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GOROSHKO ANDRII
Khmelnytskyi National University
https://orcid.org/0000-0002-1386-2326
e-mail: horoshkoan@khmnu.edu.ua
KASHTALIAN ANTONINA
Khmelnytskyi National University
https://orcid.org/0000-0002-4925-9713
e-mail: kashtaliana@khmnu.edu.ua

INFLUENCE OF SUPPLY VOLTAGE UNBALANCE ON INDUCTION MOTOR CHARACTERISTICS

Various power quality disturbances are present in power systems, including voltage deviation, voltage asymmetry, and voltage waveform distortion. A mathematical model of an induction motor and a model of an unbalanced three-phase supply voltage for an induction motor with a Voltage Unbalance Factor of 2% are presented. The Matlab/Simulink/Simcape software was used to simulate the squirrel-cage motor under different conditions of unbalanced voltage. A simulation model of an 11 kW bipolar three-phase induction motor was developed and the motor performance was analyzed. The dependences of the motor shaft torque, mechanical power, efficiency, and time diagrams of transient processes of direct motor starting are obtained. The voltage unbalance has a significant impact on the efficiency, power factor, and mechanical characteristics of the motor. The supply voltage asymmetry causes fluctuations in torque, mechanical power, and rotor speed. Furthermore, the frequency of torque pulsations caused by the voltage unbalance is equal to twice the fundamental frequency. Speed fluctuations cause fluctuations in centrifugal force caused by rotor imbalance. However, repeated simulations and studies of the rotor with an acceptable mass eccentricity have shown that electromagnetic torque and speed fluctuations have virtually no significant effect on the radial vibrations of the rotor and stator. But significant torque fluctuations are offset by rotor inertia, and radial unbalanced forces are small with a normal allowable eccentricity of 20 µm. It can be concluded that the asymmetry of unbalance voltages within permissible limits does not cause dangerous rotor and stator vibrations. Resonance of torsional oscillations of the rotor is possible when it is large, which is not typical for low-power induction motors.
Keywords: Induction Motor, Voltage Unbalance, Electromagnetic Torque, Vibrations.

АНДРІЙ ГОРОШКО
АНТОНІНА КАШТАЛЬЯН
Хмельницький національний університет

ВПЛИВ НЕСИМЕТРІЇ НАПРУГИ ЖИВЛЕННЯ НА ХАРАКТЕРИСТИКИ АСИНХРОННОГО ДВИГУНА

В енергосистемах присутні різні порушення якості електроенергії, включаючи відхилення величини напруги, асиметрія напруги та спотворення її форми. У роботі представлено математичну модель асинхронного двигуна та модель незбалансованої трифазної напруги живлення для асинхронного двигуна з коефіцієнтом несиметрії напруги 2%. Для моделювання двигуна з короткозамкненим ротором за різних умов несиметрії напруги було використано програмне забезпечення Matlab/Simulink/Simcape. Розроблено імітаційну модель та проаналізовано роботу асинхронного трифазного двигуна з короткозамкнутим ротором потужністю 11 кВт. Отримано залежності моменту на валу двигуна, механічної потужності, ККД та часові діаграми перехідних процесів прямого пуску двигуна. Показано, що несиметрія напруги суттєво впливає на ККД, коефіцієнт потужності та механічні характеристики двигуна. Несиметрія напруги живлення викликає коливання моменту, механічної потужності та частоти обертання ротора. Крім того, частота пульсацій крутного моменту, викликаних дисбалансом напруги, дорівнює подвійній основній частоті. Коливання швидкості викликають коливання відцентрової сили, спричинені дисбалансом ротора. Однак багаторазові моделювання і дослідження ротора з прийнятним ексцентриситетом маси показали, що електромагнітні коливання моменту і швидкості практично не мають істотного впливу на радіальні коливання ротора і статора. Значні коливання моменту компенсуються інерцією ротора, а радіальні неврівноважені сили малі при нормальному допустимому ексцентриситеті 20 мкм. Можна зробити висновок, що асиметрія напруг небалансу в допустимих межах не викликає небезпечних коливань ротора і статора. Резонанс крутильних коливань ротора можливий при його великій величині, що не характерно для асинхронних двигунів малої потужності.
Keywords: асинхронний двигун, несиметрія напруги, електромагнітний момент, вібрації.

