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Original Article

Tests for Checking the Computer Model of a Three-Phase Transformer or an Inductive Reactor and the Diagram for their Implementation

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Abstract - This article proposes and substantiates a practical solution to the issue of determining the type of magnetic core of a three-phase transformer or reactor used in a mathematical model of the device. A three-legged single magnetic circuit is perhaps the most common due to its compactness. But, unlike other core configurations, it also provides strong magnetic links between the winding phases, which affects transient processes, including in unbalanced modes, as well as the ability to limit common mode currents. These circumstances are important for obtaining adequate simulation results.

Keywords - Common mode currents, Inductive reactor, Magnetic core, Mathematical model, Mutual inductance, Simulation, Three phases, Transformer.

1. Introduction

The three-phase power transformer is a widespread and significant element of modern electrical power systems and is part of the electrical equipment of a number of technological installations. An effective modern way of analyzing and designing electrical systems is the use of computer simulation. In this case, the degree of abstractness inherent in a particular mathematical or computer model is important: this determines the permissible scope of application of the developed model. In many cases, researchers are interested in the behavior of a transformer in asymmetrical operating modes.

Mathematical and computer models of three-phase transformers are widely used in various studies [1 - 4]. However, the gap is the lack of methods to check whether there is a magnetic coupling between the phase windings or not. The same issue can also be attributed to the simulation of inductive reactors. Since it is advisable to test the declared capabilities of the model, following the proverb: "Trust, but verify", the results of this work provide such an opportunity regardless of the software underlying the simulation of a three-phase transformer or inductive reactor. This is the novelty of the results of the work. In [5 - 7], the equations of a mathematical model of a three-phase two-winding transformer were published, which allows the computer implementation of all twelve groups of winding connections according to the clock notation system in a relatively simple way.

2. Materials and Methods

Scientists from the Institute of Energy of the Academy of Sciences of Moldova V.A. Bosneaga and V.M. Suslov [8 - 11] in [8] proposed methods for testing the performance of a three-legged core transformer model (a three-phase two-winding transformer with a single magnetic core). The tests are aimed at determining the presence of strong electromagnetic coupling (mutual inductance) between all the phases of the transformer, located on different legs of the magnetic core. Such a coupling is present in a transformer with a three-legged single magnetic core but will be absent in a bank of three single-phase transformers. In four-legged and five-legged transformer designs, mutual inductance between the phases is also present. However, in the absence of non-magnetic gaps in the core legs that do not carry windings, the value of mutual inductance tends to zero [12, 13], which leads to a situation similar to the bank of three single-phase transformers. The test results described below correspond to a transformer with a three-legged magnetic core.

Test mode 1. When a winding located on one of the core's legs is excited, a significant Electromotive Force (EMF) will be induced in the unexcited open windings of the other legs (slightly less than half the applied voltage, in accordance with the transformer parameters). For example, when one phase of the primary winding is excited, the test is carried out with the other two phases of the primary winding open and all phases of the secondary winding open.

Test mode 2. Similar to the previous one, but with short-circuited windings of other legs (in which significant currents arise in the short-circuited windings of unexcited legs). In the model unexcited phases of the primary winding have to be short-circuited to ground. The phases of the secondary winding can be all open, or the secondary winding can be loaded at the rated load.

This paper provides explanations for the experiments providing scheme. In all cases, the computer model of a three-phase two-winding transformer with a three-legged magnetic core has phase A of the primary winding excited - a sinusoidal voltage with an amplitude of 100 V is applied to it. The nonlinearity of the magnetization curve is not taken into account. The model equations correspond to the standard (clock) notation and windings connection Y/Y–0.

The electrical circuit diagram for conducting experiments is shown in Figure 1, where A1, B1, and C1 are beginning terminals of the transformer's primary winding phases; X1, Y1, and Z1 are ending terminals of the transformer's primary winding phases; a2, b2, c2 are beginning terminals of the transformer's secondary winding phases; x2, y2, z2 are ending terminals of the transformer's secondary winding phases. Of course, the author means three-phase transformer's mathematical or computer model terminals.

