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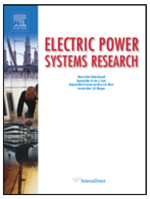

Rules to estimate the expected values of zero-sequence impedances in 3-phase core-type transformers

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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

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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 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.

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]).

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 transformers with magnetic shunts on tank walls. However, ΔZ_{0M} is approximately Z_{12} for units without magnetic shunts on tank walls [21], and this fact is taken to formulate the first rule related to Z_{0M}. On the other hand, for cases of transformers with magnetic shunts on tank walls, an additional analysis of measured and computed values of Z_{0M} in Ref. [21] indicates that ΔZ_{0M} is lower than Z_{12} for this type of transformers; this point had not been previously highlighted and it is also taken to formulate the first rule related to Z_{0M}. Thus, the first rule related to Z_{0M} is:

$$\Delta Z_{0M} = Z_{2\text{-}O} - Z_{1\text{-}O} \approx K_0 \; Z_{12} \tag{1}$$

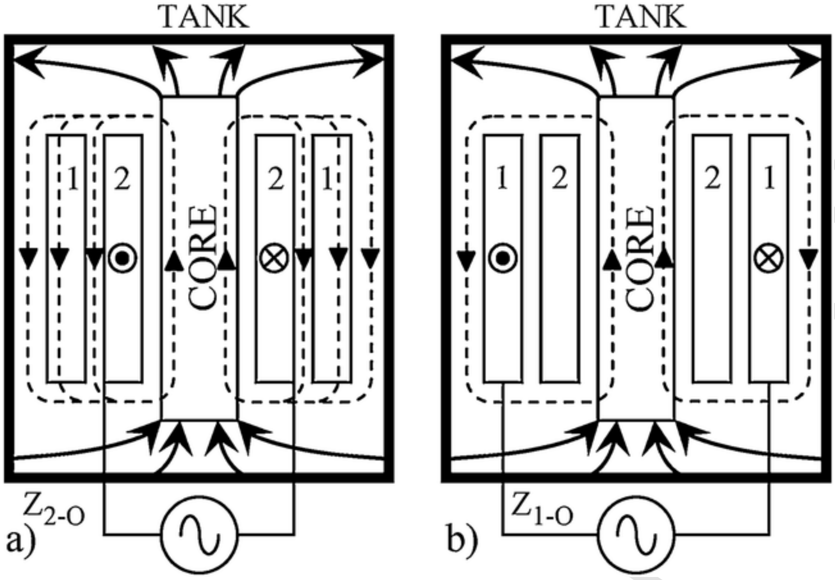

Fig. 1. Schematic view of main paths for ZSMF (arrows) during the measurements of zero-sequence magnetizing impedances. Solid lines are related to fluxes through the tank. (a) Test for $Z_{2\text{-}O}$; (b) test for $Z_{1\text{-}O}$.

$K_0 = 1$ for units without magnetic shunts on tank walls, otherwise $K_0 < 1$.

Magnetizing Z_0 values are dependent of nonlinearity of tank steel [2–5,10,22]. An example of this nonlinearity is shown in Fig. 2. Therefore, the application of this rule should be performed under some specific conditions. The recommendation from Ref. [21] is the application of this approximation when both values ($Z_{1\text{-}O}$, $Z_{2\text{-}O}$) are taken at the same current in per-unit (if both values are taken at the same zero-sequence voltage in per-unit, the approximation error is slightly greater [21]). Results of Fig. 2 are useful to confirm that ΔZ_{0M} tends to be approximately constant if the difference is taken at the same current in per-unit or at the same zero-sequence voltage in per-unit (i.e., obtained curves are practically parallel).

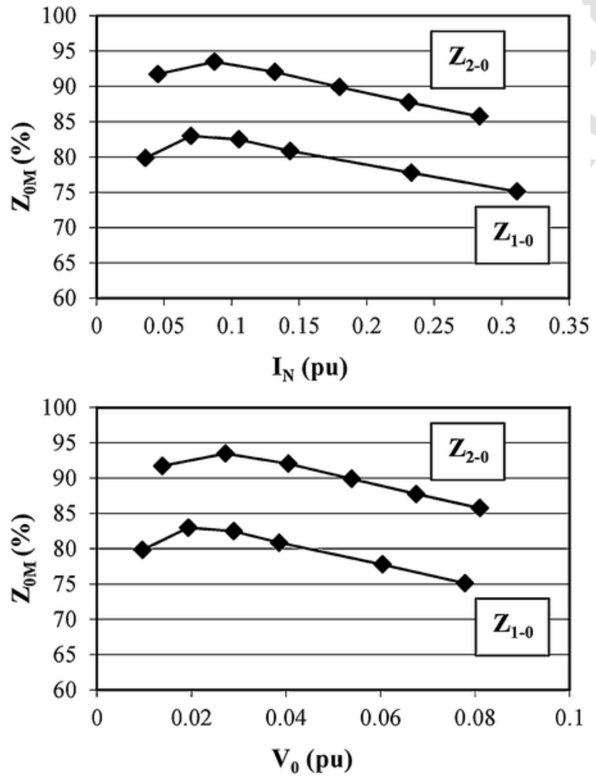

Fig. 2. Example of nonlinearity of zero-sequence magnetizing impedances in core-type transformers (the markers in the graph are the measured values in unit 5).