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Introduction

Three-phase induction motors are currently the most common types of electric motors used in industry. The advantages of their use include high specific power, simple and robust design, ease of maintenance and relatively low cost.

One of the indicators that characterize the operation of an engine is the level of mechanical vibrations. High engine vibration levels adversely affect its service life and generate additional noise. In addition, motor vibrations can be transmitted to other structural elements through the drive and stator mounting elements. In practice, situations often arise when, due to the finite values of the elastic-inertial properties of structural elements, their vibrations exceed those of the motor itself.

The causes of vibration of induction motors are mechanical eccentricity of the rotor, rotor deflection, magnetic eccentricity, misalignment of the shaft and coupling, as well as electrical problems: asymmetry of the supply voltage and its non-sinusoidality. In this paper, we consider supply voltage unbalance as the main cause of motor vibration. A balanced voltage system should be used to supply induction motors, but in practice this condition is not always met. Any difference in voltage or phase difference other than 120° is an unbalanced supply.

Analysis of research and publications

The issue of the influence of three-phase voltage unbalance of an induction motor is relevant and has been studied by many scientists. Thus, in the paper [1] the three definitions (line voltage unbalance in percent-LVUR, phase voltage unbalance in percent-PVUR and voltage unbalance factor-VUF) of voltage magnitude unbalance have been considered. In the [2] analysis of the steady-state performance of an induction motor connected to unbalanced three-phase voltages is presented. The paper [3] shows an alternative method to determine the Voltage Unbalance Factor in a power grid by using both the mean value of the line voltages and Current Unbalance Factor in induction motors. The paper [4] presents data showing that vibrations caused by voltage unbalance are significantly more pronounced in higher efficiency induction motors than in standard efficiency motors. The authors of [5] proposed the methodology and results of research conducted to study the speed and torque of an induction motor under voltage fluctuations. It will be shown that under a special condition the IM torque can even reach two times the rated torque. To show how this occurs, a qualitative discussion is given on the motor response by linearized equations.

The study [6] analyzes induction motors under VFs using experimental and finite element methods. The vibration and torque pulsations are compared for a single voltage subharmonic/interharmonic injection and VFs with various shapes of the modulating function. The results show that requirements concerning flicker severity, as well as the proposals to limit SaIs included in the standard IEEE-519:2022, do not protect induction motors against excessive vibration. Recommendations concerning the limitations of SaIs are formulated.

In [7], the authors conducted full-scale experiments, investigating the operation of an induction motor from a balanced three-phase power supply and an unbalanced power supply with different values of asymmetry. It was found that an increased level of vibration occurs not only in the radial but also in the longitudinal direction.

The authors of [8] compared the results of modeling and experimental tests on an induction motor, in particular, they studied changes in stator current, motor efficiency, power factor, and rotor pulsation under different steady-state conditions of unbalanced voltage. It is shown that, in addition to the voltage unbalance factor, the values of the forward and reverse components of the unbalanced supply voltage play an important role in the motor performance.

Despite significant progress in studying the effect of unbalanced power supply on motor performance, the effect of unbalance on radial shaft vibrations remains poorly understood.

Formulation of the objectives of the article

The aim of the work is to analyze the influence of supply voltage asymmetry on the mechanical characteristics of a three-phase induction motor and the level of radial vibrations of the stator and rotor.

