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EFFECTS OF VOLTAGE UNBALANCE ON TORQUE OSCILLATIONS IN INDUCTION MOTOR

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Abstract

The paper presents an experimental analysis of the effects of the unbalanced power supply voltage of a three-phase induction motor on the torque oscillations. The measurements of the torque, voltage and motor currents at balanced and unbalanced voltage were performed. Asymmetric power supply modes were realized using single-phase autotransformers. Acquisition equipment and LabVIEW program applications were used for the measurements. The measurements were performed during the change of the motor phase supply voltage in the range of ±10% of its nominal value. The results obtained experimentally indicate that the second harmonic of the torque is directly dependent on the voltage unbalance.

Keywords: Voltage unbalance, induction motor, torque oscillation, LabVIEW.

INTRODUCTION

Supply voltage unbalance is one of the parameters of power quality. Phase-voltage fluctuations are often present in real power networks. The reasons for this, among other things, can be: non-symmetrical load by phases which leads to different voltage drops in the phase conductors; faults in power distribution networks can cause voltage sags (a single-phase short circuit being the most common fault, and it causes voltage drops of one phase, i.e. B-type of voltage sag) [1].

Voltage unbalance can be caused by variations in phase amplitude and/or phase angle. These variations directly affect the operation of a three-phase induction motor that is connected to such a three-phase voltage. Voltage unbalance leads to the unbalance of the motor phase currents. Consequently, a negative-sequence component of the current is created which directly results in the reduction of the motor torque, additional heating of the machine and reduction of its efficiency [2, 3], as well as the appearance of mechanical vibrations [4]. Besides voltage unbalance, current unbalance can also arise due to the unequal impedances of the motor phase coils.

In addition, voltage unbalance can lead to torque oscillations of the induction motor. The oscillations result from the negative-sequence component of the current and voltage. Except for the existing static load, voltage unbalance also causes higher torque harmonics. These harmonics are multiples of even numbers and basic frequency of motor power supply (100, 200 Hz, …) [5].

Furthermore, torque oscillations can also be caused when the induction motor is powered by a frequency converter [6]. In this case, torque oscillations can be reduced by introducing modifications in different motor control algorithms [7].

The source of torque oscillations can have mechanical nature as well. These oscillations originate from an imperfect coupling of a motor shaft on one side and a load shaft on the other side. In this case the problem arises from poor alignment of the shaft axes. These oscillations have a frequency that directly depends on the rotation speed.

The following chapters present a method of confirming the existence of the aforesaid problem. The definitions of the used values, equipment and the measurement procedure are presented as well. The final chapter of the paper provides the discussion on the results of the measurement of voltage and current unbalance as well as the value of the second harmonic of the induction motor torque.

VOLTAGE UNBALANCE AND ITS EFFECT ON THE INDUCTION MOTOR TORQUE

In a three-phase voltage system, the asymmetry can be represented by using symmetric components: positive, negative, and zero component. Several standards define the values for determining voltage unbalance [8, 9]. IEC 61000-3-14 standard [10] determines voltage unbalance by symmetrical components and the voltage unbalance factor – *VUF*:

$$VUF_{\%}=100\left(V_n/V_p\right) \tag{1}$$

where V_p is a positive-sequence voltage, and V_n is a negative-sequence voltage. The current unbalance factor – *CUF* is calculated in a similar way:

$$CUF_{\%}=100\left(I_n/I_p\right) \tag{2}$$

where I_p is a positive-sequence current and I_n is a negative-sequence current.

According to the NEMA standard, the voltage unbalance factor is defined based on the unbalance of the line voltages by the following equation:

$$LVUF_{\%}=100\frac{\max\left[\left|V_{ab}-V_{avg}\right|,\left|V_{bc}-V_{avg}\right|,\left|V_{ca}-V_{avg}\right|\right]}{V_{avg}} \tag{3}$$

where V_{ab}, V_{bc}, V_{ca} are line voltages, and V_{avg} is an average value of the line voltage (V_{avg}= $(V_{ab}+V_{bc}+V_{ca})/3$).

