https://doi.org/10.33271/nvngu/2022-6/090

O. Bialobrzheskyi*,
orcid.org/0000-0003-1669-4580,
V. Nozhenko,
orcid.org/0000-0003-0126-6970,
O. Todorov,
orcid.org/0000-0001-5703-6790

Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine
* Corresponding author e-mail: seemal@kdu.edu.ua

INFLUENCE OF MISALIGNMENT OF CONNECTION OF ELECTRICAL MACHINE SHAFTS ON THE NATURE OF ELECTRIC POWER OF THE INDUCTION MOTOR

Purpose. To identify the vibration power components caused by misalignment of electrical machine shafts in the instantaneous power of the induction motor.

Methodology. The power components of the induction motor are analytically determined taking into account the power caused by torque vibrations on the shaft. Based on this, using the methods of mathematical modelling in the visual programming environment, the known model of a three-phase induction motor with a short-circuited rotor has been made. In addition, elements and connections are introduced which realize the formation of the moment caused by the imbalance of rotating masses. Using Fourier transform of the electric power of the induction motor, we determine its discrete spectrum. Experimental research is conducted on the electric power of the induction motor with a short-circuited rotor, in similar model conditions, on laboratory equipment. With the use of a virtual device synthesized in the LabVIEW package, the wavelet analysis of stator electric power of the motor of laboratory electrotechnical complex is performed.

Findings. Differential equations of the induction motor with a short-circuited rotor in *abc* coordinate system are obtained, which reflect the distribution of instantaneous power in the machine taking into account the vibration moment. As a result of modelling according to the specified equations of the induction machine, in the conditions of full symmetry of parameters of the scheme and the mode with eccentricity of rotating masses, low-frequency vibrations of electric power of a stator with frequency of 25 Hz have been found. Similar results were obtained as a result of wavelet analysis of the electric power of an induction motor of a laboratory electrotechnical complex.

Originality. Rationality of use of instantaneous electrical power of induction motor stator for detection of vibration caused by misalignment between its shaft and the shaft of another machine has been substantiated, which allows detecting vibration without complex methods of measuring vibration displacement and its derivatives.

Practical value. Detecting vibration by measuring the electrical parameters of the stator circuit of the induction motor and determining the vibrations of its instantaneous power without the use of specialized equipment significantly simplify the procedure of vibration diagnostics at its early stages.

Keywords: *induction motor, shaft misalignment, electric power, mechanical vibrations*

Introduction. The energy balance is an important issue in the study of induction motor drives. As the analysis of using electric drives made according to "semiconductor frequency converter – an induction machine" scheme has found that both traditional and modern electric drives still have underused reserves of increasing energy efficiency of electromechanical energy conversion [1].

There are some characteristics of power of the induction; high operational and energy and, consequently, economic characteristics of the induction motor (IM) are achieved mainly at operation on natural characteristics with loads close to nominal. That means, while working from the network, the motor consumes a constant reactive power equal to the nominal power at rated voltage, and while reducing the torque and consumed active power, a disadvantage of induction motors appears – a decreasing power factor [2]. Therefore, the issue of energy balance is also relevant when creating the induction machine control system to minimize losses and to provide greater economic efficiency.

The imperfection of the mechanical connection of the machine structure with the driven working mechanism and the mechanical forces occurring at the attachment points of the electric machine supports lead to vibrations in the machine. Additionally, vibrations are amplified in long-term operated machines due to the disturbance of the axial symmetry of the rotor of the corresponding air clearance [3] and wear of bearing units [4]. The use of vibration-diagnostic equipment in such cases can be difficult both technically and financially.

Literature review. A number of works are devoted to the problem of energy indicators, distribution of electrical parameters and power in the induction machine [2, 5, 6]. Thus, the method of estimation of energy indicators and criteria depending on the chosen criterion and design task at the development of induction machines is considered in [2]. The issues of research on energy and electromechanical processes of the induction machine are considered in [5]. The power balance is calculated taking into account the losses in the stator and rotor copper, as well as in the stator steel. Also, in this paper reactive power is calculated consumed from the network. The paper [6] presents a theoretical study on energy conversion in induction machines with natural characteristics and with increasing load. Namely, the analysis is conducted of changes of components of electrical losses, which are divided into losses that do not depend on the load on the shaft (magnetization losses consisting of losses in the stator copper from the magnetizing current and losses in steel) and variable losses depending on the load (load losses, consisting of losses in the stator and rotor copper from the load current). As a rule, a single-line substitution scheme is used for the calculations in the above cases [7].