On the other hand, the second rule related to Z_{0M} is: the expected values of $Z_{1\text{-}O}$ and $Z_{2\text{-}O}$ should be greater for units with magnetic shunts on tanks walls than for units without magnetic shunts on tanks walls. This rule is based on the fact that magnetic shunts on tank walls are ferromagnetic paths which facilitate the ZSMF by the space between the winding connected to the source and the tank (i.e., the aforementioned values of Z_{0M} are greater since the net reluctances are lower). Furthermore, the use of magnetic shunts on tanks walls decreases the ZSMF by the tank; consequently, tank losses during Z_{OM} tests in theses cases should be lower than in cases of units without magnetic shunts on tank walls. Therefore, the third rule related to Z_{0M} is: the expected angles of Z_{0M} should be greater for units with magnetic shunts on tanks walls than for units without magnetic shunts on tanks walls (since values of Z_{0M} are greater, and tank losses during Z_{OM} tests are lower, in cases of units with magnetic shunts on tanks walls).

3.2. *Verification of proposed rules about the magnitudes of Z_{0M}*

Table 2 shows the available Z_{0M} data for the analyzed transformers. A subset of these data was analyzed in Ref. [21] to show that ΔZ_{0M} is approximately Z_{12} for units without magnetic shunts on tank walls but not for units with magnetic shunts on tank walls (i.e., this fact is confirmed here). Two additional points can be highlighted from Table 2: (a) $Z_{1\text{-}0}$ is approximately in the range of 50%–90% for units without magnetic shunts on tank walls, and in the range of 110%–150% for units with magnetic shunts on tank walls; (b) $K_0 \approx 1$ for units without magnetic shunts on tank walls, and K_0 is approximately in the range of 0.55–0.75 for units with magnetic shunts on tank walls. Both points are in accordance with the rules derived from the conceptual analysis shown in Section 3.1. These numerical ranges of values can be improved in the future, from the analysis of additional test data from other core-type transformers (especially in case of transformers with magnetic shunts on tank walls, because the number of analyzed units is very low in this case, and the data of Z_{0M} for unit 14 were not taken exactly at the same per-unit value of I_N).

Table 2
Available data of Z_{0M} for the transformers taken as examples, and computed quotients ($\Delta Z_{0M}/Z_{12}$).

Unit	MVA	$Z_{1\text{-}O}$ (%)	$Z_{2\text{-}O}$ (%)	ΔZ_{0M} (%)	Z_{12} (%)	$\Delta Z_{0M}/Z_{12}$ (pu)	I_N or V_0 (pu)	MS
13	5	50.20	56.99	6.79	6.92	0.98	$V_0 = 0.025$	No
1	15	90.30	100.27	9.97	10.91	0.91	$I_N = 0.2$	No
		88.25	100.27	12.02	10.91	1.10	$V_0 = 0.07$	
3	25	75.05	86.19	11.14	10.76	1.04	$I_N = 0.3$	No
		70.62	83.32	12.70	10.76	1.18	$V_0 = 0.11$	
5	25	77.75	87.73	9.98			$I_N = 0.23$	No
		80.82	92.02	11.20			$V_0 = 0.04$	
14	40	152.88	–	10.42	13.90	0.75	$I_N = 0.17$	Yes
		–	163.30				$I_N = 0.12$	
15	100	109.0	116.0	7.0	12.80	0.55	$I_N = 0.3$	Yes
		55.40	69.00	13.60	12.80	1.06	$I_N = 0.3$	No
11	120	112.8	–	–	–	–	$I_N = 0.16$	Yes

3.3. Angle of Z_{0M}

Table 3 shows the available data for analyzing the angle of Z_{0M} (and the resistive part of Z_{0M}). A recommendation about using an estimated value near to 69° for the angle of Z_{0M} is mentioned in Ref. [22], for transformers without magnetic shunts on tank walls. This angle is close to 72.5°, which is an approximate value mentioned in Ref. [4] (without taking into account the presence or not of magnetic shunts). Results from Table 3 show that these approximate values should not be applied to units with magnetic shunts on tank walls. As mentioned in Section 3.1, tank losses during Z_{0M} test should be lower in this case (and, consequently, the angle of Z_{0M} is higher). Thus, a coarse approximation is: an angle of Z_{0M} near to 70° could be expected for units without magnetic shunts, and an angle of Z_{0M} near to 80° could be expected for units with magnetic shunts on tank walls. Obviously, these rough rules can be refined with more detail, in the future, by analyzing more Z_{0M} data.

