D}.

TABLE II
CONSTRUCTIVE DATA AND RESULTS FOR THE 4 CASE STUDIES

Variable (unit)	Case Study 1	Case Study 2	Case Study 3	Case Study 4
S_b (MVA)	1.33	1.26	5.67	5
f (Hz)	50	60	60	60
V_b (V)	288.7	277.1	2401.8	2401.8
N (-)	8	9	33	29
h (mm)	448.4	663.7	925.9	596.8
r_0 (mm)	182.5	155.5	235.5	253
r_1 (mm)	189.5	162.5	242.5	260
r_2 (mm)	229.5	193.5	306.5	326
r_3 (mm)	239.5	209.5	317.5	342
r_4 (mm)	293.5	252.5	396.5	423
ξ (mm)	15	10	8	8
χ (mm)	100	120	80	80
A_g (mm^2)	14734.1	20257	21563.9	33577.3
A_{ag} (mm^2)	2618.0	2230.5	1136.8	1146.7
A_{ag}/A_g (%)	17.8	11.0	5.3	3.4
X_m (%)	5.58	5.04	6.09	7.36
X_c (%)	5.16	4.73	6.03	7.31
X_a (%)	5.38	4.93	6.09	7.37
X_{3D} (%)	5.48	4.98	6.10	7.38
$\varepsilon_{m.c}$ (%)	-7.53	-6.15	-0.99	-0.68
$\varepsilon_{m.a}$ (%)	-3.58	-2.18	0.00	0.14
$\varepsilon_{m.3D}$ (%)	-1.74	-1.11	0.15	0.28

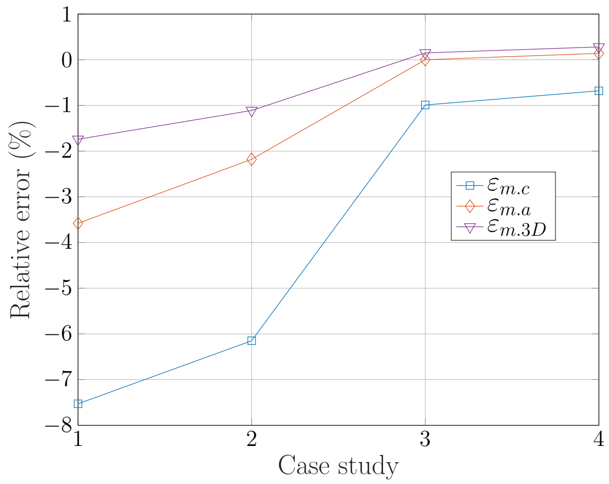


Fig. 6. Relative errors using different calculation methods for the 4 case studies

Table II shows that the case study having the greatest deviation between the measured value X_m and the calculated value using the current formulation X_c is the case with the greatest ratio between the additional leakage area A_{ag} and the main duct area A_g. This reinforces the idea that leakage reactance alteration has a strong component related to the increase in the area of the main duct.

Figure 6 shows graphically the behavior of the relative error for each case study. As can be seen, the corrected formulation gives greater accuracy than the current formulation in all case studies. The 3D finite element calculation provides the best results among the three methods. However, the average simulation time for a case study was 9.2 minutes, which is an excessively long time for design and optimization purposes.

VI. CONCLUSIONS

In this paper a corrected calculation procedure for the leakage reactance in deformed low voltage windings has been presented. It has been found that the corrected formulation gives better results than the current formulation in all case studies, by applying corrections according to the necessity: large ones for cases with large deviations from measured values (case studies 1 and 2) and small ones for cases with values close to the measurements (case studies 3 and 4).

As a rule of thumb obtained from the analysis performed, it can be concluded that transformers with a ratio between the additional area and the main duct area (A_{ag}/A_g) greater than 10 % are prone to present significant increases in leakage reactance due to deformation of the LV winding, and it is advisable to use the corrected formulation or detailed studies using FEM3D for these transformers.

It was also shown that although the most faithful model possible was implemented with FEM3D, there are still discrepancies between the calculated values and the measured values, which are not explained by the idea of the additional leakage area.