Methodology

Mathematical model. To describe the dynamic processes in an induction machine, a flat orthogonal coordinate system dq is used, which rotates at the speed ω. The electrical part of the motor is described by a fourth-order system, and the mechanical part by a second-order system. All electrical variables and parameters refer to the stator. The system of differential equations describing the dynamics of an induction machine when voltages, currents, torques, and speeds change is as follows [9]:

$$\begin{aligned}
&U_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega\psi_{ds}, && \psi_{qs} = L_s i_{qs} + L_m i'_{qr},\\
&U_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega\psi_{qs}, && \psi_{ds} = L_s i_{ds} + L_m i'_{dr}\\
& && \psi'_{qr} = L'_r i'_{qr} + L_m i_{qs},\\
&U'_{qr} = R'_r i'_{qr} + \frac{d\psi'_{qr}}{dt} + (\omega - \omega_r)\psi'_{dr}, && \psi'_{dr} = L'_r i'_{dr} + L_m i_{ds},\\
&U'_{dr} = R'_r i'_{dr} + \frac{d\psi'_{dr}}{dt} - (\omega - \omega_r)\psi'_{qr}, && L_s = L_{ls} + L_m,\\
& && L'_r = L'_{lr} + L_m,\\
&M_e = 1.5p(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}),
\end{aligned} \tag{1}$$

where $U_{qs} = U_m \cos\omega t$, $U_{qs} = U_m \sin\omega t$ are the voltages on the stator windings along the q and d axes, respectively; U'_{qr}, U'_{dr} are the rotor voltages; i_{qs}, i_{ds} are the stator currents; i'_{qr}, i'_{dr} are the rotor currents; ψ_{qs}, ψ_{ds} are the stator flux projections; $d\psi'_{qr}, d\psi'_{dr}$ are the rotor flux projections; L_s is the total stator inductance, L_{ls} is the stator dissipation inductance; L'_r the total rotor inductance, L_m is the magnetization circuit inductance; *ω is the stator angular current frequency, ω_r is the rotor electric angular velocity, M_e is the motor electromagnetic torque.*

The mechanical system of the motor can be described by the following equation:

$$\frac{d\Omega}{dt} = \frac{M_e - f\Omega - M_m}{J}, \tag{2}$$

where $\Omega = \frac{\omega_r}{p}$ is the angular speed of rotor rotation; M_e is the electromagnetic torque of the motor; M_m is the mechanical torque of the shaft, f is the total coefficient of viscous friction of the rotor and load; J is the moment of inertia of the rotor with the load. The useful mechanical power on the motor shaft can be defined as

$$P_m = M_m \Omega. \quad (3)$$

According to the standard, induction motors must deliver their rated power when the mains voltage deviates from the rated value by between -5 and +10%. Possible voltage asymmetry in a three-phase network is provided for in the current electrical regulations, in particular, in accordance with EN 50160:2022 the voltage asymmetry factor, which is the ratio of reverse-sequence voltage to forward-sequence voltage, should not exceed 2%:

$$VUF = \frac{U_2}{U_1} \cdot 100\%. \quad (4)$$

Let us consider the effect of unbalance on the operation of an induction motor using the method of symmetrical components. Without taking into account saturation, the motor performance characteristics at unbalanced voltage can be obtained by the superposition method, assuming that the forward and reverse sequence voltages act independently, and the zero sequence at a symmetrical stator winding does not affect the motor operation:

$$\underline{U}_1 = \frac{1}{3}(\underline{U}_A + a\underline{U}_B + a^2\underline{U}_C),\ \underline{U}_2 = \frac{1}{3}(\underline{U}_A + a^2\underline{U}_B + a\underline{U}_C), \text{ where } a = e^{j\frac{2\pi}{3}}. \quad (5)$$

The phase voltages are the sum of the respective forward and reverse components:

$$\underline{U}_A = \underline{U}_1 + \underline{U}_2, \underline{U}_B = a^2\underline{U}_1 + a\underline{U}_2, \underline{U}_C = a\underline{U}_1 + a^2\underline{U}_2. \quad (6)$$

Simulation model. To model the effect of asymmetric power supply on the mechanical characteristics of an induction motor, a simulation model was developed in *Matlab Simulink/Simcape* (Fig. 1). A 1.5 kW induction motor with a squirrel-cage rotor (p=1, n=3000 rpm, M_n=36.1 N·m) common in industry, was chosen for modeling.