3.4. Other rules from literature

Some authors have indicated that $Z_{1\text{-}O}$ could be estimated by multiplying Z_{12} by an empirical factor (K_1) [7–9]:

$$Z_{1\text{-}O} \approx K_1 \; Z_{12} \tag{2}$$

Proposed value of K_1 [8,9] decreases as transformer capacity is larger (e.g., $K_1 \approx 10$ for 10 MVA, and $K_1 \approx 5$ for 80 MVA, as shown in Fig. 3). Table 4 shows the result of applying this estimation to the transformers taken as examples. This comparison shows that this rule should not be applied for transformers with magnetic shunts on the tank walls. This rule of thumb can be applied for units without magnetic shunts on tank walls, considering that differences between measured and estimated values can be in the order of 20%.

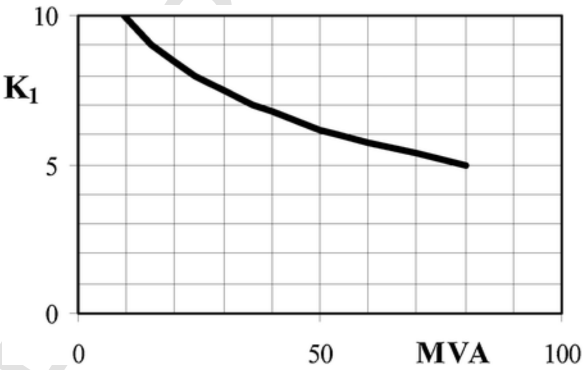

Fig. 3. Values of K_1 (figure reproduced from Ref. [8]).

Table 4
Estimation for $Z_{1\text{-}0}$ using K_1 values from [8].

Unit	MVA	MS	K_1	Z_{12} (%)	$Z_{1\text{-}0}$ (%)	
					Estimated	Measured[a]
13	5	N	11	6.92	76.12	50.20
1	15	N	9.0	10.91	98.19	90.30
3	25	N	7.8	10.76	83.93	75.05
5	25	N	7.8	10.68	83.30	77.75
14	40	Y	6.7	13.90	93.13	152.88
15	100	N	4.6	12.80	58.88	55.40
15	100	Y	4.6	12.80	58.88	109.00
11	120	Y	4.3	13.78	59.25	112.80

[a] Measurement conditions are described in Table 2 for each specific case.

On the other hand, Table 1 of IEC Std. 60076-8 [11] simply indicates two “approximate” values for Z_{0M} ($Z_{2\text{-}0} \approx 60\%$ and $Z_{1\text{-}0} \approx 50\%$), which are not very near to the values shown in Table 2. Fortunately, Section 4.3 of this standard properly indicates that these impedances are nonlinear. Measured values of Table 2 show that the mean value of $Z_{1\text{-}0}$ is nearer to 70% than to 50%, for units without magnetic shunts on tank walls, and the mean value of $Z_{1\text{-}0}$ is near to 130% for units with magnetic shunts on tank walls (variations in results are in the order of 20% in both cases).

Table 3
Data of transformers to analyze the resistive part of Z_{0M}.

Unit		1	3	YNyn
MVA		15	25	40
Measured values (%)	Z_{12}	10.91/87.15°	10.76/87.48°	13.90/88.86°
	Z_{13}	18.25/86.41°	20.03/86.58°	–
	Z_{23}	5.26/79.43°	6.34/80.90°	–
	$Z_{1\text{-}O}$	88.25/65.59°	70.62/70.18°	152.88/77.95°
	$Z_{2\text{-}O}$	100.27/67.71°	83.32/72.30°	163.30/77.78°
$R_{1\text{-}0}$ (%)		36.47	23.93	31.91
$R_{2\text{-}0}$ (%)		38.03	25.33	34.57

Note: R is the real part of the impedances.

3.5. Summary of proposed rules about Z_{0M}

First of all, it should be emphasized that Z_{0M} values are nonlinear. Section 3.2 shows that $Z_{1\text{-}0}$ is approximately in the range of 50%–90% for units without magnetic shunts on tank walls, and in the range of 110%–150% for units with magnetic shunts on tank walls. Eq. (1) shows that $Z_{2\text{-}O}$ can be estimated as $Z_{1\text{-}O} + K_0 \; Z_{12}$ ($Z_{2\text{-}O}$ and $Z_{1\text{-}O}$ values must be taken at the same current in per-unit or at the same zero-sequence voltage in per-unit), and Section 3.2 shows that $K_0 \approx 1$ for units without magnetic shunts on tank walls, and K_0 is approximately in the range of 0.55–0.75 for units with magnetic shunts on tank walls. Thus, these rules allow the estimation of $Z_{1\text{-}O}$ and $Z_{2\text{-}O}$ values.

On the other hand, Section 3.3 shows that a coarse approximation for the angle of Z_{0M} is: (a) near to 70° for units without magnetic shunts; (b) near to 80° for units with magnetic shunts on tank walls.

