The Influence of the Supply Voltage Unbalance on the Squirrel Cage Induction Motor Operation

Georgi I.Ganev [1] and George T.Todorov [2]

Abstract – **An influence of the three phase supply voltage unbalance on a squirrel cage induction motor operation is investigated. A method for motor's currents prediction is presented. Experimental investigations are performed and the results are analyzed and compared to the predicted values.**

Keywords – **squirrel cage induction motor operation, supply voltage unbalance, power quality.**

I. INTRODUCTION

Induction motors due to their better characteristics and cost are the most commonly used device that converts alternating current energy to mechanical one. More than one-half of the total electricity is consumed by motor-driving systems. A large part of them are induction motors with small rated power (less than 2kW). Being the induction motors most popular in the industry it is very important to carry out studies about the effect of power quality on the efficiency and reliability of the three-phase motors. On the other side the optimization of induction motor's operation will improve the operation of whole power system.

The two-ax transformation [10] and the symmetrical components transformation [7] are usually applied for induction motors investigation. D-Q transformation is used for investigation of the induction machines' transient processes [8], non-sinusoidal supply voltages influence [5] and induction motors driven by speed-control systems [13]. The Fortesque transformation is commonly used for induction motors steady-state operation studying [1,2,3,4,6,9,11,12], including symmetrical and non-symmetrical behavior. In case of non-symmetrical supply voltage, the three phase voltage system is decomposed into three subsystems – with positive, with negative and zero sequences. This way the induction motor's operation with unbalanced supply voltage is treated as a simultaneously operation of two machines – the first one operates as a motor (produces driving torque) and the second one - as machine breaker (produces torque with opposite direction). The zero sequences currents are neglected. Some disadvantages of this method should be mentioned, in spite of its popularity:

- the induction machine parameters for the positive and the negative sequences are assumed as a constants;
- the saturation of induction machine magnetic core is neglected;
- the superposition principle is used, equalizing the induction machine as a two simple machines with motor and breaker operation, etc.

Most of the papers do not discuss the influence of the voltage unbalance on the motor's currents and efficiency.

An investigation of the influence of the supply voltage unbalance on the operating performance of three-phase squirrel cage induction motor with small power is presented in this paper. An approach for the motor currents prediction is proposed, in case of unbalanced supply with deviation of one-phase voltage.

II. UNBALANCED CURRENT PREDICTION METHOD

A steady–state operation of symmetrical three-phase squirrel cage induction motor is under study in the present paper. An unbalanced three-phase system with variation of the voltage of only one phase supplies the motor. It is assumed that the stator winding is "Y" connected, the motor's parameters are preliminarily known and they remain constant (independent of the magnetic core saturation).

When the squirrel cage induction motor is supplied by three-phase symmetrical voltage system the consumed three-phase currents will form symmetrical system also. Each phase current lags behind the corresponding phase voltage to an angle φ.

Assume that the voltages applied to phases B and C remain constant and the voltage of the phase A decreases. This causes a change in the current drawn by phase A, but some variation in the currents of the other phases also [14].

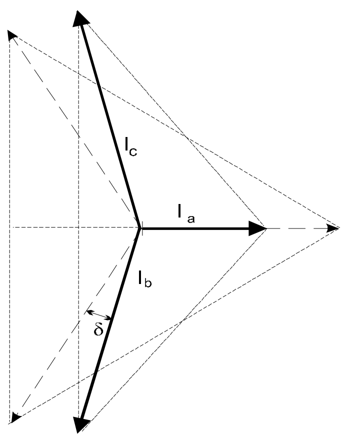

Fig.1. Phasor diagram of the input currents

As it is shown in the Fig.1, the currents I_b and I_c are changed by magnitude and by phases

$$\Delta i_a + \Delta i_b + \Delta i_c = 0 \qquad (1)$$

As the voltages U_b and U_c are constant, we can assert that the currents I_b and I_c variation is coused only by the current I_a change and

$$\Delta i_b = \Delta i_c \quad . \qquad (2)$$

The current I_b shift is in counter-clockwise direction and the I_c shift – clockwise.