In the case of Test 1, resistances R1 ... R5 tend to infinity.

In the case of Test 2, resistances R1 and R2 tend to zero. If the secondary winding is open, then R3...R5 tend to infinity. If a load (Rload, Lload) is connected to the secondary winding, then R3…R5 tend to be zero.

Let us carry out Test 2 with the secondary winding open. Then, the equations for the phases of the primary winding will be as follows [5 - 7]:

$$v_{a1} - r_{a1} i_{a1} - L_{\sigma a1} \frac{di_{a1}}{dt} = v_{a01}; \qquad (1)$$

$$v_{b1} - r_{b1} i_{b1} - L_{\sigma b1} \frac{di_{b1}}{dt} = v_{b01}; \tag{2}$$

$$v_{c1} - r_{c1} i_{c1} - L_{\sigma c1} \frac{di_{c1}}{dt} = v_{c01}. \tag{3}$$

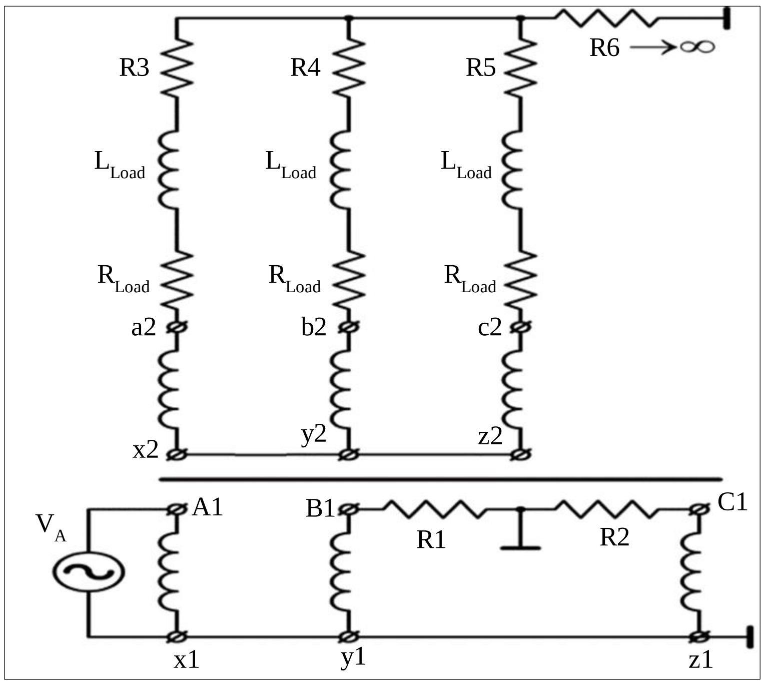

Fig. 1 Electrical circuit diagram for testing a computer model of a three-phase transformer

At the same time, the author reminds us that phases B and C are short-circuited to ground - no voltage is applied to them. In addition, in phases B and C, the EMF of the magnetization branch is induced.

$$e_{b01} = e_{c01} \approx -\frac{e_{a01}}{2} = \frac{u_{a01}}{2}. \tag{4}$$

Therefore, an author can rewrite the equations for the phases of the primary winding of the transformer as follows:

$$v_{a1} - v_{a01} = r_{a1} i_{a1} + L_{\sigma a1} \frac{di_{a1}}{dt}; \tag{5}$$

$$\frac{v_{a01}}{2} \approx r_{b1} i_{b1} + L_{\sigma b1} \frac{di_{b1}}{dt}; \tag{6}$$

$$\frac{v_{a01}}{2} \approx r_{c1} i_{c1} + L_{\sigma c1} \frac{di_{c1}}{dt}. \tag{7}$$