4. Zero-sequence short-circuit impedances

4.1. Analysis of magnetic circuits

The equilibrium of magnetomotive forces during Z_{0SC} tests is different than in case of positive-sequence short-circuit tests. For positive-sequence short-circuit tests, $N_1I_1 = N_2I_2$ if there are currents only in two windings, and $N_1I_1 = N_2I_2 + N_3I_3$ if there are currents in the three windings (N_1, N_2, N_3 are the numbers of turns; I_1, I_2, I_3 are the winding currents). Nevertheless, these equations are invalid for zero-sequence tests since zero-sequence currents can circulate in the tank.

a) Zero-sequence currents in only two windings

In these cases, the zero-sequence magnetic fluxes (ZSMF) pass through the zone between the winding connected to the source and the short-circuited winding (the closed-delta is considered a short-circuited winding for zero-sequence currents). This fact establishes the following similarities with positive-sequence impedance values: $Z_{1\text{-}S}$ and $Z_{2\text{-}S}$ are similar to Z_{12}, $Z_{2\text{-}O\text{-}D}$ is similar to Z_{23}, and $Z_{1\text{-}O\text{-}D}$ is similar to Z_{13}.

Main return paths for ZSMF are imposed by the relative position of short-circuited winding since the net flux linkages should be almost zero inside it (voltage drop in winding resistance can be considered negligible). The main ZSMF paths for the different tests are shown in Figs. 4 and 5. There are main return paths through the magnetic core if the short-circuited winding is outer than the winding connected to the power source (Figs. 4a, 5a, c, and d), otherwise there are main return paths through the tank (Figs. 4b–d, and 5b).

When the main return paths are through the core, the Z_{0SC} value is very similar to the sequence-positive value:

$$Z_{2\text{-}S} \approx Z_{12} \tag{3}$$

$$Z_{2\text{-}O\text{-}D} \approx Z_{23} \text{ for case 21T} \tag{4}$$

$$Z_{1\text{-}O\text{-}D} \approx Z_{13} \text{ for case 21T} \tag{5}$$

When the main return paths are through the tank, the Z_{0SC} value is lower than the sequence-positive value (and the stray losses are greater because there are more losses in the tank):

$$Z_{1\text{-}S} < Z_{12} \tag{6}$$

$$Z_{2\text{-}O\text{-}D} < Z_{23} \text{ for case T21} \tag{7}$$

$$Z_{1\text{-}O\text{-}D} < Z_{13} \text{ for case T21} \tag{8}$$

b) Zero-sequence currents in the three windings

In these cases, one winding is connected to the power source and two windings are short-circuited. The reference values for the Z_{0SC} values will be the equivalent positive-sequence impedances for the same condition:

$$Z_{123} \approx Z_1 + Z_2Z_3/(Z_2 + Z_3) \tag{9}$$

$$Z_{213} \approx Z_2 + Z_1Z_3/(Z_1 + Z_3) \tag{10}$$

Z_{123} is the sequence-positive equivalent impedance when winding 1 is connected to the source and the other windings are short-circuited. Z_{213} is the correspondent value when winding 2 is connected to the source.

Figs. 6 and 7 show the ZSMF paths for the different tests, for cases T21 and 21T, respectively. There are main return paths of ZSMF through the tank only for $Z_{1\text{-}S\text{-}D}$ in case T21 (Fig. 6b). Thus:

$$Z_{2\text{-}S\text{-}D} \approx Z_{213} \tag{11}$$

$$Z_{1\text{-}S\text{-}D} \approx Z_{123} \text{ for case 21T} \tag{12}$$

$$Z_{1\text{-}S\text{-}D} < Z_{123} \text{ for case T21} \tag{13}$$

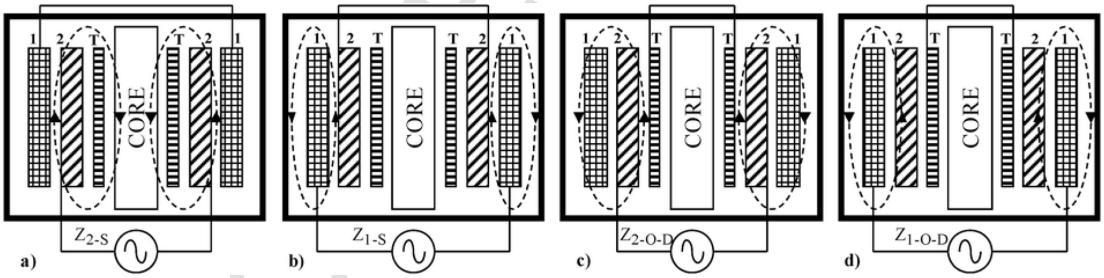

Fig. 4. Schematic view of main paths for ZSMF during Z_{0SC} tests, with zero-sequence currents in only two windings. Case: T21.