Taking into account the permissible level of asymmetry VUF=2% using dependencies (6), the amplitudes of the phase voltages of the forward and reverse sequence were obtained: U_{m1}=311.3 V, U_{m2}=6.22 v. he corresponding phase voltage amplitudes at the motor terminals are equal to

$$\underline{U}_A\text{=317.35 V}, \underline{U}_B = 307.8e^{-j120.4^{\circ}}\text{V}, \underline{U}_C = 307.8e^{j120.4^{\circ}}\text{V}.$$

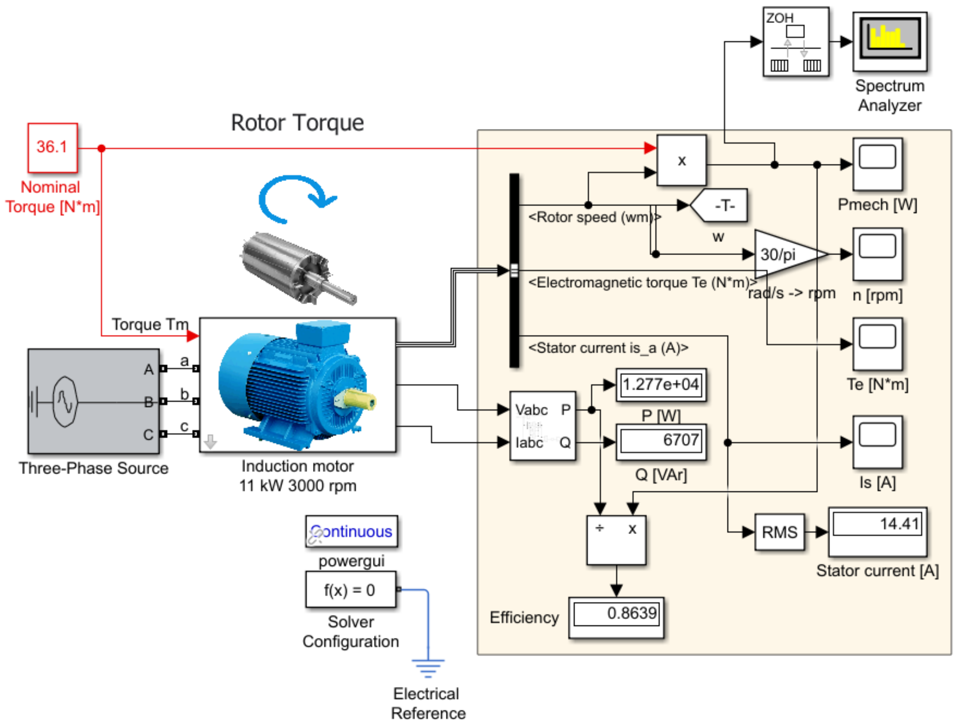

Fig. 1. The S-model under study

Modeling and simulation results. The modeling results indicate a significant effect of the power supply asymmetry on the motor characteristics even at the permissible value of the voltage asymmetry. Fig. 2 shows the comparative dependence of the stator current on the shaft load for symmetrical and asymmetrical power supply VUF=2%.

Along with the torques generated by the forward and reverse sequence voltages, pulsating electromagnetic torques also occur in the motor due to the interaction of reverse rotor currents with the forward stator field and forward rotor currents with the reverse stator field. These moments pulsate with a frequency of 2ω and create vibrations. Comparative time dependences of the stator electromagnetic torque are shown in Fig. 3. The modeling results show that the electromagnetic torque, shaft torque, mechanical power, and rotational speed are oscillatory in nature (Figs. 3-5).