Of course, more complex analytical models are used when dealing with induction machine modes, caused by both stator voltage and current, which are due to asymmetric parameters [8, 9].

Special attention should be paid to the study on energy processes in inductive machines that are subject to vibration, because the causes of this phenomenon are quite numerous. Vibrations of electrical machines can occur both from the power supply, load, technological connections, and from the motor itself. So, in [10], studies were carried out on the influence of mechanical vibrations of the induction motor on electrical and mechanical power due to unbalanced shaft of the working mechanism. Analysis of the obtained results showed that the vibration of the motor leads to power fluctuations in the steady state, while the fluctuation amplitude of electric power is greater than the amplitude of the mechanical power. In paper [11], non-stationary processes during engine start-up and run-out are considered with fastening defects available, which indicate the occurrence of resonant amplification of vibrations, which leads to an increase in electromechanical power on the motor shaft. In paper [12], it an analysis is carried out of experimental studies on vibration power of the induction motor when operated from an asymmetric power supply, which showed that vibration power is a significant part of engine power consumption, which must be taken into account in the overall energy balance, but the authors carry out calculation of mechanical power on the basis of the data obtained from vibration sensors in the laboratory.

At the same time the problem of determining the energy distribution of inductive machine remains relevant due to the fact of its power supply from a three-phase electric source [7]. It is necessary to take into account the fact that energy conversion processes in an induction machine are accompanied by time changes in phase voltages and currents in each phase as well as change in mechanical momentum and speed on the shaft. It means that there is a conversion of energy, which is transmitted by three channels through the phase lines connected to the stator and the channel of energy transmission on the machine shaft, taking into account electromagnetic, electromechanical and mechanical processes.

Purpose. Justification of the expediency of using the instantaneous power of the inductive machine to identify vibrations that occur under the influence of mechanical disturbances.

Results. Analytical representation of the inductive electrical machine is performed on the basis of balance equations of its electromagnetic system, taking into account the process of electromechanical transformation and mechanical movement of the rotor [13, 14]. The development of views from the position of construction of control systems for induction electrical machines leads to the use of mathematical techniques that simplify the synthesis of control systems. As a result, certain transformations are used and are considered the equations of the machine in moving coordinates *abc*, moving coordinate system *xyz* oriented by the given vector, fixed coordinate system $\alpha\beta0$, moving coordinate system *dq*0 oriented by vector of rotor flux linkage ratio [13, 14].

Let us consider the initial system of equations of the induction machine. The equation of electric balance of stator and rotor windings is [14]

$$\begin{cases} u_{as} = r_{as} i_{as} + \dfrac{d\psi_{as}}{dt} \\ u_{bs} = r_{bs} i_{bs} + \dfrac{d\psi_{bs}}{dt} \\ u_{cs} = r_{cs} i_{cs} + \dfrac{d\psi_{cs}}{dt} \\ \dfrac{d\psi_{ar}}{dt} = r_{ar} i_{ar} + u_{ar} \\ \dfrac{d\psi_{br}}{dt} = r_{br} i_{br} + u_{br} \\ \dfrac{d\psi_{cr}}{dt} = r_{cr} i_{cr} + u_{cr} \end{cases}, \qquad (1)$$

where u_s, u_r are stator and rotor phase voltages; ψ_s, ψ_r are stator and rotor phase flux linkages; i_s, i_r are stator and rotor phase currents; r_s, r_r are active resistance of stator and rotor windings. In case of a short-circuited rotor – $u_r = 0$.

