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About the difference between zero-sequence magnetizing impedances of a 3-phase core-type transformer

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ABSTRACT

This paper analyzes the difference between zero-sequence magnetizing impedances (Z_{0M}) of a 3-phase core-type transformer. Z_{0M} in per-unit is smaller for an external winding than for an internal winding. The difference between both Z_{0M} values is similar to the positive-sequence short-circuit impedance between both windings for units without magnetic shunts on the tank wall as well as for units without tank. This fact can be observed in measured values, and in the results of 3D models. However, the results of simple 2D models do not show this behavior; therefore, this paper demonstrates that this fact only can be explained from 3D models. The results are shown for different cases: transformers with and without magnetic shunts on the tank wall, and transformers without tank. In transformers with magnetic shunts on the tank wall, or in magnetostatic simulations of transformers with tank, the difference between both Z_{0M} values is not very similar to the positive-sequence short-circuit impedance between both windings.

1. Introduction

Zero-sequence impedances (Z_0) of 3-phase core-type transformers can be classified as [1] magnetizing impedances (Z_{0M}), and short circuit impedances. Z_{0M} values are measured with zero-sequence currents in only one transformer side (i.e., without current in other windings). Z_{0M} values for the outer windings (Z_{0M1}) are lower than for the internal windings (Z_{0M2}) [1–6]. Some papers indicate that the difference between these two Z_{0M} values ($Z_{0M2} - Z_{0M1} = \Delta Z_{0M}$) is equal to the short-circuit positive-sequence impedance between correspondent windings (Z_{12}) [2–4]. An "analytical demonstration" of this relationship ($\Delta Z_{0M} = Z_{12}$) is shown in Ref. [2], by means of the analysis of a simplified magnetic circuit. However, if this relationship were exact, then only two Z_0 values would be enough to obtain the equivalent circuit of YNyn transformers, and the international standards [6,7] clearly indicate that three Z_0 values are required for this purpose. An example with the measured Z_{0M} values for three different conditions (with tank, without tank, and with magnetic shunts on the tank wall) is shown in Ref. [8], and a different value of ΔZ_{0M} can be computed for each condition.

Z_{0M} values are nonlinear, mainly due to the tank effect. Some references show Z_{0M} as a function of zero-sequence voltage [1,9–11], while other references show Z_{0M} as a function of neutral current [6,8]. Both magnitudes, zero-sequence voltage (V_0) and neutral current (I_N), are measured during the tests to obtain Z_{0M}. Those papers that indicate the ΔZ_{0M} is equal to Z_{12} [2–4], do not indicate if ΔZ_{0M} should be computed with impedances measured at the same per-unit value of V_0, or at the same per-unit value of I_N (or at any other specific condition).

This paper analyzes the difference between Z_{0M} values by considering measured values, and results of 3D models, in order to show that ΔZ_{0M} is similar (but not equal) to Z_{12}, for cases without magnetic shunts on the tank wall and for cases without tank. Results of ΔZ_{0M} from 2D models are not very similar to Z_{12}; therefore, this paper shows that this condition ($\Delta Z_{0M} \approx Z_{12}$) cannot be deduced from simple 2D models. On the other hand, in transformers with magnetic shunts on the tank wall, or in magnetostatic simulations of transformers with tank, ΔZ_{0M} is not very similar to Z_{12}.

The use of measured values and the use of results of models are important for the analysis of the difference between Z_{0M} values. Many models for the calculation of transformer inductances are based on computing magnetic fields by using numerical methods. Numerical methods for computing magnetic fields have shown to be reliable as tools for design and analysis of power transformers (some examples are in Refs. [12–18], but the literature about this point is really abundant). On the other hand, the literature about

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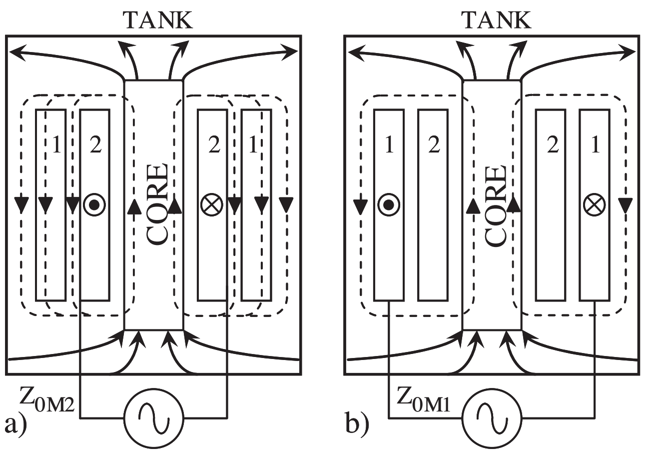

Fig. 1. Main paths for ZSMF (arrows) during Z_{0M} tests. Solid lines are related to fluxes through the tank. (a) Test for Z_{0M2}; (b) test for Z_{0M1}.

the use of numerical methods for the calculation of Z_0 values of 3-phase core-type transformers is not abundant. Recently, it has been shown that Z_{0M} can be computed with 2D axisymmetrical models, by applying some approximations in order to consider that the real 3D geometry is not axisymmetrical [19,20]. However, a detailed analysis about the difference between the Z_{0M} values of a 3-phase core-type transformer had not been shown in the literature

2. Zero-sequence magnetic fluxes during Z_{0M} tests

A qualitative description of zero-sequence magnetic fluxes (ZSMF) during Z_{0M} tests is useful for the understanding of phenomena related to this paper. Fig. 1 shows the two main paths for the ZSMF: the ZSMF inside the winding connected to the power source may return through the tank, or through the space between this winding and the tank.