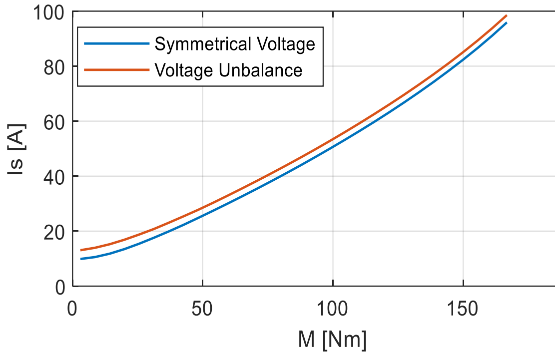

Fig. 2. Comparative dependence of stator current on load for symmetrical and asymmetrical power supply (*VUF*=2%)

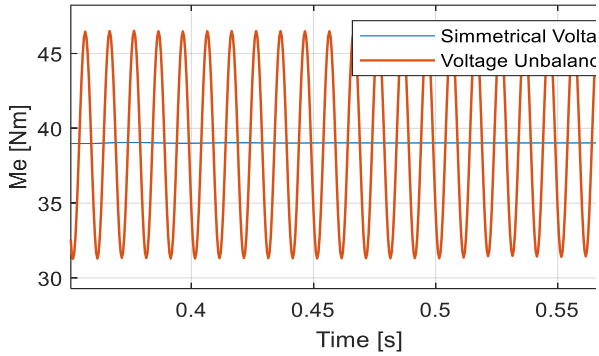

Fig. 3. Comparative time dependences of stator electromagnetic torque for symmetrical and asymmetrical power supply (*VUF*=2%)

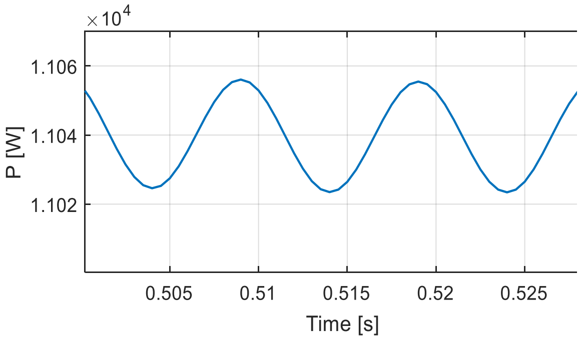

Fig. 4. Oscillogram of power change on the shaft in asymmetric mode (*VUF*=2%)

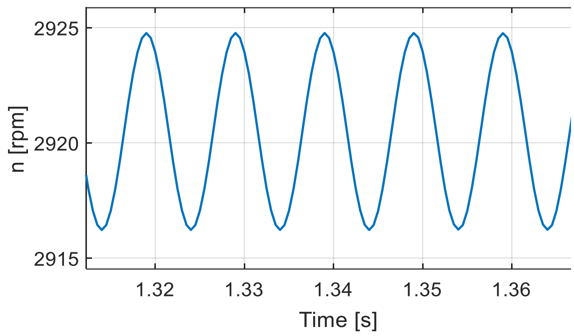

Fig. 5. Oscillogram of rotor shaft speed change in asymmetric mode (VUF=2%)

Conclusion and discussion questions

The results obtained are in full agreement with those of other authors [6-8]. The voltage asymmetry has a significant impact on the efficiency, power factor, and mechanical characteristics of the motor. The supply voltage asymmetry causes fluctuations in torque, mechanical power, and rotor speed. Speed fluctuations cause fluctuations in centrifugal force caused by rotor imbalance. However, repeated simulations and studies of the rotor with an acceptable mass eccentricity have shown that electromagnetic torque and speed fluctuations have virtually no significant effect on the radial vibrations of the rotor and stator. It can be concluded that the asymmetry of the supply voltages within the permissible limits does not cause dangerous vibrations of the rotor and stator. The resonance of torsional vibrations of the rotor is possible under conditions of its large dimensions, which is not typical for induction motors of low power.

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