3. Results and Discussion

With the given parameters of the model, sinusoidal signals with amplitudes were obtained: $V_{b01m} = V_{c01m} = 33.159$V (these signals are in phase); Va01m = 66.319V (this signal is antiphase to the previous two). It is also necessary to remember that a sinusoidal voltage with amplitude Va1m = 100V is applied to phase A (it is practically in phase with the signal v_{a01}). Calculating the signal amplitude on the left side of the equation for phase A, the author obtains 100 – 66.319 = 33.681 V. This differs slightly from the signal amplitudes on the left side of the equations for phases B and C and the signals in all phases are in phase. It is not surprising that the currents in all phases of the primary winding of the transformer are almost the same $I_{b1} = I_{c1} = 0.995.I_{a1}$.

Figures 2 and 3 graphically show the results of testing a computer model of a three-phase, two-winding transformer with a three-legged magnetic core. Figure 2 shows the results of test mode 1: EMF in the excited and unexcited phases of the primary winding. Figure 3 shows the results of test mode 2: currents in the excited and unexcited phases of the primary winding with open phases of the secondary winding. Figure 4 shows the results of test mode 2: currents in the excited and unexcited phases of the primary winding at a rated load connected to the secondary winding.

From the analysis of the graphs in Figures 2 to 4, everybody can conclude that the tested computer model meets the performance criteria formulated in [8] in Figure 2 $E_{b1} = E_{c1} = 0.499.E_{a1}$; Figure 3 $I_{b1} = I_{c1} = 0.995.I_{a1}$, and Figure 4 $I_{b1} = I_{c1} = 0.913.I_{a1}$. That is, the model reflects the strong electromagnetic coupling of the phases with each other, ensured by the presence of a three-legged single magnetic circuit. Consequently, the mathematical model of a three-phase transformer described in [5 - 7] is suitable for studying both symmetrical and asymmetrical operating modes.

Laboratory verification of the correctness of the circuit operation results (Figure 1) in test modes on a real three-phase transformer with a three-legged core was successful, confirming the adequacy of the computer simulation results obtained.

The design of the transformer core has an important influence on the value of the zero sequence impedance [12, 13].

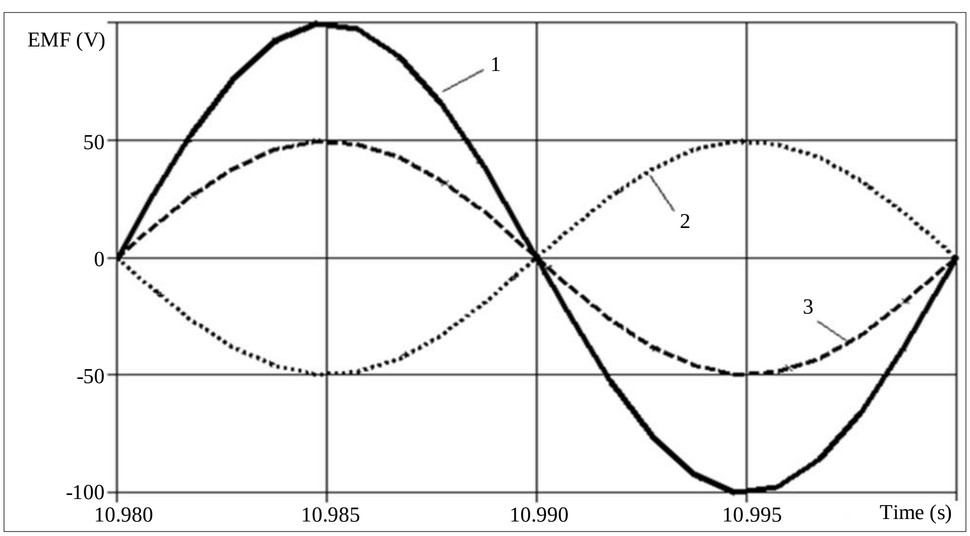

Fig. 2 Test mode 1: EMF in the excited and unexcited phases of the primary winding: 1 - e_{a1}, 2 - e_{b1}, 3 – $(-e_{c1})$