Flux linkages are the most complex dependencies, which analytically look as follows

$$\begin{cases} \psi_{as} = (\psi_{asas} + \psi_{asbs} + \psi_{ascs}) + (\psi_{asar} + \psi_{asbr} + \psi_{ascr}) \\ \psi_{bs} = (\psi_{bsas} + \psi_{bsbs} + \psi_{bscs}) + (\psi_{bsar} + \psi_{bsbr} + \psi_{bscr}) \\ \psi_{cs} = (\psi_{csas} + \psi_{csbs} + \psi_{cscs}) + (\psi_{csar} + \psi_{csbr} + \psi_{cscr}) \\ \psi_{ar} = (\psi_{arar} + \psi_{arbr} + \psi_{arcr}) + (\psi_{aras} + \psi_{arbs} + \psi_{arcs}) \\ \psi_{br} = (\psi_{brar} + \psi_{brbr} + \psi_{brcr}) + (\psi_{bras} + \psi_{brbs} + \psi_{brcs}) \\ \psi_{cr} = (\psi_{crar} + \psi_{crbr} + \psi_{crcr}) + (\psi_{cras} + \psi_{crbs} + \psi_{crcs}) \end{cases},$$

where ψ_{xsys}, ψ_{xsyr}, ψ_{xryr} are flux linkages of stator phase and stator phase, stator phase and rotor phase, rotor phase and rotor phase, respectively. These flux linkages are due to the phenomena of self-induction and mutual induction of the respective windings.

Electromagnetic moment M_{em} formed in this case by the magnetic flux in the air gap is balanced by the moment of mechanical load M_{ld}, dynamic moment due to the inertia of rotating masses J and the moment of resistance to rotation of the machine M_{am}

$$M_{em} = \frac{Z_p}{\sqrt{3}} \Big[i_{ar} (\psi_{asbr} - \psi_{ascr}) + i_{br} (\psi_{bscr} - \psi_{bsar}) + \\ + i_{cr} (\psi_{csar} - \psi_{csbr}) \Big] = M_{ld} + J \frac{d\omega}{dt} + M_{am}. \qquad (2)$$

Determine the power balance of the rotor and stator circuits by multiplying the left and right sides of the electrical balance equations by the stator and rotor current respectively

$$\begin{cases} i_{as} u_{as} = r_{as} i_{as}^2 + \dfrac{d}{dt}(\psi_{asas} + \psi_{asbs} + \psi_{ascs}) i_{as} + \dfrac{d}{dt}(\psi_{asar} + \psi_{asbr} + \psi_{ascr}) i_{as} \\ u_{bs} i_{bs} = r_{bs} i_{bs}^2 + \dfrac{d}{dt}(\psi_{bsas} + \psi_{bsbs} + \psi_{bscs}) i_{bs} + \dfrac{d}{dt}(\psi_{bsar} + \psi_{bsbr} + \psi_{bscr}) i_{bs} \\ u_{cs} i_{cs} = r_{cs} i_{cs}^2 + \dfrac{d}{dt}(\psi_{csas} + \psi_{csbs} + \psi_{cscs}) i_{cs} + \dfrac{d}{dt}(\psi_{csar} + \psi_{csbr} + \psi_{cscr}) i_{cs} \\ \dfrac{d}{dt}(\psi_{aras} + \psi_{arbs} + \psi_{arcs}) i_{ar} = r_{ar} i_{ar}^2 + \dfrac{d}{dt}(\psi_{arar} + \psi_{arbr} + \psi_{arcr}) i_{ar} \\ \dfrac{d}{dt}(\psi_{bras} + \psi_{brbs} + \psi_{brcs}) i_{br} = r_{br} i_{br}^2 + \dfrac{d}{dt}(\psi_{brar} + \psi_{brbr} + \psi_{brcr}) i_{br} \\ \dfrac{d}{dt}(\psi_{cras} + \psi_{crbs} + \psi_{crcs}) i_{cr} = r_{cr} i_{cr}^2 + \dfrac{d}{dt}(\psi_{crar} + \psi_{crbr} + \psi_{crcr}) i_{cr} \end{cases}. \qquad (3)$$