The path through the tank has high magnetic permeability but there is a gap for the ZSMF in this path. On the other hand, the currents induced in tank limit the ZSMF through the tank.

The ZSMF through the space between the tank and the winding connected to the power source is not negligible, and this non-ferromagnetic area is different whether this winding is the innermost one or the outermost one. Due to this reason, the two measured Z_{0M} values are different from each other.

Fig. 2 shows simplified magnetic circuits for the conditions of the Z_{0M} tests. F is the exciting magnetomotive force. R_C is the core reluctance. R_1 is the reluctance of the space between the magnetic core and the winding connected to the power source. R_3 is the non ferromagnetic reluctance of the return path of the flux, outside the

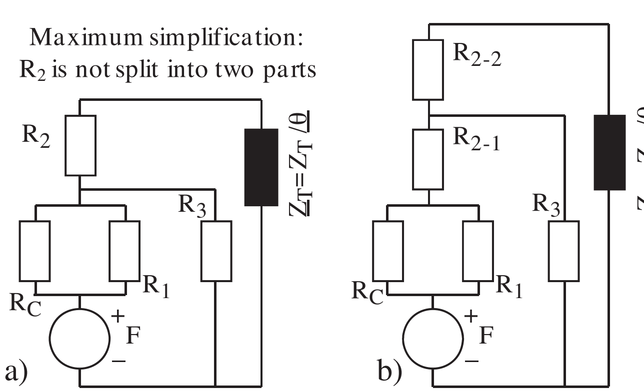

Fig. 2. Simplified magnetic circuits for representing Z_{0M} tests.

Table 1
Main characteristics of analyzed transformers.

Unit	kVA	kV_1	kV_2
1	100 000	259.05	55
2	75 000	220	71
3	25 000	45	16.05
4	15 000	45	16.05
5	5000	34.5	13.8
6	5000	34.5	13.8
7	1500	14.4	4.8
8	500	22.7	0.48
9	5.2	0.416	0.24

Note: Data of unit 1 were taken from Ref. [8].

winding connected to the power source (the space between this winding and the tank). R_2 is a simplified reluctance for the gap between the core and the tank (Fig. 2a). R_2 can be split into two parts ($R_{2\text{-}1}$ and $R_{2\text{-}2}$; Fig. 2b), as it is described in Appendix A. $\underline{Z}_T$ is the complex reluctance of the tank (a complex value is necessary in order to consider the effect of induced currents on the magnetic fluxes [18]; this effect is negligible in the core).

If R_2 is not split into two parts (Fig. 2a), then R_3 could be seen as: (a) a single value ($R_{3\text{-}1}$), for the case of Z_{0M1}; (b) $R_{3\text{-}1}$ in parallel with the reluctance between windings (R_{12}), for the case of Z_{0M2}. This simplification leads to $\Delta Z_{0M} = Z_{12}$, as it is shown in Appendix B, because Z_{12} is directly related to R_{12}. Thus, this simplification is equivalent to the "analytical demonstration" shown in Ref. [2].

If R_2 is considered to be split into two parts (Fig. 2b), then the exact point for the connection of R_3 depends on the ratio between $R_{2\text{-}1}$ and $R_{2\text{-}2}$. This ratio depends on the winding connected to the power source. Therefore, the exact point for the connection of R_3 is not the same for both tests (Z_{0M1} and Z_{0M2}), if R_2 is considered to be split into two parts, and $R_{3\text{-}1}$ would not be directly in parallel with R_{12} for the case of Z_{0M2}. This simplified explanation justifies why ΔZ_{0M} is not exactly equal to Z_{12}. Another simplified way to see that $R_{3\text{-}1}$ is not directly in parallel with R_{12} for the case of Z_{0M2} is by considering that the width of windings has an influence on a more detailed map of reluctances for these cases.

On the other hand, if the winding connected to the power source is the outer one, then: (a) R_1 has a lower value because the area between the winding and the magnetic core is greater, and this fact tends to increase Z_{0M}; (b) R_3 has a greater value because the area between winding and tank is lower in this case, and this fact tends to decrease Z_{0M}. The effect of R_3 is more important because R_1 is in parallel with R_C, and $R_C \ll R_1$. Therefore, this fact demonstrates that Z_{0M} is smaller for an external winding than for an internal winding ($Z_{0M1} < Z_{0M2}$). This simplified explanation is valid for Fig. 2b, and it is also valid for Fig. 2a.

3. Analyzed units

Table 1 shows the main characteristics of the analyzed units. Only measured data are available in some cases, only results of simulations are available in other cases, and there are some cases with measured data and results of simulations. The computed values were obtained with a FEM software [21] by applying linear models. Unit 9 is very small, and results for this unit are analyzed at the end of this paper.

4. Cases with tank, without magnetic shunts

4.1. Measured values

Table 2 shows the available Z_{0M} measurements. For units 3 and 4, measured values at the same I_N (pu) and at the same V_0 (pu) are available. Approximately, the difference between ΔZ_{0M} and Z_{12} is