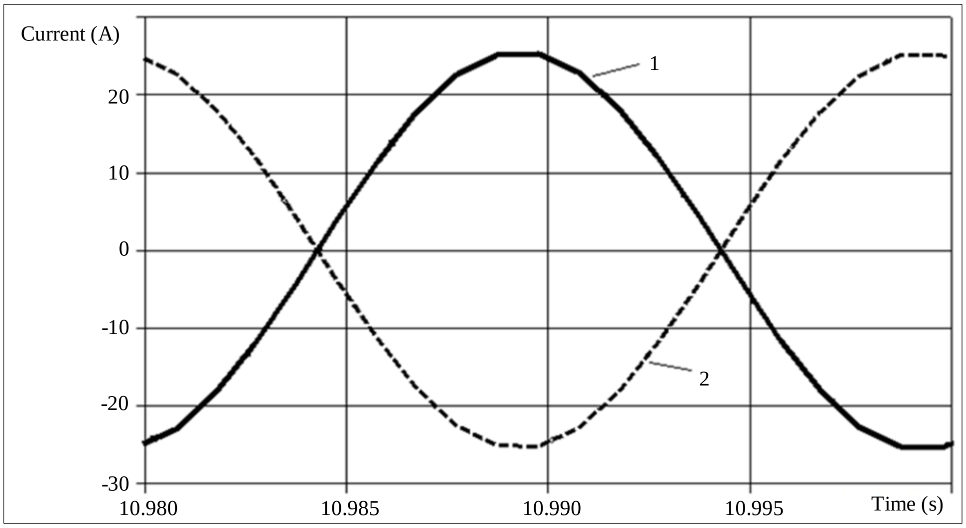

Fig. 3 Test mode 2: Currents in the excited and unexcited phases of the primary winding, where curves 1 - i_{a1}, 2 - $(-i_{b1})$ and $(-i_{c1})$. Secondary winding phases are open.

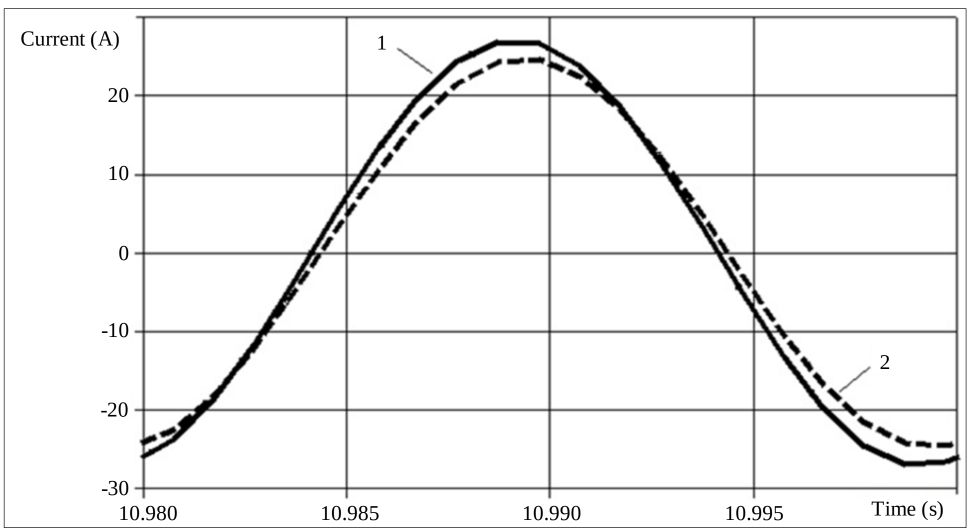

Fig. 4 Test mode 2: Currents in the excited and unexcited phases of the primary winding at a rated load connected to the secondary winding, where curves 1 - i_{a1}, 2 - i_{b1} and i_{c1}