In case of the change in voltage amplitude of a single phase, the unbalance can be expressed by the *VUF* calculated by the equation:

$$VUF_{\%}=100\left|\frac{k-1}{k+2}\right| \tag{4}$$

where k is the value of phase voltage change per units. The derivation of this equation is given in the Appendix.

Voltage unbalance directly causes the oscillations of the resulting electromagnetic torque of the induction motor. An analytic equation for determining the amplitude of the torque second harmonic is given in paper [5]. The paper shows that the dominant torque oscillation frequency is two times higher than the motor power supply frequency. The equation was determined based on the positive-sequence and negative-sequence equivalent circuits of the induction motor.

According to [6], the induction motor torque at an unbalanced voltage can be represented by a direct torque component and two torque components at higher frequencies. These two torque components are two and four times higher than the basic power supply frequency (i.e. they have frequencies of 100 and 200 Hz).

USED EQUIPMENT AND METHOD OF MEASUREMENT

An experimental setup for the measurement of the effects of voltage unbalance on the torque oscillations was realized in the Laboratory of electrical machines, drives and regulation within Faculty of Technical Sciences in Cacak [11]. A block scheme of the used equipment is shown in Fig. 1. The induction motor IM was powered by three single-phase autotransformers and one three-phase autotransformer. These autotransformers provide voltage amplitude change in all three phases separately. The unbalance caused by a phase angle drift from its default value cannot be provided by this equipment so it will not be considered as an unbalance factor. The three-phase autotransformer enabled simultaneous voltage changes in all three phases.

A three-phase induction motor with a rated power of 1.1 kW was used in the measurement. The other parameters of the motor are given in Table 1 in the Appendix.

The induction motor is coupled with an electromagnetic brake by a torque meter and flexible bellows couplings. The induction motor load was set by controlling the direct current intensity through the coils of the electromagnetic brake [12].

A HBM T20WN torque meter was used for the measurement of the current values of torque and speed. The torque meter is equipped with an appurtenant connection box which picks up voltage signals of the torque and motor shaft rotation speed.

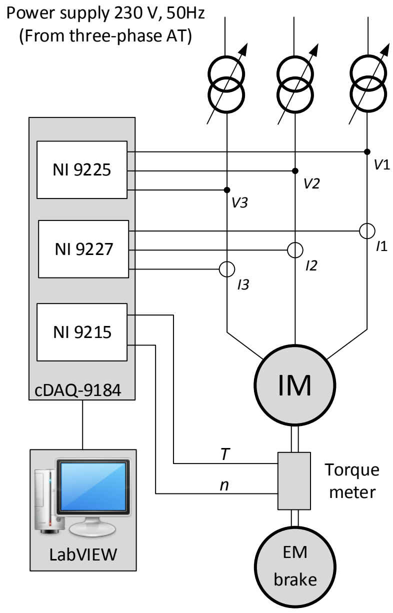

Fig. 1. Block scheme of measurement system

The quantities necessary for the analysis were measured using the cDAQ-9184 platform with the following modules: NI 9227 and NI 9225– for measuring motor currents and phase voltages respectively; NI 9215 – for measuring torque and speed signals. Voltages and currents are measured by NI 9225 and NI 9227 modules, with phase conductors being directly connected to these modules.

The display and recording of the measured values were realized by a LabVIEW application. Graphical user interface (GUI) of the application is shown in Fig. 2. All measured values can be saved in a .lvm file (table form) and prepared for further processing by selecting the "Zapamti" (Save) button.