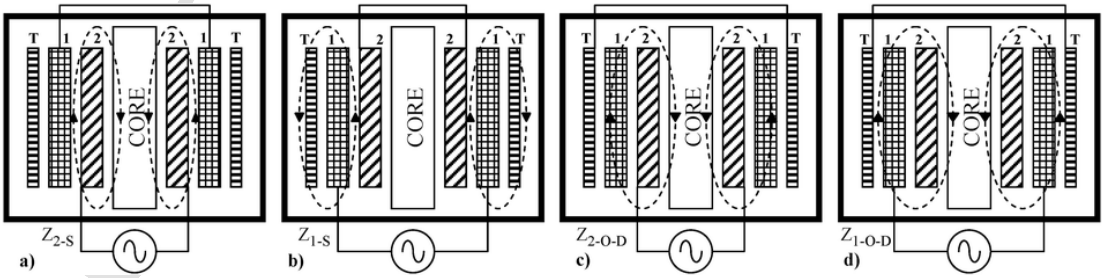

Fig. 5. Schematic view of main paths for ZSMF during Z_{0SC} tests, with zero-sequence currents in only two windings. Case: 21T.

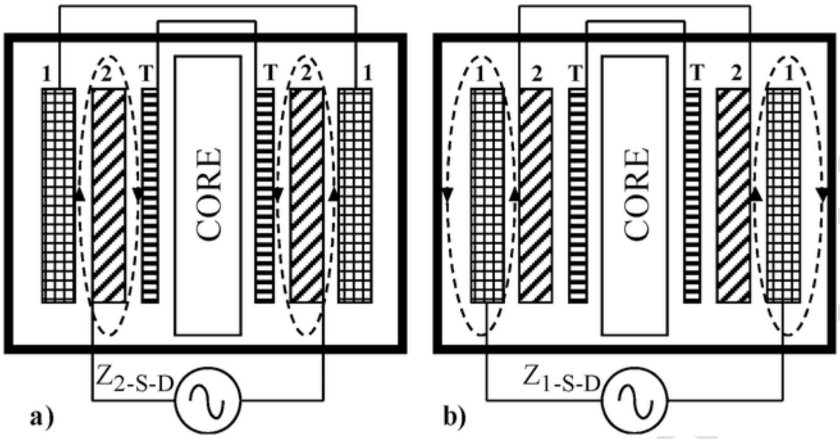

Fig. 6. Schematic view of main paths for ZSMF during Z_{0SC} tests, with zero-sequence currents in the three windings. Case: T21.

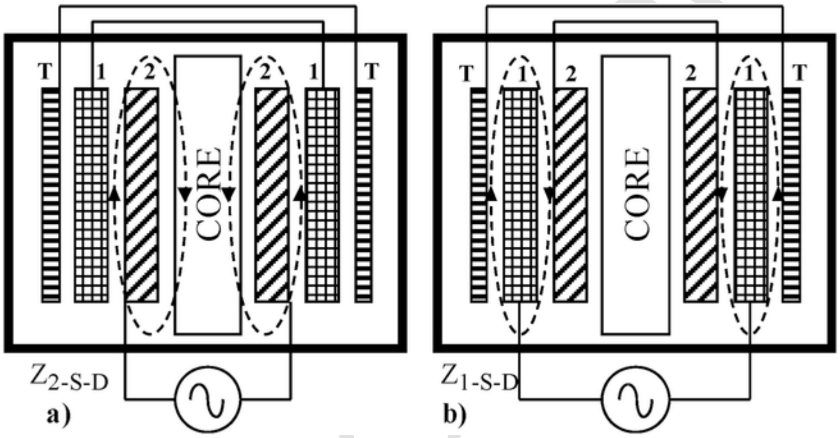

Fig. 7. Schematic view of main paths for ZSMF during Z_{0SC} tests, with zero-sequence currents in the three windings. Case: 21T.

4.2. Verification of proposed rules

Table 5 shows the data for the 15 transformers taken as examples, as well as computed quotients of Z_{0SC} divided by the correspondent positive-sequence impedances. These quotients show that approximations from Eqs. (3) to (13) are very good.

Table 5
Data of Z_{0SC} for fifteen transformers taken as examples, and computed quotients for Z_{0SC}.

