Influence of the Non-symmetrical Three-Phase Loads on the Transformer and Supply Grid

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Abstract - **The paper discusses the operation of the distribution transformer with non-symmetrical load connected. The transformer operates with an isolated neutral wire of the star-connected secondary winding. The influence of the load variation on the voltage of the supply grid is analysed and analytical expressions for the additional core loss are given. Experiments confirm the influence of the load non-symmetry on the losses, power factor and reactive power of the transformer.**

Keywords - **transformer, non-symmetrical load, losses.**

I. Introduction

Different modes of operation of the three-phase power transformers with symmetrical and non-symmetrical load are discussed in a number of books [1,4,5,6,7]. Short circuit on the secondary (low voltage) winding is usually presented as a typical non-symmetrical mode. It is assumed also that the grid supplies the transformer with a sinusoidal waveform symmetrical three-phase voltage. This is correct for the high-power network transformers while for the distribution transformers 20/0,4 kV non-symmetry of the supply voltage may occur in certain load. Strong requirements to the electric power quality are defined in the European and national standards [2,9], including to the symmetry of the three-phase voltage. According to [9] the RMS value of the negative sequence voltage must not exceed 2% (and 3% only for some regions).

Normally the LV grid operates with an earth-connected neutral but in recent years it is of frequent occurrence the transformer to operate with a neutral wire isolated for a certain period of time. The aim of the present paper is to analyse the operation of the three-phase distribution transformer with an isolated neutral wire connected to non-symmetrical three-phase load.

II. Supply voltage non-symmetry

Core type (three-leg) distribution transformer with D/y connection is under consideration. The neutral wire of the star-connected secondary winding is isolated. Three-phase resistive load is connected to the secondary winding at steady state.

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According to the reasons the non-symmetry of the primary voltage could be:

- So called "transverse" non-symmetry in the supply grid (MV line)

It occurs at transient phase to earth or phase to phase short-circuit in the MV line. This transient short-circuit causes drops in the sinusoidal waveform of the supply voltage. It is possible in MV grids with a neutral wire connected to the earth via Peterson's coil and could lead to fleeting non-symmetry in the three-phase voltage. This kind of non-symmetry is of short duration, happens accidentally and is not under consideration in the present paper.

- Non-symmetry caused by the non-symmetrical load connected

The equivalent circuit in Fig.1 shows the investigated distribution transformer connected to the symmetrical three-phase voltage supply E_A, E_B, E_C via symmetrical line with an impedance Z_1.

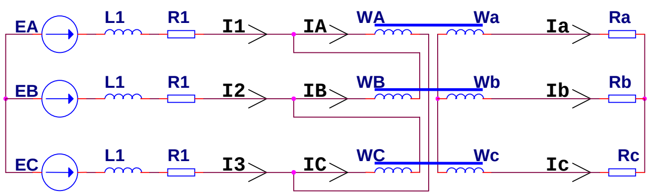

Fig.1 Equivalent circuit

Three-phase resistive load is connected to the secondary winding of the transformer. As the neutral is isolated

$$\dot{I}_a + \dot{I}_b + \dot{I}_c = 0 .$$

At the symmetrical load the currents $\dot{I}_a$, $\dot{I}_b$ and $\dot{I}_c$ are equal with a lag of 120° (Fig. 2a). Each phase current lags behind the corresponding phase voltage to a small angle.

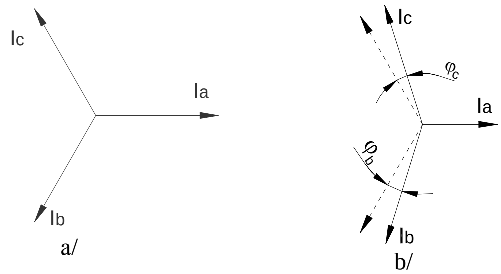

Fig 2. Phasor diagram of the transformer's secondary currents at symmetrical (a) and non-symmetrical (b) load

Assume that we reduce the load of phase *A* keeping constant the load of phases *B* and *C*. As seen in Fig. 2b this will change the lag between the currents - $\dot{I}_b$ will go at φ_b ahead and $\dot{I}_c$ - at φ_c behind the corresponding vectors at symmetrical load.

In this case I_b will lead the voltage U_b and I_c will increase the lag behind U_c despite of the resistive load.

If we keep constant the load of phase *A* *(R_a=const)* and reduce the load of phases *B* and *C* the lag between the currents will change in opposite direction – the current I_b will lag behind the voltage U_b and I_c will lead the voltage U_c. At a constant total load of the transformer (*Pr=const*) the result of this changed current's lag is an increase in the current values and the transformer losses.