Let us make an energy balance for the induction machine in all phases [14]. Power entering the stator

$$p_s = u_{as}i_{as} + u_{as}i_{as} + u_{as}i_{as} \quad (4)$$

is divided by the active resistance of the stator windings (p_{rs}), electromagnetic power of self-induction and mutual induction of the stator ($p_{\sigma s}$) and power transmitted through the air gap (p_{ems})

$$\begin{aligned} p_s = p_{r.s} + p_{\sigma.s} + p_{em.s} = (r_{as}i_{as}^2 + r_{bs}i_{bs}^2 + r_{cs}i_{cs}^2) + \\ + \Bigg[\frac{d}{dt}(\psi_{asas} + \psi_{asbs} + \psi_{ascs})i_{as} + \frac{d}{dt}(\psi_{bsas} + \\ + \psi_{bsbs} + \psi_{bscs})i_{bs} + \frac{d}{dt}(\psi_{csas} + \psi_{csbs} + \psi_{cscs})i_{cs}\Bigg] + \\ + \Bigg[\frac{d}{dt}(\psi_{asar} + \psi_{asbr} + \psi_{ascr})i_{as} + \frac{d}{dt}(\psi_{bsar} + \\ + \psi_{bsbr} + \psi_{bscr})i_{bs} + \frac{d}{dt}(\psi_{csar} + \psi_{csbr} + \psi_{cscr})i_{cs}\Bigg]. \end{aligned} \quad (5)$$

The power transmitted through the air gap is equal to the sum of the mechanical power and electromagnetic power of the rotor

$$p_{em.s} = p_{em} + p_{em.r}. \quad (6)$$

Mechanical power has the form

$$\begin{aligned} p_{em} = M_{em}\omega = \frac{d\psi_{asar}}{dt}(i_{as} - i_{ar}) + \frac{d\psi_{asbr}}{dt}(i_{as} - i_{br}) + \\ + \frac{d\psi_{ascr}}{dt}(i_{as} - i_{cr}) + \frac{d\psi_{bsar}}{dt}(i_{bs} - i_{ar}) + \frac{d\psi_{bsbr}}{dt}(i_{bs} - i_{br}) + \\ + \frac{d\psi_{bscr}}{dt}(i_{bs} - i_{cr}) + \frac{d\psi_{csar}}{dt}(i_{cs} - i_{ar}) + \frac{d\psi_{csbr}}{dt}(i_{cs} - i_{br}) + \\ + \frac{d\psi_{cscr}}{dt}(i_{cs} - i_{cr}) = M_{ld}\omega + J\frac{d\omega}{dt}\omega + M_{am}\omega = p_{ld} + p_j + p_m. \end{aligned} \quad (7)$$

The electromagnetic power of the rotor is equal to the sum of the power of self-induction and mutual induction of the rotor windings ($p_{\sigma.r}$) and power losses in the active resistance of the rotor windings ($p_{r.r}$)

$$\begin{aligned} p_{\mathring{a}m.r} = p_{\sigma.r} + p_{r.r} = \frac{d}{dt}(\psi_{arar} + \psi_{arbr} + \psi_{arcr})i_{ar} + \\ + \frac{d}{dt}(\psi_{brar} + \psi_{brbr} + \psi_{brcr})i_{br} + \frac{d}{dt}(\psi_{crar} + \psi_{crbr} + \psi_{crcr})i_{cr} + \\ + (r_{ar}i_{ar}^2 + r_{br}i_{br}^2 + r_{cr}i_{cr}^2). \end{aligned} \quad (8)$$

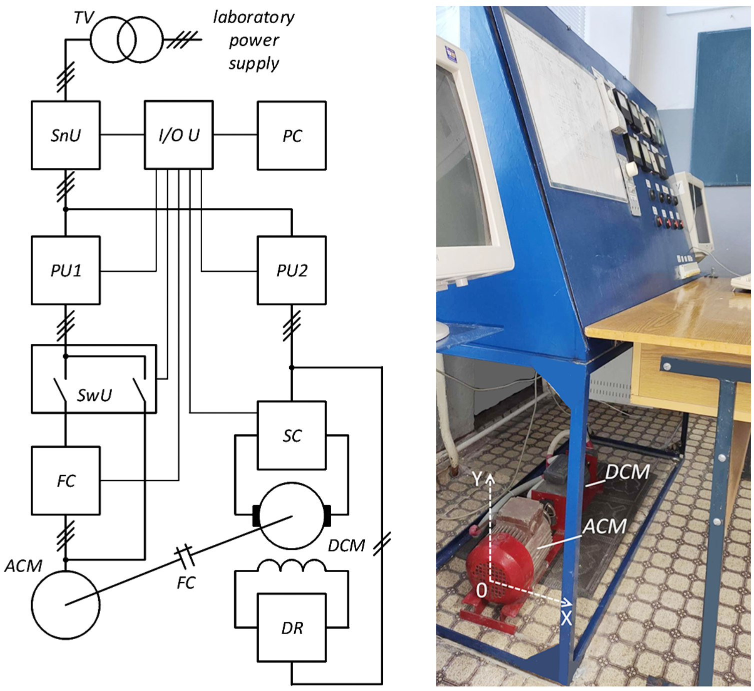
Thus, the equation of power balance for the induction motor with a short-circuited rotor is