Connection	YNynd (T21)									YNynd (21T)			YNyn		
Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MVA	15	15	25	25	25	30	30	75	100	120	120	150	5	40	100
Z_{12}	10.91	10.64	10.76	10.90	10.68	10.90	14.06	14.00	8.87	14.45	13.78	14.11	6.92	13.90	12.80
Z_{13}	18.25	17.55	20.03	19.11	18.10	17.10	21.39	20.79	14.58	21.69	22.47	17.65	–	–	–
Z_{23}	5.26	4.98	6.34	5.55	4.75	4.26	5.04	4.92	4.58	40.17	40.53	35.57	–	–	–
$Z_{1\text{-O-D}}$	16.28	–	16.47	–	15.17	–	–	19.40	13.60	20.88	21.91	–	–	–	–
$Z_{1\text{-S-D}}$	9.95	8.81	9.45	9.59	9.20	10.10	12.87	13.30	8.49	7.65	7.46	7.01	–	–	–
$Z_{2\text{-O-D}}$	5.29	–	5.66	–	4.72	–	–	4.81	4.46	38.86	–	–	–	–	–
$Z_{2\text{-S-D}}$	3.39	3.20	3.3	3.12	3.03	2.67	3.28	3.32	–	14.39	–	14.04	–	–	–
$Z_{1\text{-S}}$	10.17	9.13	9.73	9.85	9.56	10.30	13.12	13.40	–	13.07	12.95	12.71	6.20	13.24	12.10
$Z_{2\text{-S}}$	–	10.41	10.77	11.00	11.00	11.00	14.06	13.60	–	14.57	–	14.16	6.83	–	–
$Z_{2\text{-S}}/Z_{12}$	–	0.98	1.00	1.01	1.03	1.01	1.00	0.97	–	1.01	–	1.00	0.99	–	–
$Z_{1\text{-S}}/Z_{12}$	0.93	0.86	0.90	0.90	0.90	0.94	0.93	0.96	–	0.90	0.94	0.90	0.90	0.95	0.95
$Z_{2\text{-O-D}}/Z_{23}$	1.01	–	0.89	–	0.99	–	–	0.98	0.97	0.97	–	–	–	–	–
$Z_{1\text{-O-D}}/Z_{13}$	0.89	–	0.82	–	0.84	–	–	0.93	0.93	0.96	0.98	–	–	–	–
$Z_{2\text{-S-D}}/Z_{213}$	1.10	1.08	1.00	1.02	1.10	1.00	1.01	1.01	–	1.01	–	1.01	–	–	–
$Z_{1\text{-S-D}}/Z_{123}$	0.93	0.84	0.91	0.91	0.89	0.95	0.93	0.96	0.96	0.99	0.99	1.02	–	–	–

The computed quotients allow the following refinement for the cases of the inequalities:

a) Zero-sequence currents in only two windings

$$Z_{1\text{-S}} \approx 0.91\ Z_{12} \tag{14}$$

$$Z_{2\text{-O-D}} \approx 0.95\ Z_{23} \text{ for case T21} \tag{15}$$

$$Z_{1\text{-O-D}} \approx 0.87\ Z_{13} \text{ for case T21} \tag{16}$$

b) Zero-sequence currents in the three windings

$$Z_{1\text{-S-D}} \approx 0.9\ Z_{123} \text{ for case T21} \tag{17}$$

These four factors (0.91, 0.95, 0.87, 0.9) were selected in order to minimize the maximum errors in comparison with the quotients shown in Table 5. The other factors, in Eqs. (3)–(5) and (9)–(12), are equal to unity. Table 6 shows the errors between these factors and the quotients computed from the measured data. Each error is the difference of the computed quotients minus the factors in Eqs. (3)–(5), (9)–(12), and (14)–(17). A wider set of transformers can be evaluated, of course, in order to improve these factors and the certainty about their accuracy.

Almost all the errors in Table 5 are lower than 0.07. The three exceptions are for $Z_{2\text{-S-D}}$ in case T21, and their errors are also acceptably low. For these three exceptions, the measured value is slightly higher than the expected value. In other similar cases, the detected mistake was an excessive voltage drop in the conductors (thus, the measured voltage is slightly higher than the voltage at transformer terminals); however, this mistake only can be corrected during the tests.

4.3. Application of the proposed rules to an example from the literature

These rules were also applied to an example (T21) from the literature. The measured positive-sequence impedances are [24,25]: $Z_{12} = 13.78\%$, $Z_{13} = 33.3\%$, $Z_{23} = 18\%$. Table 7 shows the comparison between estimated and measured values. These results also confirm the validity of these rules.

4.4. Resistive part of Z_{0SC}

Section 4.1 indicates that stray losses are greater when main return paths for ZSMF are through the tank because there are more losses in the tank. Therefore, the rules are:

a) Zero-sequence currents in only two windings

Figs. 4 and 5 show when the main paths for ZSMF are through the tank (for these cases, the effective resistance must be greater than in positive-sequence). Thus:

$$R_{2\text{-S}} \approx R_{12} \tag{18}$$

$$R_{2\text{-O-D}} \approx R_{23} \text{ for case 21T} \tag{19}$$

$$R_{1\text{-O-D}} \approx R_{13} \text{ for case 21T} \tag{20}$$

$$R_{1\text{-S}} > R_{12} \tag{21}$$

$$R_{2\text{-O-D}} > R_{23} \text{ for case T21} \tag{22}$$

$$R_{1\text{-O-D}} > R_{13} \text{ for case T21} \tag{23}$$

b) Zero-sequence currents in the three windings

Figs. 6 and 7 show the main path for ZSMF. Thus:

$$R_{2\text{-S-D}} \approx R_{213} \tag{24}$$

$$R_{1\text{-S-D}} \approx R_{123} \text{ for case 21T} \tag{25}$$

$$R_{1\text{-S-D}} > R_{123} \text{ for case T21} \tag{26}$$

Table 8 shows the available data and computed quotients of resistive part of Z_{0SC} divided by the resistive part of the correspondent positive-sequence impedances. These quotients confirm the proposed rules for cases T21 and YNyn (cases 21T could not be confirmed, due to unavailability of data).