The non-symmetry of the load currents causes lag change of the currents in the primary winding of the transformer also and change of the reactive power consumption. Under considered example the transformer's consumption will be different for the three phases – mainly resistive power for phase *A*, resistive-capacitive power for phase *B* and resistive-inductive power for phase *C*. The reactive power components increase proportional to the load current's non-symmetry.

Although the transformer is connected to the symmetrical three-phase voltage E_A, E_B, E_C, the load's non-symmetry affects on the transformer's supply voltage. Due to the different values and lag of the currents in the transformer's primary winding, the voltage drops in the line impedance Z_1 are different and the voltage on the transformer's terminals forms non-symmetrical system (Fig. 3).

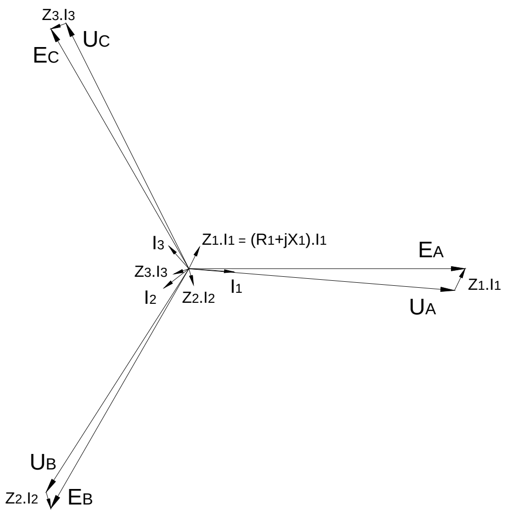

Fig. 3. Phasor diagram of the transformer's supply voltage

III. INFLUENCE OF THE VOLTAGE NON-SYMMETRY ON THE TRANSFORMER'S LOSSES

The operation of the transformer with non-symmetrical supply voltage is analysed in [3]. Using the symmetric component method (Fortescue transformation) it is shown that the transformer's core loss depends on the coefficient of the voltage non-symmetry ε_U:

$$\frac{P_{a,\varepsilon}}{P_a} = 1 + \frac{\varepsilon_U}{2 + 1{,}5\, l_a / l_b} + \varepsilon_U^2 \,, \qquad (1)$$

where ε_U - coefficient of the voltage non-symmetry $\varepsilon_U = U_2 / U_1$

U_1 - positive sequence component voltage;

U_2 - negative sequence component voltage;

l_a, l_b – leg and yoke length.

The zero sequence voltage produces zero sequence magnetic flux in the transformer's legs, which causes additional core loss in the legs

$$\frac{P_{a,\alpha}}{P_a} = \frac{2\alpha^2}{1 + 0{,}75.l_a / l_b} \left(\frac{1-\lambda}{2+\lambda} \right)^2 , \qquad (2)$$

where α – unbalance coefficient $\alpha = U_o / U_1$;

λ - coefficient equal to $\lambda = \Lambda_{\mu,2} / \Lambda_{\mu,1} = (3l_a + 2l_b)/2l_b$;

$\Lambda_{\mu,1}$, $\Lambda_{\mu,2}$ are the magnetic permeability coefficients of the end legs and middle leg of the transformer respectively.

The loss in the transformer's tank and accessories due to the zero sequence magnetic flux is equal to:

$$\frac{P_{k,\alpha}}{P_k} = \left(1 + 4.\alpha.\frac{1-\lambda}{2+\lambda} \right)^2 \qquad (3)$$

For the distribution transformers manufactured by Elprom-Trafo CH AG, Kjustendil, Bulgaria, widely used in Bulgarian energy power system, the above equations can be written as follows:

$$\begin{aligned} P_{a,\varepsilon} / P_a &= 1 + 0{,}354.\varepsilon_U + \varepsilon_U^2 \\ P_{a,\alpha} / P_a &= 0{,}425.\alpha^2 \\ P_{k,\alpha} / P_k &= (1 - 2{,}2.\alpha)^2 \end{aligned} \qquad (4)$$

IV. EXPERIMENTAL RESULTS

Series of experiments are made to verify the theoretical analysis of the load non-symmetry influence. Three-phase transformer TT16002 with ratings as follows is used: S_r=1200VA, P_{sc}=68W, P_0=21,6W, winding's connection D/y, isolated Y-center of the secondary winding. Power quality analyzers MI2192 (manufactored by METREL - Slovenia) and CA8332 (manufactored by Chouven Arnoux - France) are used to carry out the measurements. Three-phase resistive load is connected to the secondary winding of the transformer. All experiments start form symmetric load and next we vary one of the currents in large range – from 0,9.I_r to 0,2.I_r. Three series of experiments are carried out - at 0,9I_r; 0,67I_r and 0,33I_r, compared to the symmetrical load.