A three-phase inductive reactor differs from a transformer in the absence of secondary windings. As well as a transformer three-phase inductive reactor with a magnetic core can be obtained using: 1) a bank of three single-phase reactors, each on an individual closed magnetic core [14, 15]; 2) a three-phase reactor with a three-legged magnetic core [15]; 3) three-phase reactor with a five-legged [15] or a four-legged magnetic core [16]. Assuming that the parameters of each phase of the inductive reactor are identical (structural symmetry), the equations in matrix form according to Kirchhoff's second law for a bank of three single-phase reactors without taking into account iron losses can be written as:

$$\begin{vmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{vmatrix} = \begin{vmatrix} L+L_{\sigma} & 0 & 0 \\ 0 & L+L_{\sigma} & 0 \\ 0 & 0 & L+L_{\sigma} \end{vmatrix} \times \begin{vmatrix} p \cdot i_{La} \\ p \cdot i_{Lb} \\ p \cdot i_{Lc} \end{vmatrix} + \begin{vmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{vmatrix} \times \begin{vmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{vmatrix}, \tag{8}$$

Where: V_{La}, V_{Lb}, V_{Lc} – voltage drop between the beginning and the end of each phase of the reactor due to i_{La}, i_{Lb}, i_{Lc} currents flowing;

r – resistance of phase;

L– phase self-inductance;

L_σ– leakage inductance of phase.

Equations (8) are also valid for three-phase inductive reactors with four- and five-legged magnetic cores [17, 18], the conditions of which are explained in [15]. Due to the fact that in the above reactor designs, magnetic fluxes of any sequence, including zero, are closed along the steel magnetic cores, the circuit parameters for the flow of current of any sequence in phase will also be the same.

Similar equations for a three-phase inductive reactor with a three-legged magnetic core:

$$\begin{vmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{vmatrix} = \begin{vmatrix} L+L_\sigma & M & M \\ M & L+L_\sigma & M \\ M & M & L+L_\sigma \end{vmatrix} \times \begin{vmatrix} p \cdot i_{La} \\ p \cdot i_{Lb} \\ p \cdot i_{Lc} \end{vmatrix} + \begin{vmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{vmatrix} \times \begin{vmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{vmatrix}, \qquad (9)$$

Where, M– mutual inductance of two phases.

In [15], the relation is accepted

$$M = -L/2 \qquad (10)$$

In Equations (9), taking into account (10), the author now pays attention to the fact that for the common mode current in each of the phases, only the leakage inductance remains, which is much smaller than the reactor's self-inductance. This will lead to a very low impedance of the phases of a three-phase reactor with a three-legged magnetic core to common mode currents, which is fraught with a significant increase in the magnitude of common mode currents. Because all phases of the transformer's secondary winding can be open at Test 1 and Test 2, as mentioned above. It is equal to the total absence of secondary winding; the circuit diagram in Figure 1 is suitable for testing not only the three-phase transformer's core construction adopted in the mathematical model but the three-phase inductive reactor's core construction, too.

The difference between core configurations of three-phase inductive reactors can be very significant in the case of their usage as equalizing reactors when the parallel connection of several inverters or active rectifiers, having a common DC link and electrical connection on the AC side, is used [19 - 30]. An example of such a device author shown in Figure 5, where L1 and L2 are equalizing reactors, T – power transformers, connecting active rectifiers with three phase AC grid. The design of the transformer and reactors must ensure, among other things, effective suppression of zero-sequence (common mode) currents.

4. Conclusion

The paper proposes and describes the tool to determine whether a selected computer model of a three-phase transformer or inductive reactor is suitable for use in simulating specific operating conditions of the device. The results presented show that the circuit and tests performed with its help allow determining whether the magnetic core in the studied transformer or inductive reactor model is three-legged or has another configuration. This is particularly important for obtaining correct simulation results for unbalanced operating modes and for limiting zero-sequence currents.