$$p_s = p_{r.s} + p_{\sigma.s} + p_{ld} + p_j + p_m + p_{\sigma.r} + p_{r.r}. \quad (9)$$

In characterising the power consumption of the induction motor, it should be noted that the time dependence of this power, under steady-state static load and supply voltage, is constant and conditioned by the mechanical power (p_{ld}), power of mechanical losses (p_m) and the power of the ohmic resistance of the windings ($p_{r.s} + p_{r.r}$). The electromagnetic induction power of stator ($p_{\sigma.s}$) and rotor ($p_{\sigma.r}$), provided that the parameters of the machine and the mode parameters are symmetrical, are mutually compensated summing up the phases. The rotating mass of the flywheels is also equal to zero (p_j). The change in the nature of power can be caused by both mechanical vibrations and electromagnetic ones due to internal defects [8]. Internal defects include violations of the symmetry of the stator electromagnetic system, rotor electromagnetic system due to defects in steel or windings, unbalanced air clearance, defects in bearing assemblies [15]. Of course, the availability of changes in the mechanical load and voltage degradation affect the change in the nature of power consumption that is used to build electric drive control systems [9].

Practical part. Consider an electromechanical system, which is an electric machine with a load attached to its shaft. This system in the laboratory is implemented by connecting the induction motor and the DC motor (Fig. 1, *a*).

Electric machines are rigidly mounted on the frame, their mechanical connection is made by a coupling with elastic elements (Fig. 1, *b*). In the absence of specialized equipment for shaft alignment, the alignment is performed with an error resulting in mechanical vibrations. Frequency converter (*FC*) and thyristor converter (*SC*) (Fig. 1, *a*) were used to regulate



a *b*

Fig. 1. Computerised laboratory complex:
a – functional diagram; b – external view

the mode of induction motor (*ACM*) and DC motor (*DCM*), respectively. The DC machine excitation winding is powered by a diode bridge rectifier (DR). The induction machine can be powered without the use of a frequency converter provided by the operation of the switching unit (*SwU*). The power circuits are protected by protection units (*PU*1 and *PU*2). Using the current and voltage sensor (*SnU*) unit, the corresponding signals can be detected and transmitted to Input/Output (I/O) device USB6008. The specified device is connected to a computer using the USB2.0 interface. The stand receives electricity from a laboratory transformer (*TV*) whose primary winding is connected to the laboratory network. The protection devices used in the stand are not shown in the functional diagram (Fig. 1, *a*).

The study on the mode of electric energy consumption by the induction motor in case of shaft alignment error is carried out. To do this, in accordance with the differential equations above, taking into account the method of modelling the induction motor [7], we investigate the change in electric power of the induction motor. To do this, [7] we will introduce elements and connections that realize the formation of mechanical vibration moment in the known model [16]. For this purpose, the mechanical movements caused by the rotation of the motor shaft are taken into account in the availability of a specific unbalance (*e*) which is numerically equal to the distance of the centre of shaft mass from its axis of rotation. Provided the vertical stiffness, which is characterized by coefficients (c_x, c_y) and damping, which is characterized by coefficients (b_x, b_y). The accelerations arising during the rotation of the shaft, as shown in [10], are determined by the following equations in the coordinates *OX* and *OY*