For future work the authors propose an investigation of the 3D effects of the current distribution in the foil conductor and the bar leads on leakage reactance. It is clear that the necessary computational resources to perform this type of simulation will be much greater due to the fact that each single foil will have to be modelled and discretized.

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VIII. APPENDIX

A. Test Data of the Case Studies

The test data for each case study is presented in Table III. The variable S_n represents the three-phase rated power of the transformer, V_n is the HV rated voltage (line to line), V_{scm} is the short-circuit voltage measured from the HV side, P_{scm} is the measured short-circuit power, R_m is the percentage resistance, Z_m is the percentage impedance and finally X_m is the measured percentage leakage reactance.

It is important to note that variables the V_{scm} and P_{scm} are

TABLE III
TEST DATA OF THE CASE STUDIES

Variable (unit)	Case Study 1	Case Study 2	Case Study 3	Case Study 4
Vector Group	Dyn5	Dyn11	Dyn1	Dyn1
S_n (kVA)	4000	3780	17000	15000
V_n (V)	10000	13800	13800	13200
V_{scm} (V)	564	703	842	973
P_{scm} (W)	31865	28538	61501	63090
R_m (%)	0.80	0.75	0.36	0.42
Z_m (%)	5.64	5.09	6.10	7.37
X_m (%)	5.58	5.04	6.09	7.36

obtained from direct measurements, while R_m, Z_m and X_m are obtained indirectly from the following expressions [15]

$$R_m = \frac{P_{scm}}{S_n}$$
$$Z_m = \frac{V_{scm}}{V_n}$$
$$X_m = \sqrt{Z_m^2 - R_m^2}$$

The general test conditions for all case studies are described next: *a)* The tests were performed by short-circuiting the three LV phases and fed from HV side with a three-phase synchronous generator; *b)* All test data are referred to a test temperature of 20 degrees Celsius; *c)* The value of the short-circuit voltage V_{scm} reported in Table III corresponds to the average of the voltages measured on the three lines; *d)* For case study 2, the data of two identical units were available. The data reported in the Table for V_{scm} and P_{scm} correspond to the average of the data of both units.

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Guillermo A. Diaz F. Was born in Bogota, Colombia, in 1984. He received a B.S. degree in electrical engineering from the Universidad de La Salle (2006) and a Ph.D. degree in electrical engineering from Universidad Nacional de San Juan (2013). He worked as a researcher, electrical designer and programmer from 2006 to 2013 at the Siemens Andina Transformers Factory. In addition, he performed a research internship at the High Voltage Institute of RWTH, Aachen, Germany. He presently works in the Faculty of Engineering of the La Salle University, Colombia, as a Lecturer and Researcher. His main fields of interest are design, optimization and magnetic/electric modeling of electrical equipment such as transformers, motors and electric generators.

Enrique Esteban Mombello (IEEE M’95-SM’00) was born in Buenos Aires, Argentina, in 1957. He received the B.S. degree in electrical engineering and the Ph.D. degree in electrical engineering in 1982 and 1998, respectively from Universidad Nacional de San Juan. He has more than 20 years of experience in research projects which include topics like electrical transients and resonance processes within transformers as Researcher of the National Council of Technical and Scientific Research (CONICET, Argentina). He has worked from 1989 to 1991 at the High Voltage Institute of RWTH, Aachen, Germany. He is presently at the Instituto de Energia Electrica of the University of San Juan, Argentina, as a Lecturer and Researcher since 1982. His main fields of interest are design, modeling and diagnostics of power transformers, asset management, transformer life management, electromagnetic transients in electric machines and networks, modeling of equipment, corona losses in overhead transmission lines, low frequency electromagnetic fields.

Guillermo D. Guidi Venerdini was born in San Juan, Argentina on January 8, 1980. He received the electrical engineer degree from Universidad Nacional de San Juan (UNSJ), Argentina, in 2007 and the Ph.D. Degree in Electrical Engineering in 2011 from the UNSJ. Currently, he is a Researcher with the Instituto de Energa Elctrica of CONICET-UNSJ. His research interests are electromagnetic transients and renewable energies.