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As it is seen in Fig.1

$$\cos\left(\delta+\frac{\pi}{3}\right)=\frac{I_a/2}{I_b}=\frac{(1+\Delta i_a)}{2.(1+\Delta i_b)}\cdot\frac{I}{I} \qquad (3)$$

where Δi_a, Δi_b are the changes of the phase A and B currents respectively and δ is the shift of I_b and I_c in relation to the corresponding phasor at symmetrical power supply (the symmetrical currents are shifted at 120º from each other and at angle φ, compared to the phase voltages). As it is seen, the current I_b leads, while I_c lags with an angle δ the corresponding currents at symmetrical conditions.

Let us assume that the torque and power output of the induction motor are unaltered at symmetrical and non-symmetrical supply. Hence

$$U_a I_a \cos\varphi_a + U_b I_b \cos\varphi_b + U_c I_c \cos\varphi_c = 3.UI\cos\varphi \qquad (4)$$

The variation of the voltages, currents and their phase shift are:

$$\Delta i_a=\frac{\Delta I_a}{I};\quad \Delta i_b=\frac{\Delta I_b}{I};\quad \Delta i_c=\frac{\Delta I_c}{I};\quad \Delta u=\frac{\Delta U}{U};$$

$$U.(1+\Delta u).I.(1+\Delta i_a).\cos\varphi_a + U.I.(1+\Delta i_b)\cos(\varphi_b+\Delta\varphi_b)$$
$$+U.I.(1+\Delta i_c).\cos(\varphi_c+\Delta\varphi_c)=3.U.I.\cos\varphi$$

Furthermore, $\Delta\varphi_b=+\delta$; $\Delta\varphi_c=-\delta$ (see Fig.1).

Equation (4) can be rearranged, as follows:

$$(1+\Delta u).(1+\Delta i_a)+(2-\Delta i_a).\cos\delta=3 \qquad (5)$$

The predicted changes of the currents Δi_a, Δi_b and the shift angle δ, are:

$$\Delta i_a=-\left(\frac{2\Delta u/3}{1+2\Delta u/3}\right)^2 \pm \frac{\sqrt{3.\Delta u.(\Delta u+1)}}{(1+2\Delta u/3)^2} \qquad (6)$$

$$\Delta i_b=\Delta i_a/2 \qquad (7)$$

$$\delta=\pm\left(\arccos\frac{1+\Delta i_a}{2-\Delta i_a}-\frac{\pi}{3}\right) \qquad (8)$$

The predicted values of Δi_a , Δi_b and δ, versus voltage deviation Δu are presented in Fig.2

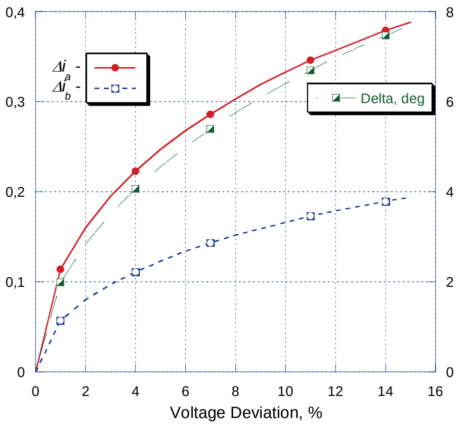

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Fig.2. The predicted values of drawn currents' change and the corresponding shift

III. EXPERIMENTAL RESULTS

Series of experiments have been made with an induction motor type AO-71A2, with following parameters: U_r = 380 V, n_r =2860 min^{-1}, I_r =0.94 A, η_r=0.72, cos φ= 0.83, I_{st}/I_r= 5.2, M_{st}/M_r= 2, M_{max}/M_r =2.25. The motor under test was coupled with DC generator and supplied by three auto-transformers type ATJI-9 with rated current I_r =9A. Power quality analyzer CA8332, serial number 00200226, produced by Chouven Arnoux have been used to measure the voltages, currents and power of the motor.

The motor's characteristics have been taken under balanced supply voltage and under two cases of unbalanced supply, changing the voltage of one phase (phase A). The same load torque has been applied at the motor shaft for all three cases.

The measured values of the unbalanced factor versus the one-phase voltage deviation (phase A) are shown in Fig.3.