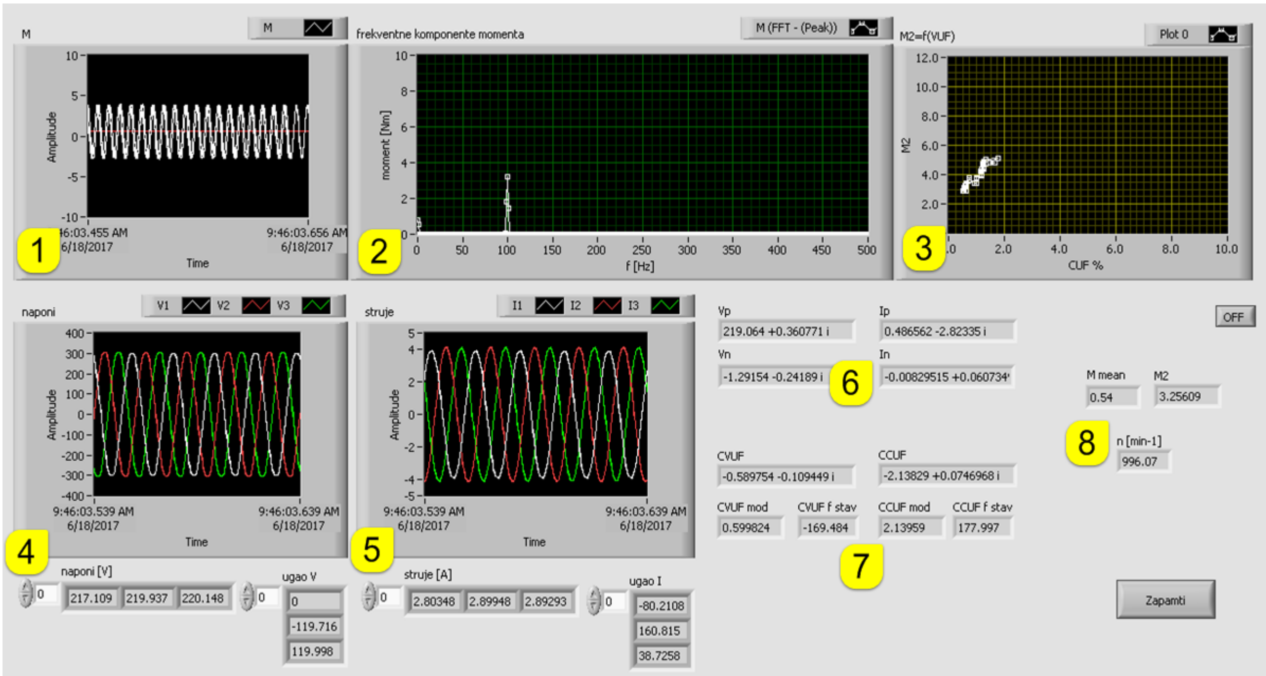

Fig. 2. Graphical user interface of the application used in the measurement

(1– instantaneous torque; 2– torque harmonic spectral components; 3– torque T2 dependence on VUF; 4– profile, rms values and phase angles of voltages; 5– profile, rms values and phase angles of currents; 6– numerical values of positive and negative components of motor voltage and currents; 7– complex values of VUF and CUF; 8– numerical values of direct torque component, torque T2 component and motor speed)

MEASUREMENT RESULTS

The measurements of the torque oscillations were performed by changing the voltage of one phase in the range of 0.9-1.1 p.u. At the same time, the voltages of the other two phases had the same nominal value (220V). After that, the measurements were conducted at two-phase unbalance, that is, by changing the voltages of two phases, while the voltage of one phase had a nominal value. The unbalance is expressed by two factors: *VUF* and *CUF*.

Figure 3 shows the values of the *VUF* and *CUF* measured at the voltage change of one phase. Diagrams 1, 2 and 3, shown in this figure, represent the values of the *VUF* and

CUF obtained by changing the voltage of the first, second and third phase, respectively. As it was already pointed out, during the change in voltage of one phase, the voltages of the remaining two phases had the nominal value of 220 V. In addition to the measured *VUF* values, the graph of the equation (4) is also presented. In all three cases, it is obvious that the unbalance factor linearly depends on the phase voltage. The values of the *VUF* obtained by the measurements and those obtained by the equation (4) are almost equivalent. The measured values have the expected linear dependence. However, in some cases, the measured values and the values determined by the equation (4) differ, which shows that the unbalance defined by the given equation was not fully realized during the measurement.