The phasor diagrams in Fig. 4 show the currents measured in the transformer's primary winding at variation of the load non-symmetry. At a symmetrical load (Fig. 4a) the lag between currents is equal to 120°. Diagrams in the next three figures (Figs. 4b,c,d) show the change of the primary current's lag, caused by the reduction of the load current I_c. Although the load is resistive, it's non-symmetry increases the current's lag proportionally to the non-symmetry increase.

The change of the lag of the currents in the MV line (φ_A, φ_B, φ_C) and the load currents (φ_a, φ_b, φ_c) versus the coefficient of the current non-symmetry ε is shown in Fig. 5. As it is seen in the figure due to the load non-symmetry the lag is bigger in the primary currents.

The reactive power consumption depends on the non-symmetry also. Measurements are carried out for 3 values of the load current and the results are shown in Fig. 6. The reactive power of each phase is shown in relation to one third of the transformer's magnetizing power at symmetrical load. Fig. 6a shows the reactive power variation when the currents $I_a = I_b \approx 0{,}9 I_r$ and the current I_c vary from $0{,}9.I_r$ to $0{,}2.I_r$. When the load current is lower than the rated one - $I_a = I_b \approx 0{,}67 I_r$ (Fig. 6b) and $I_a = I_b \approx 0{,}33 I_r$ (Fig. 6c), and the current I_c vary from $0{,}9.I_r$ to $0{,}2.I_r$ the reactive power depends on the relation between the currents. For example the reactive power of phase B is inductive at $I_a, I_b < I_c$ and capacitive at $I_a, I_b > I_c$.

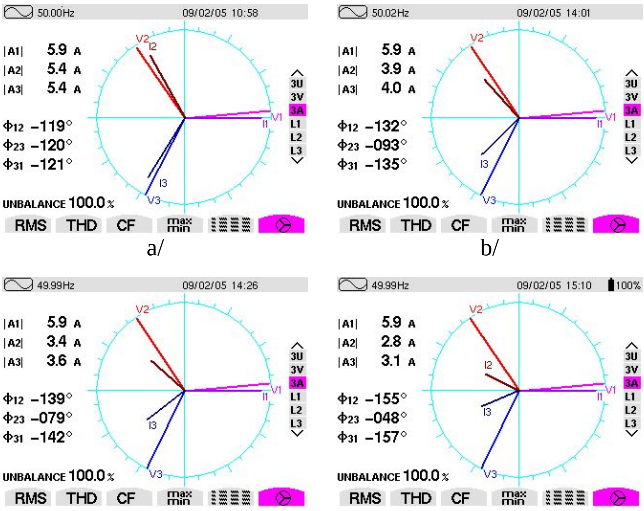

Fig. 4. Phasor diagrams of of the primary winding currents and voltages at 4 values of the load

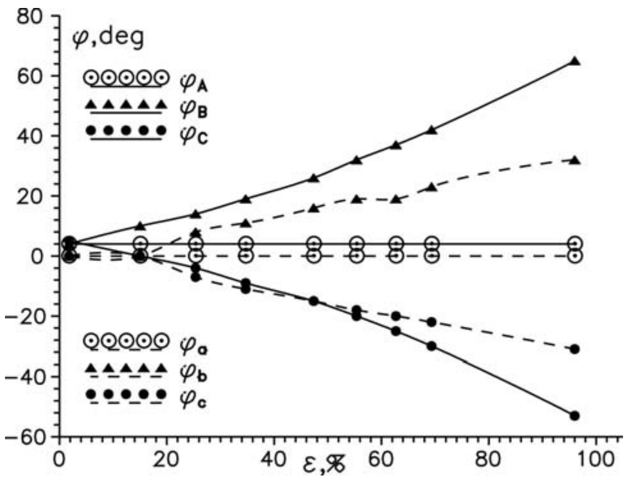

Fig. 5. Change of the lag of the primary winding currents and the load currents

The coefficient of the voltage non-symmetry increases with the increase of the load current non-symmetry (Fig. 7). The value of this coefficient is calculated as follows:

$$\varepsilon_U = \varepsilon_{U,nonsym} - \varepsilon_{U,sym} \tag{5}$$

Due to the non-symmetry of the resistive load the relative magnetizing power slightly increases (Fig. 8) and the power factor significantly decreases (Fig. 9). The reason is the increase of the reactive components of the currents and of the total input power of the transformer. An increase of the transformer loss was found also (Fig.10).