$$x'' = \frac{m_v}{m_\Sigma} e\left(\phi'' \sin\phi + \phi'^2 \cos\phi\right) - \frac{1}{m_\Sigma}\left(b_x x' + c_x x\right);$$

$$y'' = \frac{m_v}{m_\Sigma} e\left(\phi'' \cos\phi - \phi'^2 \sin\phi\right) - \frac{1}{m_\Sigma}\left(b_y y' + c_y y\right),$$

where x; y; $x' = \frac{dx}{dt}$; $y' = \frac{dy}{dt}$; $x'' = \frac{d^2x}{dt}$; $y'' = \frac{d^2y}{dt}$ are displacement, velocity and acceleration along the axis *OX* and *OY* respectively; m_Σ is the total weight of induction motor, DC motor, couplings with elastic elements and metal frame; m_v is mass of the unbalanced part formed by the misalignment of the motor shafts; ϕ is a shaft rotation angle. As a result of the action of these accelerations, there is a corresponding moment on the motor shaft

$$M_{vib} = m_v e(x'' \sin\phi + y'' \cos\phi + g\cos\phi),$$

where g = 9.8 m/s^2 – free fall acceleration. This component must be taken into account in the equation of electromechanical power with the corresponding power of vibration $P_{vib} = M_{vib}\omega$

$$p_{em} = M_{ld}\omega + J\frac{d\omega}{dt}\omega + M_{am}\omega + M_{vib}\omega =$$
$$= p_{ld} + p_j + p_m + p_{vib}.$$

Based on the visual programming given in the complex the simulation of the operation mode of the induction motor is carried out when powered from the network with valid phase voltage value U = 220 В. Induction motor series АИР71А4У3 with parameters: P_n = 0.55 kW, n_0 = 1500 r.p.m., I_n = 1.17 A, k_i = 5.2, η = 0.71, J_d = 0.0011 kg · m^2. Parameters of the mechanical part are m_Σ = 31.1 kg, m_v = 3.5 kg, e = 0.003 m, c_x = = c_y = 326 · 10^4 N/m; b_x = b_y = 2615 Ns/m. According to formula (4), the phase powers and the total stator power of the induction motor are obtained. Fig. 2 shows the timing diagram of phase A power, and Fig. 3 shows the discrete power spectrum of phase A in steady state. The spectrum is determined at the fundamental frequency of 5 Hz. There is a dominance of the constant power component, the 100 Hz component and

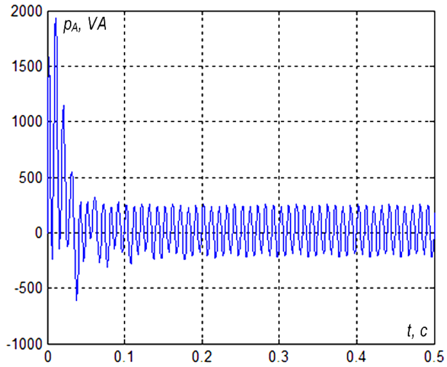


Fig. 2. Time diagram of A phase power

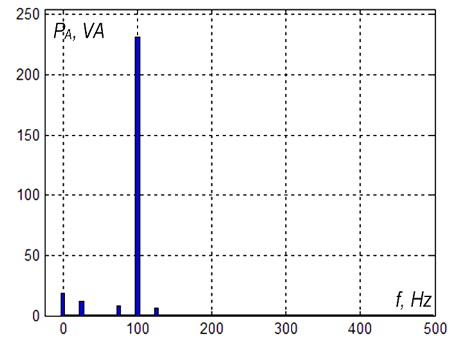


Fig. 3. Discrete power spectrum of A phase

the 25 Hz component due to mechanical vibration on the motor shaft [16, 17].

Fig. 4 shows the motor stator power timing diagram for all phases, Fig. 5 shows the spectrum of this power. Spectrum analysis shows that components with a frequency of 100 Hz are compensated, while components with a frequency of 25 Hz are amplified. Thus, the power components due to vibration have a frequency lower than the mains voltage frequency. Accordingly, the time interval for which the stator phase currents and voltages of an induction motor should be recorded as primary power data carriers should be greater than 0.02 s.