The reduction of voltage to 0.91 p.u. leads to an increase in the values of *VUF* in the range of 2.5-3%. The same happens when the voltage increases, i.e. an increase in voltage up to 1.1 p.u. leads to an increase in the *VUF* value of 3%. The values of the *CUF* at the same voltage change are about four times higher than the values of the *VUF*. The *CUF* also changes linearly with voltage, as in the case of *VUF*. The voltage of 0.9 p.u. leads to an increase in the value of *CUF* up to 12%. The same happens when the voltage increases and has a value of 1.1 p.u.

Figure 4 shows the instantaneous motor torque and its frequency components. In this case, there was no load on the motor. However, there was some friction torque. The measured average torque (T_0) was 0.55 Nm. The voltages had approximately the same value (220 V), but a small unbalance of the power supply as well as the motor unbalance caused torque oscillations. The dominant harmonic of the torque (T_2) is at the frequency of 100 Hz. The amplitude of these harmonic changes with the change in voltage, thus the increase in the unbalance (*VUF*) leads to the increase of T_2. The same figure shows that the torque components are present at several different frequencies. Slightly more prominent torque components are at the frequencies of 200 and 300 Hz (designated by number 1). These frequencies also occur due to the unbalance. There are also components at the frequencies of 16 and 48 Hz (designated by number 2). These components are the result of mechanical vibrations and their frequency changes with the change in the speed of rotation.