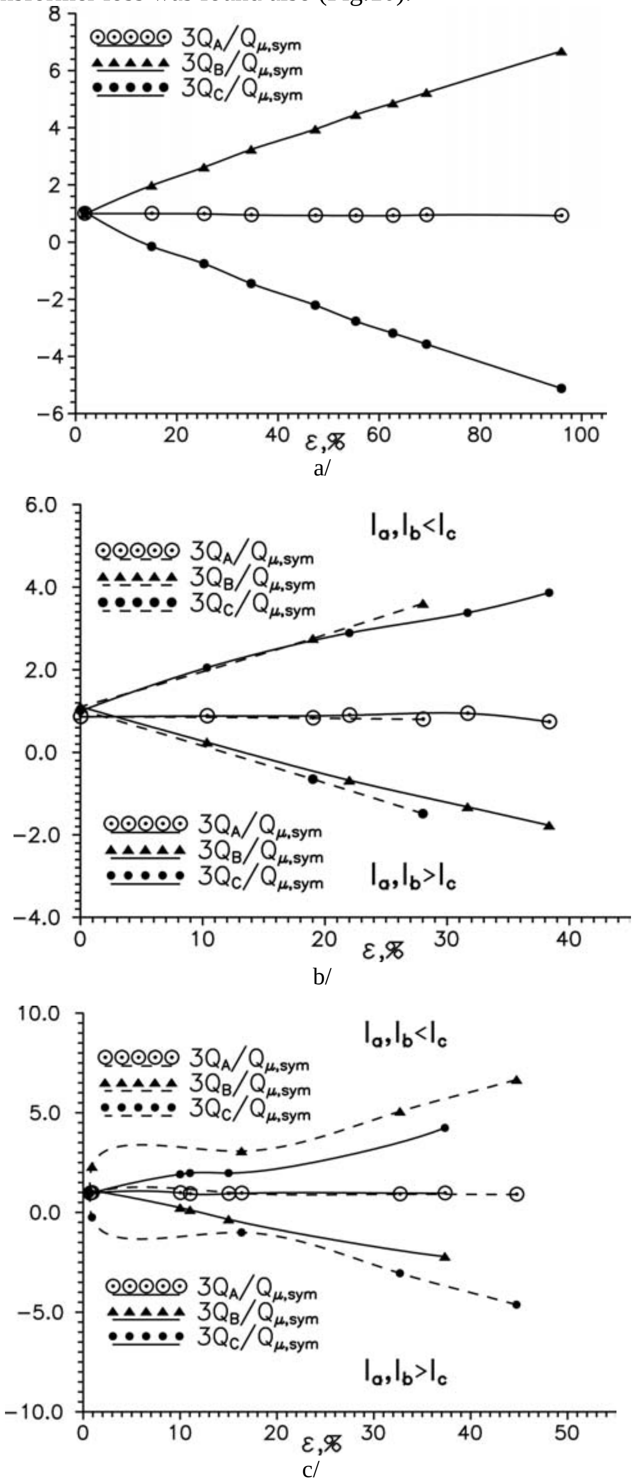

Fig. 6. The relative reactive power versus the coefficient of the current non-symmetry

V. CONCLUSION

1. The non-symmetrical load connected to the secondary winding with an isolated neutral causes change in the phase currents lag. It depends on the values and the proportion between the currents.

2. The non-symmetry of the load currents causes also lag change of the currents in the primary winding and non-symmetry of the transformer's supply voltage.
3. Due to the non-symmetry the power factor decreases and an increase in the losses and the reactive power occurred even though the load is resistive.

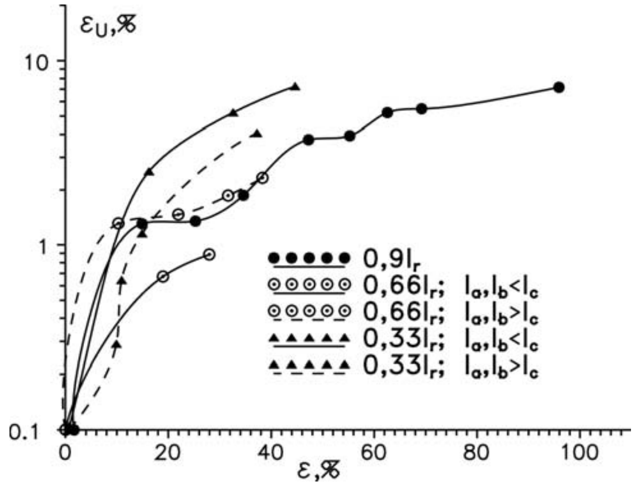

Fig. 7. Coefficient of the voltage non-symmetry versus coefficient of the current non-symmetry