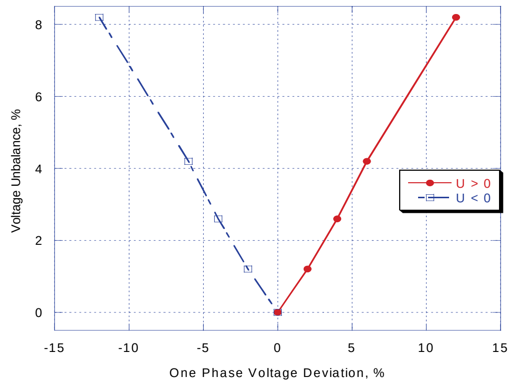

Fig.3. The voltage unbalance versus voltage deviation

Fig.4 shows the three-phase voltage phasors and the three-phase current phasors for three cases. Rated load have been applied to the motor shaft for all three cases. Fig.4(a) and 4(b) show the voltage and current phasors respectively in case of symmetrical supply. In Fig.4(c) and 4(d) the phasors when the supply voltage of phase A is bigger than rated value U_A =1,12U_r are shown. In Fig.4(e) and 4(f) are shown the phasors at U_A =0,88U_r. All values for the measured current are in mA.

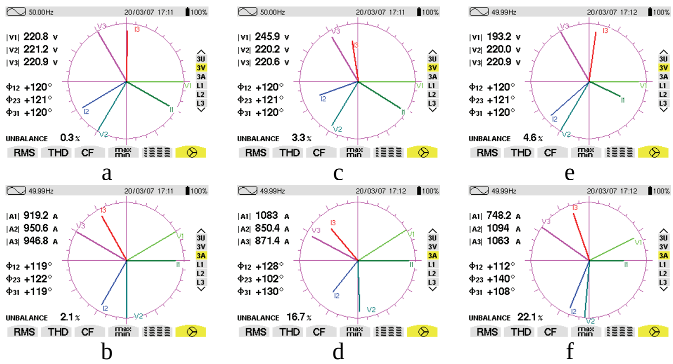

Fig.4. The voltage and current phasors

Test results from measurements performed with variation of the voltage deviation of phase A from -15% to +15% are presented in Fig. 5÷12. The measured quantities for currents, power and rotor speed are referred to the rated values.

