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Rules to estimate the expected values of zero-sequence impedances in 3-phase core-type transformers

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ABSTRACT

Simple rules to estimate the expected values of zero-sequence impedance measurements for 3-phase core-type transformers are shown. The proposed rules are based on the analysis of magnetic circuits. Due to this fact, a conceptual description about zero-sequence impedances of these transformers is included. The rules were verified with measurements on fifteen transformers, and these measurements were used for refining the rules. In case of magnetizing zero-sequence impedances, the presence or not of magnetic shunts on tank walls defines the details of these rules. In case of short-circuit zero-sequence impedances, only the positive-sequence transformer impedances are necessary to apply the proposed rules. These rules are important in order to reduce the probability of errors during the tests. Some rules related to the resistive part of the impedances are also presented.

1. Introduction

Three-phase core-type transformers are also known in the literature as 3-phase 3-limb transformers, or 3-phase 3-leg transformers. Zero-sequence impedances (Z_0) of 3-phase core-type transformers have been studied for years [1–20]. There are standardized procedures for Z_0 measurements [11–13], which are based on feeding a wye side of the transformer with zero-sequence currents. Induced zero-sequence currents could be or not circulating in other transformer sides, depending on the specific test. Only the standardized procedures for Z_0 measurements are considered in this paper.

Z_0 values of transformers depend on their design. Measured values of Z_0 for transformers may be classified as [1]: "no-load type" (very high value), "reactor type" (Z_0 is in the order of 1 pu), and "short-circuit type" (Z_0 values are relatively low, in the same order of positive-sequence short-circuit impedances). "No-load type" and "reactor type" values are measured with current only in the winding connected to the source (under these conditions, 3-phase core-type units have "reactor type" values, whereas 3-phase units with closed ferromagnetic path for zero-sequence fluxes have "no-load type" values). For 3-phase core-type transformers, "reactor type" values can be also called zero sequence magnetizing impedances (Z_{0M}) because there is not circulating current in the other windings (but there is induced zero-sequence current in the tank). Zero-sequence short-circuit impedances (Z_{0SC}) are measured with induced zero-sequence currents in other wye side or in delta windings.

Most of available values for this article were taken from measurements on YNynd transformers. The analysis of YNynd transformers requires the study of YNyn and Dyn connections. For 3-phase core-type YNynd transformers: (a) Z_{0M} are measured with the other wye side in open-circuit and the tertiary in open-delta condition; (b) all the other possible measurements are Z_{0SC}, and they can be obtained with one transformer side without current or with all the windings with currents.

These differences between the Z_0 values are not evident in some literature about this topic. There are references with a clear difference between the diverse Z_0 values [1–13], but some documents only present a wide range of "reactor-type" values [14–16]. The relative position (inner/outer) of the winding connected to the source during the test determines the values of the measurements in core-type transformers, and only few references [6–11] consider this key point, but useful ways to estimate the measurements are only available in a subset of them [10,11]. Fortunately, an IEC standard [11] has some rules for estimating the values of Z_0 measurements, but without any explanation about the origin of such rules. Some concepts related to the nature of these Z_0 values were previously analyzed (in papers about their determination, with the help of computing magnetic fields in transformer geometry [21–23]), but an integral description about them is still necessary, and this paper is a contribution for it.

Unavailability of expected values for Z_0 has an influence in some human errors during the tests (and such errors could be easily corrected during the tests if the persons know the expected values for Z_0). For

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Table 1
Main data of analyzed transformers.

Unit	Connection	MVA	kV	MS
1	YNynd	15/15/5	45/16.05/10	N
2	YNynd	15/15/5	45/16.05/10	N
3	YNynd	25/25/8.33	45/16.05/10	N
4	YNynd	25/25/8.33	66/21/10	N
5	YNynd	25/25/8.33	45/16.05/10	N
6	YNynd	30/30/10	136/21/10	?
7	YNynd	30/30/10	132/16.05/10	Y
8	YNynd	75/75/25	220/71/10	Y
9	YNynd	100/100/60	220/60/10	?
10	YNynd	120/120/40	230/46/10	?
11	YNynd	120/120/40	230/45/10	Y
12	YNynd	150/150/50	230/71/20	N
13	YNyn	5	34.5/13.8	N
14	YNyn	40	115/12	Y
15	YNyn	100	259.05/55	B

Note: Column "MS" indicates the presence of magnetic shunts on tank walls; "Y" is Yes, "N" is No, "?" is unknown, and "B" indicates that measurements for both cases are available. These magnetic shunts on inner tank walls are included in some power transformers to reduce the tank heating due to leakage flux (a detailed description about them can be found in Ref. [10]).

example, during the analysis of the test data for this research, different mistakes were detected and corrected (in the reported ranges of measurement devices, in the reported taps of instrument transformers, and in the use of per-unit system), and other mistakes were corrected during some factory tests. These facts illustrate the practical usefulness of having rules for estimating the Z_0 values in order to reduce the probability of human errors during these tests.

The aim of this paper is the presentation of simple rules to estimate the measurements of Z_0 for 3-phase core-type transformers, from the positive-sequence impedances. A conceptual description about the nature of Z_0 in these transformers is included because the proposed rules are based on it. The proposed rules can be considered as a complement for the rules of the aforementioned IEC standard [11]. The rules were verified with measurements on transformers from 5 to 150 MVA, which are typically installed in substations of electric utilities.