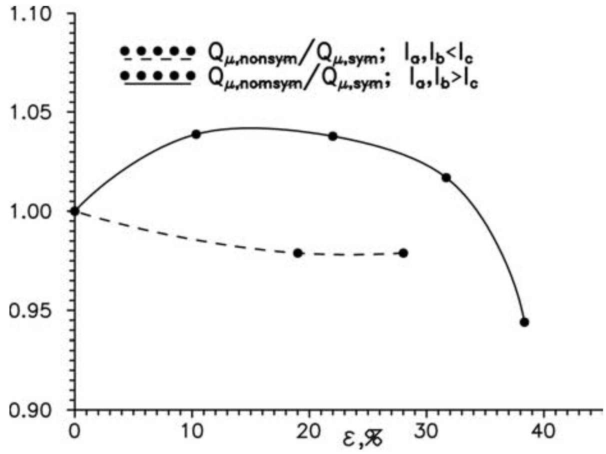

Fig. 8. Relative magnetizing power at load current 2/3 of the rated

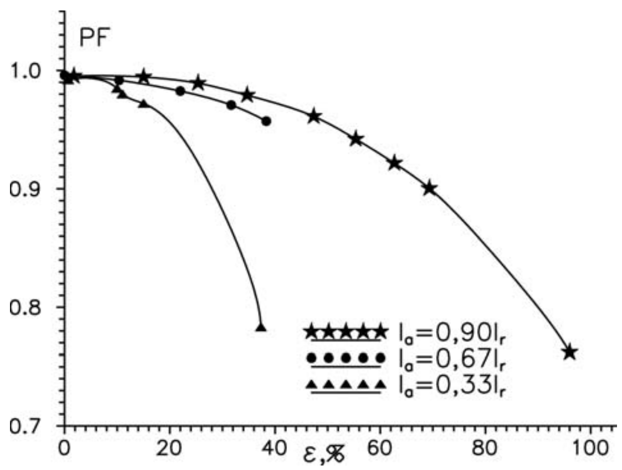

Fig. 9. Power factor versus current non-symmetry coefficient

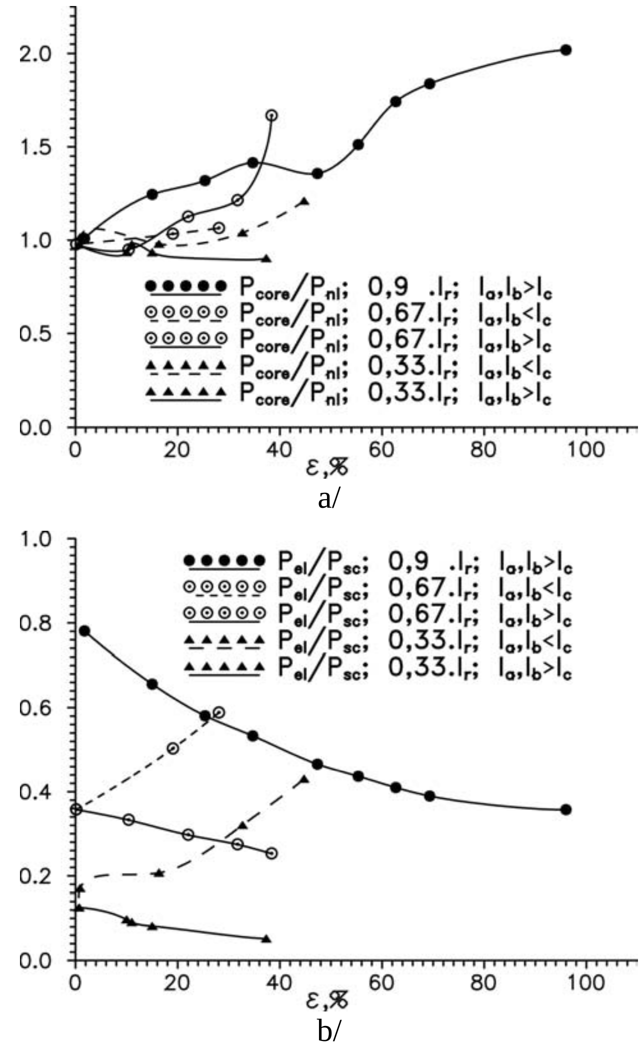

Fig. 10. Transformer losses versus current non-symmetry coefficient

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