In order to verify the results of induction motor simulation, an experimental study similar to the previously described was performed on a laboratory stand (Fig. 1). Due to the fact that the vibrations caused by the alignment error occur at a frequency lower than the mains voltage frequency.

The expected value of the vibration frequency is known only from the results of mathematical modelling for the analysis of the power spectrum using the wavelet transform. This analysis tool allows us to realise a time domain timing of the signal to the frequency-time domain, thereby imple-

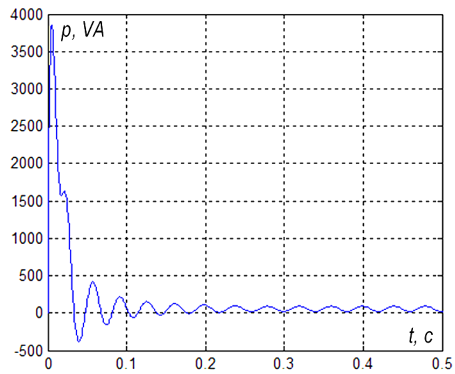


Fig. 4. Motor stator power time diagram for all phases

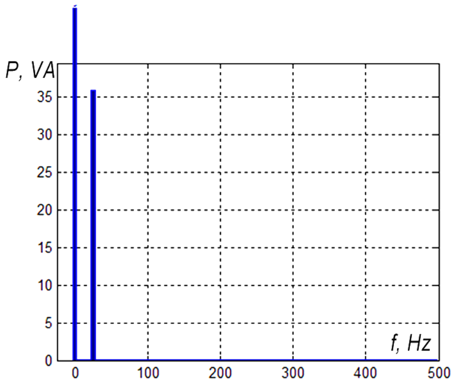


Fig. 5. Discrete power spectrum of the motor stator for all phases

menting the localization of the existing components in the signal of individual frequencies in time. The wavelet itself is a function, usually of a vibratory nature, which meets a number of conditions for use in the transformation process [18, 19]:

- locality condition – the wavelet must be continuous, have a compact medium and be localized in both time and frequency space;
- condition of zero moment – the area of the wavelet must be equal to zero;
- limitation – the function used as a wavelet must have a finite value of energy.

To localize the low-frequency power component, the *2nd* order Gaussian wavelet is used as the parent wavelet

$$\psi(t) = (1 - t^2) \cdot e^{-\frac{t^2}{2}}. \qquad (10)$$

In the case of continuous wavelet transform, for operation in the frequency-time domain, the function of the parent wavelet $\psi(t)$ takes the form

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \cdot \psi\left(\frac{t-b}{a}\right), \qquad (11)$$

where a is the scaling parameter that affects the number of samples included in the wavelet zone; b is the shift parameter that changes the position of the wavelet zone in the array proportional to the magnitude of the signal array.

Wavelet transform has a structure similar to the Fourier transform

$$W_{a,b} = \int_{-\infty}^{\infty} f(t) \cdot \overline{\psi_{a,b}(t)} dt, \qquad (12)$$

where $f(t)$ is signal function; $\overline{\psi_{a,b}(t)}$ is complex conjugate wavelet function.

In theory, the conversion is applied to an infinitely long continuous signal, but due to the limited capabilities of measuring equipment, such a signal cannot be obtained. As a result of work, the signal on a certain time interval with duration T is fixed. Therefore, during the measurement, a process of sampling on time with fixing of signal values $f(t_i)$ on the established discrete time interval $dt = t_i - t_{i-1}$ is carried out. As a result, an array with dimension $N = Tf_s$, is formed, where the sampling frequency f_s for USB6008 unit used in the laboratory stand is 10 kHz.