2. Main data of analyzed transformers and nomenclature for zero-sequence impedances

Table 1 shows the main data of 15 analyzed transformers, from 8 different manufacturers. Data of unit 15 were taken from Ref. [1]. Only the highest MVA rated value of YNynd transformers is identified in the following sections (and this value is considered to show all the impedances in per-unit).

Z_0 of YNynd transformers can be measured by feeding a wye side with the other wye side open-circuited or short-circuited, and the tertiary delta can be connected or opened. This fact implies eight possible Z_0 measurements. The analysis of YNynd transformers requires the study of YNyn and Dyn connections because one side of the YNynd transformer can be without current during the test (and only the windings with currents determine the magnetic fluxes within the transformer). Therefore: (a) the YNynd transformer with open-delta is similar to the YNyn connection; (b) the YNynd transformer with closed-delta and with the other wye side open-circuited is similar to the Dyn connection.

The eight possible Z_0 measurements for the YNynd connection are: $Z_{1\text{-}O}$, $Z_{2\text{-}O}$, $Z_{1\text{-}S}$, $Z_{2\text{-}S}$, $Z_{1\text{-}O\text{-}D}$, $Z_{2\text{-}O\text{-}D}$, $Z_{1\text{-}S\text{-}D}$, $Z_{2\text{-}S\text{-}D}$. The first subscript represents the wye winding connected to the source during the test (1: outer; 2: inner), the second subscript represents the connection of the other wye winding (O: open; S: short-circuited), and the third subscript represents the connection of the tertiary (none: open-delta; D: closed-delta).

The measured positive-sequence short-circuit impedances are: Z_{12}, Z_{13}, Z_{23} (subscript 3 is for tertiary-delta). The values for the positive-sequence equivalent circuit are: Z_1, Z_2, Z_3.

This article considers that tertiary can be the most internal winding (T21) or tertiary can be the most external winding (21T). Codes T21 and 21T indicate the order of windings, from the innermost one to the outermost one.

In case of YNyn transformers, there are only four possible measurements ($Z_{1\text{-}O}$, $Z_{2\text{-}O}$, $Z_{1\text{-}S}$, $Z_{2\text{-}S}$). That is, the nomenclature is equivalent to the YNynd case with open-delta.

All these possible measurements for Z_0 are not available in the analyzed transformers because all these measurements are not mandatory in the current standards [11–13]. Furthermore, the measurements of active power during these tests are not mandatory [11–13], and the number of units with available data about the angle of Z_0 is very low.

Information about the presence of magnetic shunts on tank walls is not available for units 6, 9 and 10. This fact is not important for the purpose of this article, since only Z_{0SC} values are analyzed for units 6, 9 and 10, and the presence of magnetic shunts on tank walls has no influence on the developed rules for Z_{0SC}.

3. Zero-sequence magnetizing impedances

3.1. Analysis of magnetic circuits

Fig. 1 shows the two main paths for the zero-sequence magnetic flux (ZSMF) during the tests for the measurement of zero-sequence magnetizing impedances ($Z_{1\text{-}O}$, $Z_{2\text{-}O}$). In case of YNynd transformers, Fig. 1 only shows the two wye windings because the delta is opened (this condition is similar to the YNyn connection).

ZSMF inside the winding connected to the source can 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 (Z_0 is "reactor-type"). On the other hand, the currents induced in the tank limit the ZSMF through the tank.

The ZSMF through the space between the tank and the winding connected to the source is not negligible, and this non-ferromagnetic area is different if this winding is the inner one or the outer one. Due to this reason, the measured Z_0 values are different when the inner winding or the outer winding is connected to the source. In general, $Z_{2\text{-}O}$ is greater than $Z_{1\text{-}O}$, and this fact has been previously demonstrated with the help of a simplified magnetic circuit [21].

An oversimplification of the magnetic circuit would lead to obtain that the difference (ΔZ_{0M}) between $Z_{2\text{-}O}$ and $Z_{1\text{-}O}$ is the positive-sequence impedance between these windings (Z_{12}), and it has been previously shown [21] that this rule should not be applied in case of

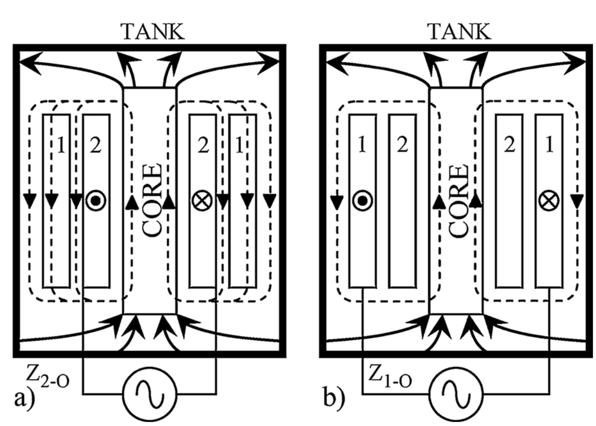

Fig. 1. Schematic view of main paths for ZSMF (arrows) during the measurements of zero-sequence magnetizing impedances. Solid lines are related to fluxes through the tank. (a) Test for $Z_{2\text{-}O}$; (b) test for $Z_{1\text{-}O}$.