$R_{2\text{-O-D}}/R_{23}$ is lower than $R_{1\text{-S}}/R_{12}$ and $R_{1\text{-O-D}}/R_{13}$ because the case of $Z_{2\text{-O-D}}$ has longer distance between tank and winding connected to the source. Due to the same reason, the proposed factor in Section 4.2 for $Z_{2\text{-O-D}}$ (0.95) is the highest one.

Units 9 and 14 have magnetic shunts on tank walls. Due to this fact, the quotients which are larger than unity should be lower for these cases. This result is obtained for $R_{1\text{-S-D}}/R_{123}$ and $R_{1\text{-O-D}}/R_{13}$ in unit 9 (and not for $R_{2\text{-O-D}}/R_{23}$, because this quotient is very near to unity, due to the reason explained in the previous paragraph). For unit 14, $R_{1\text{-S}}/R_{12}$ is lower than for units without magnetic shunts on tank walls but the difference shown in Table 8 is very low (and greater differences can be expected in other cases). Again, more refinement of these rules can be obtained in the future by analyzing more data.

4.5. Summary of proposed rules about Z_{0SC} and comparison with IEC standard 60076-8

Table 9 shows a summary of the proposed rules about Z_{0SC}, taken from Eqs. (3) to (17), as well as a comparison between these rules and the rules from the IEC Std. 60076-8 [11]. This standard utilizes three factors (a_1, a_2, and a_3), and it only gives the following relationship for them:

$$0.8 < a_1 < a_2 < a_3 < 1 \tag{24}$$

Therefore, the rules of this paper are in accordance with the IEC Std. 60076-8 and can be considered as a complement for the standard. Values of a_2 and a_3 are near to unity, and the value of a_1 has been specified for each case. The accuracy of this refinement for a_1 could be improved in the future, by including data from a wider set of transformers.

On the other hand, the Eqs. (18)–(26) summarize the proposed rules for the resistive part of Z_{0SC}. IEC Std. 60076-8 does not give information about these values.

Table 6

Errors in computed quotients for Z_{0SC}, in comparison with the factors of Eqs. (3), (7)–(12), and (14)–(17).

Connection	YNynd (T21)									YNynd (21T)			YNyn		
Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MVA	15	15	25	25	25	30	30	75	100	120	120	150	5	40	100
$Z_{2\text{-S}}/Z_{12}$	–	−0.02	0.00	0.01	0.03	0.01	0.00	−0.03	–	0.01	–	–	−0.01	–	–
$Z_{1\text{-S}}/Z_{12}$	0.02	−0.05	−0.01	−0.01	−0.01	0.03	0.02	0.05	–	−0.01	0.03	0.03	−0.01	0.04	0.04
$Z_{2\text{-O-D}}/Z_{23}$	0.06	–	−0.06	–	0.04	–		0.03	0.02	−0.03	–	–	–	–	–
$Z_{1\text{-O-D}}/Z_{13}$	0.02	–	−0.05	–	−0.03	–		0.04	0.04	−0.04	−0.02	−0.02	–	–	–
$Z_{2\text{-S-D}}/Z_{213}$	0.10	0.08	0.00	0.02	0.10	0.00	0.01	0.01	–	0.01	–	–	–	–	–
$Z_{1\text{-S-D}}/Z_{123}$	0.03	−0.06	0.01	0.01	−0.01	0.05	0.03	0.06	0.06	−0.01	−0.01	−0.01	–	–	–

Table 7
Application of these Z_{0SC} rules to an example from the literature.

Value	Estimated	Measured [24,25]	Error in the quotient
$Z_{1\text{-S}}$	$0.91\ Z_{12} = 12.54\%$	12.82%	0.02
$Z_{2\text{-S}}$	$Z_{12} = 13.78\%$	13.63%	−0.01
$Z_{1\text{-O-D}}$	$0.87\ Z_{13} = 28.97\%$	28.89%	0.03
$Z_{2\text{-O-D}}$	$0.95\ Z_{23} = 17.10\%$	17.21%	0.01
$Z_{1\text{-S-D}}$	$0.9\ Z_{123} = 12.37\%$	12.82%	0.03
$Z_{2\text{-S-D}}$	$Z_{213} = 7.43\%$	7.36%	−0.01

Table 8
Data of transformers for analyzing the resistive part of Z_{0SC}.