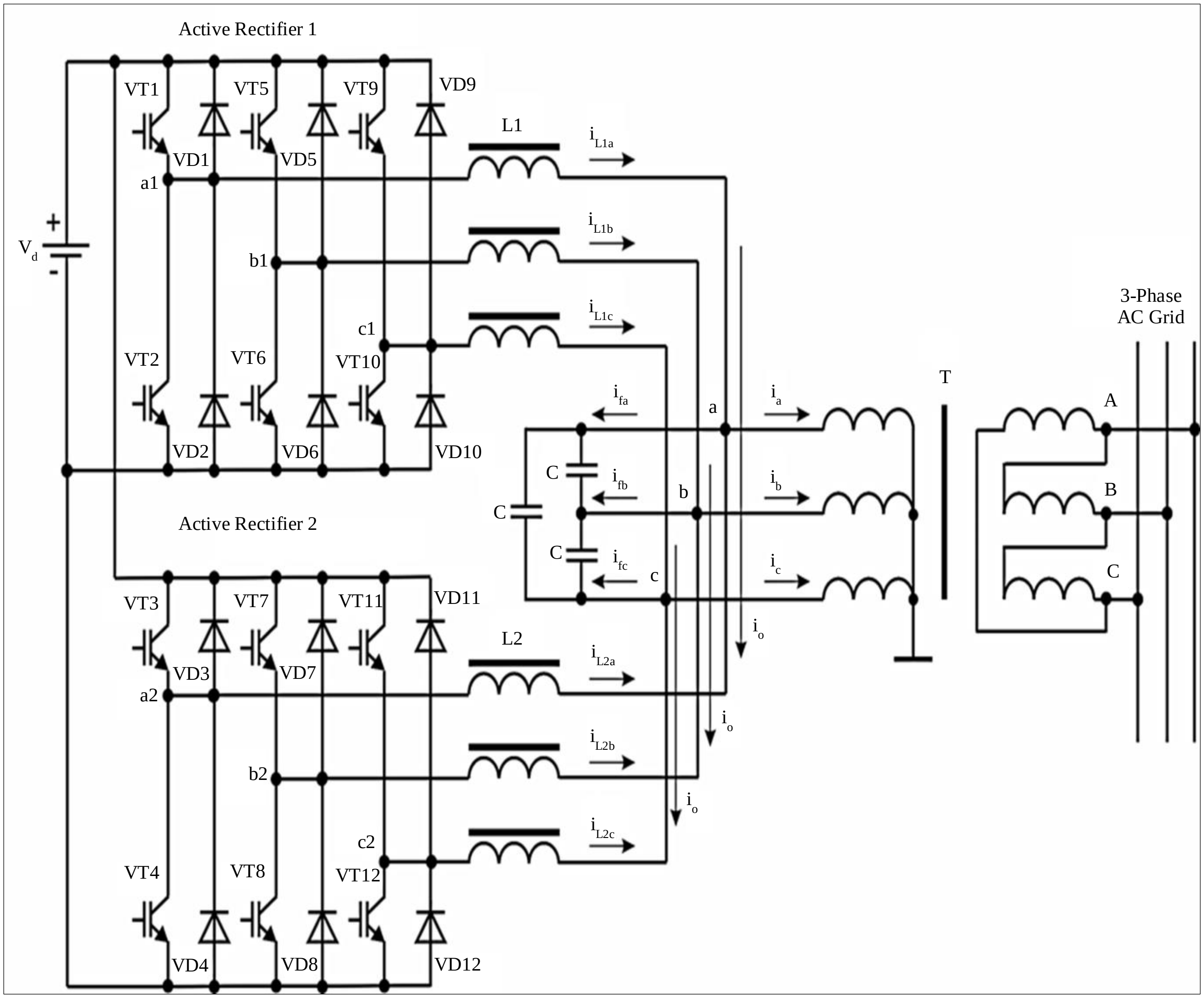

Fig. 5 An example of a parallel connection of several active rectifiers having a common DC link and electrical connection on the AC side

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