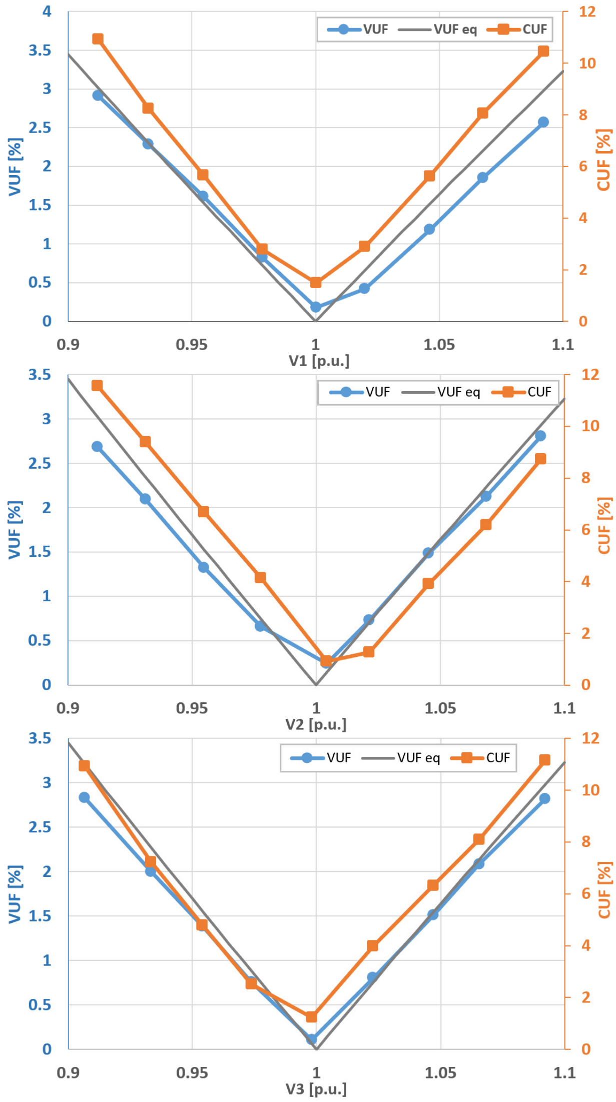

Fig. 3. *VUF and CUF at single-phase unbalance*

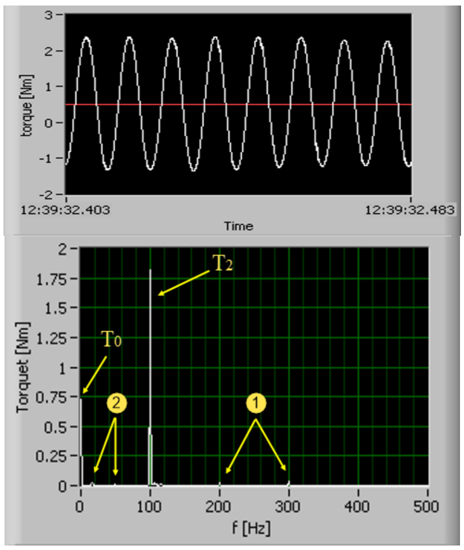

Fig. 4. *Profile of the torque and its frequency components*

Figure 5 presents a diagram of T_2 amplitude dependence on single-phase voltages. T_2 is given per units (with the base value T_n = 11.4 Nm). All values were measured at a motor load of 1.7 Nm. The diagram shows the changes in T_2 amplitude: it rises with the change in voltage and increase in unbalance. It can be seen that the values of T_2 amplitudes at the voltages of 0.9 and 1.1 p.u. reach the value of 0.9 p.u. Moreover, it is noticeable that the characteristics obtained at the V_2 and V_3 voltage unbalance are equivalent. When it comes to the characteristic of V_1 voltage, the values obtained deviate from the other two phases. The discrepancy between the characteristics of V_1 and V_2, V_3 can be caused by the unbalance of motor windings.

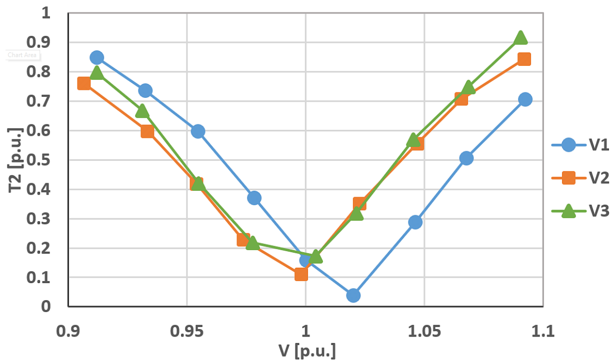

Fig. 5. *T_2 at single-phase unbalance*

As noted above, the measurements of T_2 at two-phase unbalance were also performed. The results of these measurements are shown in Figure 6 along with the results for the single-phase unbalance. The measurements of T_2 and *VUF* were performed at the following types of unbalance: 1P-UV - single-phase undervoltage; 1P-OV - single-phase overvoltage; 2P-UV - two-phase undervoltage; 2P-OV - two-phase overvoltage. The change in phase voltages was performed in the range from 0.9 p.u. (undervoltage) to 1.1 p.u. (overvoltage). The results show that high T_2 amplitude appears for all four types of unbalance. The highest values occur at the overvoltage unbalance (V=1-1.1 p.u.). In the case of undervoltage (V=0.9-1 p.u.), T_2 amplitude is lower by approximately 0.2 p.u. than T_2 amplitude at overvoltages. This shows that in the case of two-phase unbalance there is also a high value of T_2 amplitude and that these values are similar to those occurring at the single-phase unbalance.