Unit		1	3	9	14
Connection		YNynd (T21)			YNyn
MVA		15	25	100	40
Measured values (%)	Z_{12}	10.91/87.15°	10.76/87.48°	8.87/88.78°	13.90/88.
	Z_{13}	18.25/86.41°	20.03/86.58°	14.58/88.95°	–
	Z_{23}	5.26/79.43°	6.34/80.90°	4.58/87.47°	–
	$Z_{1\text{-O-D}}$	16.28/82.81°	16.47/82.54°	13.60/88.59°	–
	$Z_{1\text{-S-D}}$	9.95/83.81°	9.45/84.08°	8.49/88.25°	–
	$Z_{2\text{-O-D}}$	5.29/78.17°	5.66/79.38°	4.46/87.11°	–
	$Z_{2\text{-S-D}}$	3.39/79.04°	3.3/81.37°	–	–
	$Z_{1\text{-S}}$	10.17/84.51°	9.73/84.72°	–	13.24/87.
	$Z_{2\text{-S}}$	–	10.77/87.48°	–	–
$R_{2\text{-S}}/R_{12}$		–	1.00	–	–
$R_{1\text{-S}}/R_{12}$		1.79	1.89	–	1.74
$R_{2\text{-O-D}}/R_{23}$		1.12	1.04	1.11	–
$R_{1\text{-O-D}}/R_{13}$		1.78	1.79	1.25	–
$R_{2\text{-S-D}}/R_{213}$		1.15	0.96	–	–
$R_{1\text{-S-D}}/R_{123}$		1.64	1.64	1.26	–

Note: R is the real part of impedances.

Table 9
Comparison of Z_{0SC} rules of this paper with IEC Std. 60076-8.

Case	Rules of this paper	IEC Std. 60076-8
Both	$Z_{1\text{-S}} \approx 0.91\ Z_{12}$	$Z_{1\text{-S}} \approx a_1\ Z_{12}$
Both	$Z_{2\text{-S}} \approx Z_{12}$	$Z_{2\text{-S}} \approx a_2\ Z_{12}$
T21	$Z_{2\text{-O-D}} \approx 0.95\ Z_{23}$	$Z_{2\text{-O-D}} \approx a_1\ Z_{23}$
	$Z_{1\text{-O-D}} \approx 0.87\ Z_{13}$	$Z_{1\text{-O-D}} \approx a_1\ Z_{13}$
21T	$Z_{2\text{-O-D}} \approx Z_{23}$	$Z_{2\text{-O-D}} \approx a_2\ Z_{23}$
	$Z_{1\text{-O-D}} \approx Z_{13}$	$Z_{1\text{-O-D}} \approx a_2\ Z_{13}$
T21	$Z_{1\text{-S-D}} \approx 0.9\ Z_{123}$	$Z_{1\text{-S-D}} \approx a_1\ Z_{123}$
21T	$Z_{1\text{-S-D}} \approx Z_{123}$	$Z_{1\text{-S-D}} \approx a_2\ Z_{123}$
T21	$Z_{2\text{-S-D}} \approx Z_{213}$	$Z_{2\text{-S-D}} \approx a_2\ Z_{213}$
21T		$Z_{2\text{-S-D}} \approx a_3\ Z_{213}$

5. Conclusion

Simple rules to estimate the results of measurements of zero-sequence impedances for 3-phase core-type transformers were developed. In case of magnetizing zero-sequence impedances, the presence or not of magnetic shunts on tank walls defines the details of the proposed rules. For short-circuit zero-sequence impedances, only the positive-sequence transformer impedances are necessary to apply the proposed rules. These rules were applied to a set of fifteen transformers, from 5 to 150 MVA. The proposed rules were conceptually developed from the analysis of magnetic circuits of these transformers, and the data from standardized tests were important in order to obtain a numerical refinement for the estimation of the measurements of zero-sequence impedances. This numerical refinement was developed for transformers which are typically installed in the substations of electric utilities. A wider set of transformers can be evaluated in the future, in order to improve the accuracy of such refinement.

Some rules for the real part (or the angle) of zero-sequence impedances were also developed, and they were also verified with test data. However, there are few available data for this purpose, and a refinement similar to the obtained one for the module of zero-sequence impedances was not possible.

The practical usefulness of developed rules is related to the reduction of probability of human errors during the tests, as well as with the analysis of test results. For example, during the analysis of test data for this research, some mistakes were corrected (but some mistakes only can be corrected during the tests).

The developed rules can be seen as a complement for the rules of the IEC Std. 60076-8 because: (a) the physical fundamentals for the rules have been explained here; (b) some numerical factors, from real tests, have been included here, and these factors can be updated in the future by using more test data of transformers; (c) some new rules, for the real part or the angle of zero-sequence impedances, were included here; (d) a rule to estimate the difference between the two magnetizing impedances is included here; (e) the presence of magnetic shunts on tank walls has an effect on results and this effect has been considered here.

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