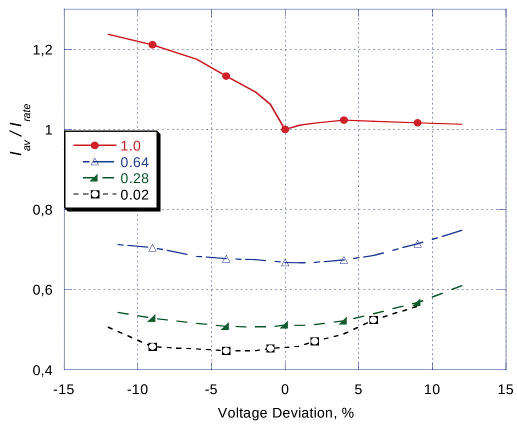

Fig.5. Average input current

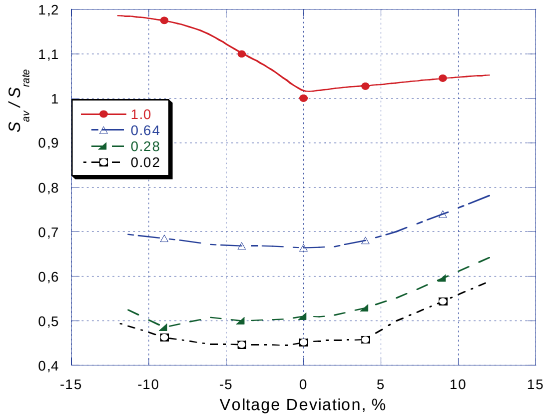

Fig. 9. Average input apparent power

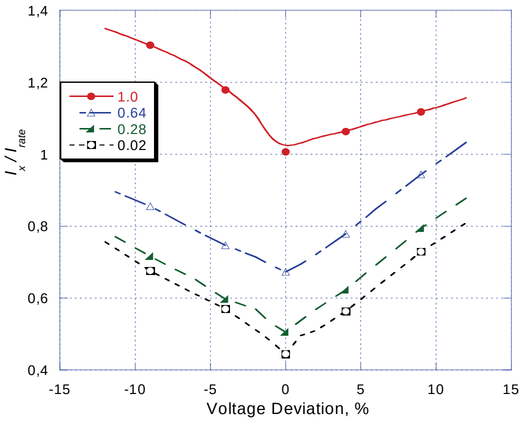

Fig.6. Over-loaded phase input current

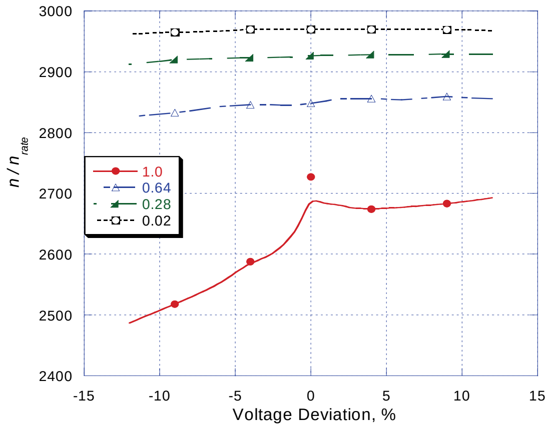

Fig.10. Induction motor speed

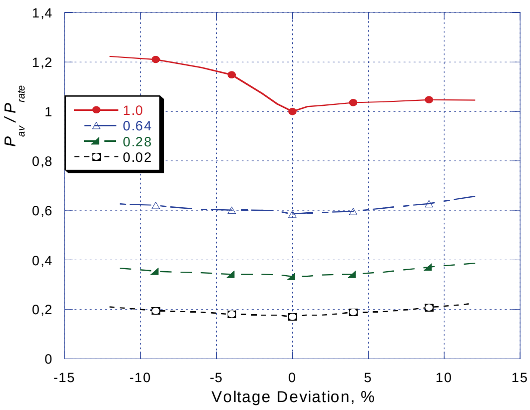

Fig. 7. Average input active power

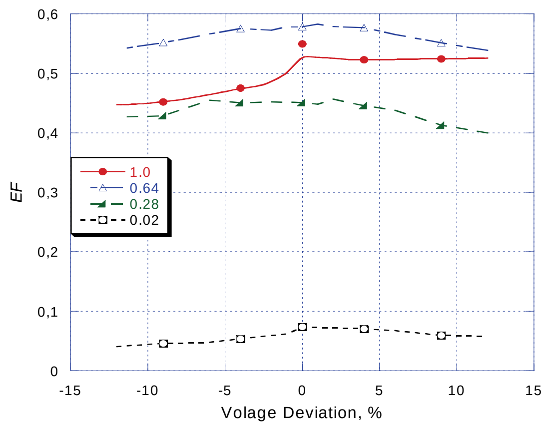

Fig.11. Induction motor efficiency

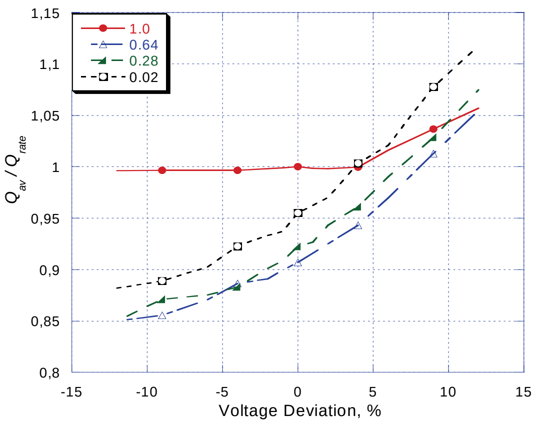

Fig. 8. Average input reactive power

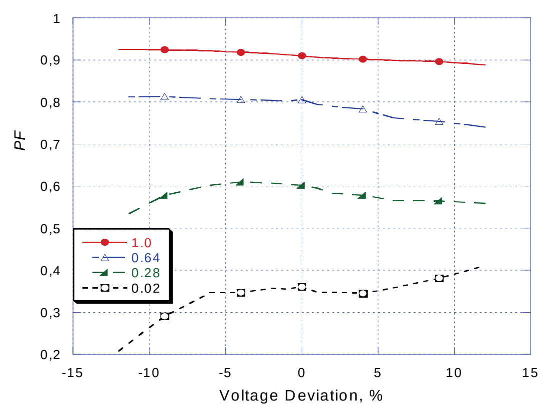

Fig.12. Induction motor power factor

The characteristics have been taken at four levels of the load applied and four characteristics have been drawn in each figure – at rated load (1.0), at load 64% of the rated (0.64), at load 28% of the rated (0.28) and at 2% of the rated (0.02). All characteristics have been drawn versus the voltage deviation of phase A while the voltage of phases B and C remains equal to the rated value.

The operation of the motor under unbalanced voltage supply could be analyzed by aid of these characteristics. Currents of the overloaded phase of the motor are shown in Fig. 6.When the supply voltage of phase A is over the rated value the current I_A increases too. If the voltage of phase A decreases below the rated value, the induction motor will draw bigger current from the two other phases. Hence, in case of under-voltage the troubles-free phases (phases B and C) are overloaded.

The currents of all three phases are changed not only by magnitude, but by phase too. This means that the active and reactive currents' components are changed and it causes the induction motor active and reactive power varying respectively (see Fig.7, Fig.8 and Fig.9).

Due to the unbalanced supply voltage the magnetic field of the motor is non-symmetrical. As a result the input current and power are bigger and the efficiency is lower (Fig.11), compared to the values at balanced supply voltage. In one-phase over-voltage case, the non-symmetrical magnetic field causes saturation of some sections of the magnetic core and the power factor reduces (see Fig.8 and Fig.12).