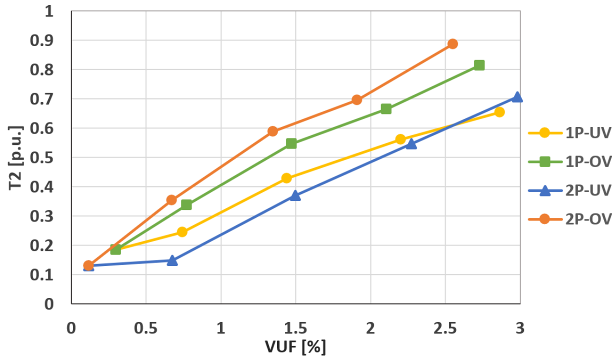

Fig. 6. *T_2 at single-phase and two-phase unbalance*

Paper [5] provides the equation for T_2, whose value depends on the motor slip (speed). The equation shows that the increase of slip and reduction of speed cause the decrease in the value of T_2 amplitude. Figure 7 presents the values of T_2 at single-phase unbalance and different torque loads. A change in load causes a change in the value of T_2 amplitude. Figure 8 shows the values of T_2 amplitudes at single-phase unbalance. The results are shown for three cases: when the phase voltages are 1, 0.954 and 1.045 p.u. The values of the other two voltages were around 1 p.u. The results of the measurement show that the load increase affects the value of T_2 amplitude, by reducing this value linearly. For all three cases of the unbalance there is a linear reduction of T_2 with approximately the same coefficient of reduction.

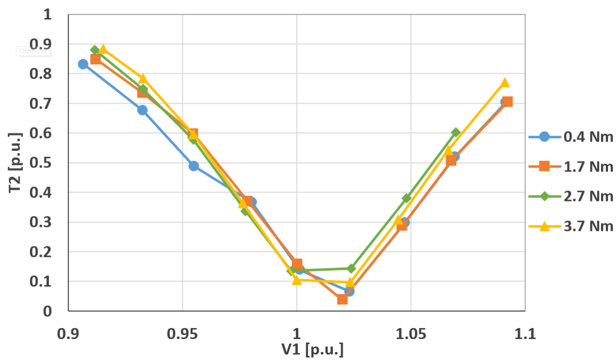

Fig. 7. *T_2 dependence on voltage and load*

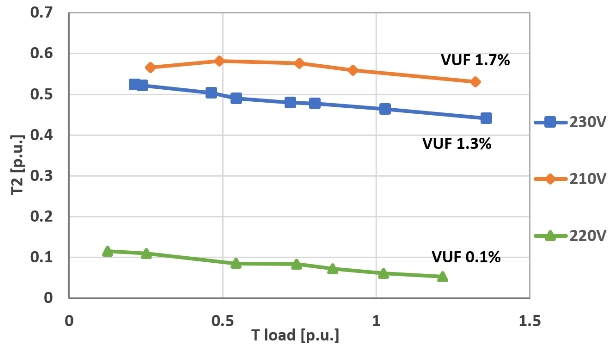

Fig. 8. *T_2 dependence on load*

CONCLUSION

This paper presents the effects of the unbalanced power supply voltage on the torque oscillations of the three-phase induction motor. The measurements showed that the torque oscillations occur due to the unbalanced power supply of the three-phase induction motor. The existing measurement and acquisition equipment and a LabVIEW application were used for measuring the torque, *VUF* and *CUF* of the induction motor with power of 1.1 kW. It is shown that the second harmonic of the torque directly depends on the factor of the voltage unbalance of the motor power supply. At the voltage change in the range of ± 10%, the torque amplitude reaches the value of 0.9 p.u. Furthermore, the paper confirms that an increase of the load leads to the reduction of the second harmonic of the torque.

APPENDIX

Induction motor parameters

Tab. 1. *Induction motor parameters*

U_n	380 V (Y)
I_n	3.5 A
n_n	920 min^{-1}
P_n	1.1 kW
$cos\varphi$	0.7
f_n	50 Hz

Calculation of VUF at single-phase unbalance

The positive and negative-sequence components of the voltage are:

$$V_p = \frac{1}{3}\left(V_1 + aV_2 + a^2V_3\right) = \frac{1}{3}\left(kV + aa^2V + a^2aV\right) = \frac{1}{3}V(k+2)$$

$$V_n = \frac{1}{3}\left(V_1 + a^2V_2 + aV_3\right) = \frac{1}{3}\left(kV + a^2a^2V + aaV\right) = \frac{1}{3}V(k-1)$$

Therefore, the voltage unbalance factor is:

$$VUF_{\%} = 100\frac{V_n}{V_p} = 100\left|\frac{k-1}{k+2}\right|$$

Where k is a phase voltage amplitude in p.u.

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