Finally a comparison between predicted and measured values of the phase currents and currents' phase shift is given in Fig.13.

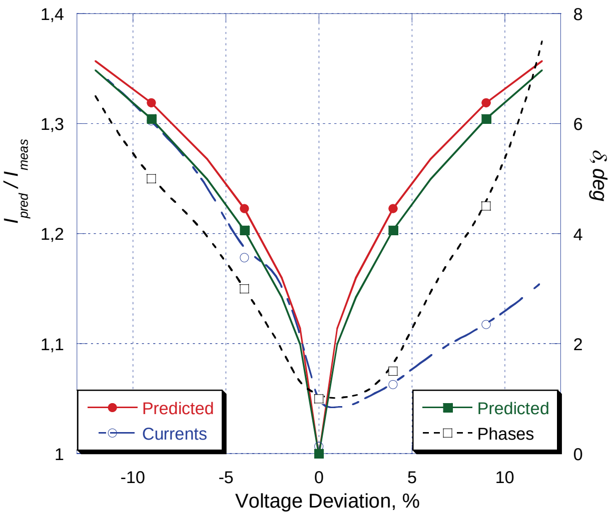

Fig.13. Predicted values and measured values of the phase currents and currents' phase shift

IV. Conclusion

1. An approach for motor currents prediction, when the motor is supplied by unbalanced three-phase voltage with deviation of the one-phase voltage, is proposed. The predicted values are close to the measured values. The differences could be caused by the small power of the motor under test.

2. It has been found out that at the same voltage unbalance values, the over-voltages and under-voltages cause different effects on the induction motor performance. This means that unbalance behavior establishment has to render an account of the voltage variation direction.

3. The supply voltage unbalance influence to the squirrel cage induction motor is:

- if the voltage decreases the average input currents will increase, the average input active and apparent power will increase too, the rotor speed will decrease. The efficiency and power factor slightly decrease. In the studied case, the currents' increase reaches to high value - $1{,}2I_r$ with only 3% unbalanced voltage.
- if the voltage increases over the rated value, the reactive power will increase and it will determine an increase in the apparent power, the rotor speed will remain nearly constant and the power factor and efficiency will decrease slightly.

4. The supply voltage unbalance makes the squirrel cage induction motor performance worst – the current drawn increases and the efficiency decreases, which means an increase in exploitation expenses.

5. Further experimental investigations with induction motors with bigger rated power will be made for verification of the proposed method.

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