The transformation of A phase power and total power was performed directly over the array of recorded moments, so the graphs (Figs. 6, 7) of the abscissa correspond to the shift index in the array, while the ordinate value scales by the number of moments, to move to frequency-time values, the shift and scaling values must be converted to physical quantities and if the shift index is a time value

$$T_i = i \cdot dt; \quad i = 0, 1, 2, \ldots, N-1.$$

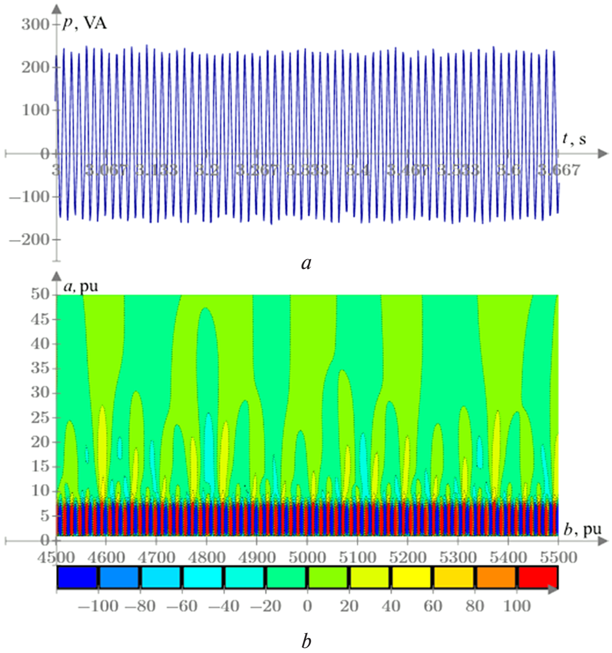


Fig. 6. Power graphs phase A:
a – time plane; b – frequency-time plane

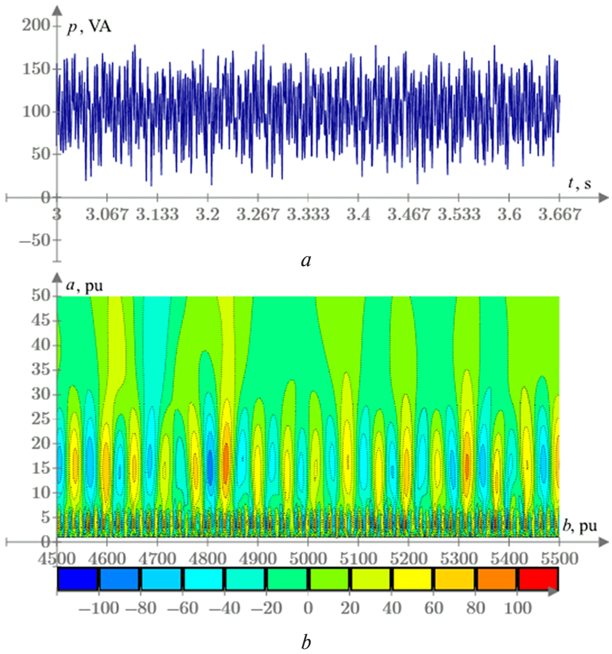


Fig. 7. Total power:
a – time plane; b – frequency-time plane

Conversion of scaling from quantitative to frequency for a periodic signal is performed taking into account the fact that the signal has a limited number of samples per period and is defined as

$$f = \frac{1}{2 \cdot \Delta_x \cdot 2 \cdot a \cdot dt},$$

where Δ_x is localization area.

From the graphs of A phase power (Fig. 6) and total power (Fig. 7), there are two ranges of the scaling parameter $a = 3.5 \pm 0.5$, which corresponds to frequencies close to 100 Hz and $a = 15 \pm 5$, which corresponds to frequencies close to 25 Hz. The graphs also show a significant deviation of the power of *A* phase in 25-hertz range compared to the total power with evident epicentres. Thus, the results obtained during the experimental study, with a certain quantitative error, confirm the possibility of assessing the vibration processes of the mechanical part according to the spectrum of electrical power of the stator, based on qualitative phenomena.

Conclusions.

1. Power distribution equation for three-phase induction machine with a short-circuited rotor has been analytically obtained in three-phase time coordinate system, which generally reflects electromagnetic and electromechanical processes and can be used for analysis of machine instantaneous power.

2. The research on the earlier known model of three-phase induction motor with symmetrical structure of phase windings, uniform clearance and linear magnetization characteristics with a symmetrical stator voltage system, provided the mechanical eccentricity of the loader shaft. By means of wavelet analysis, it was found that in the instantaneous power of the induction motor, under these assumptions, the components due to the frequency of the stator voltage and current are mutually compensated and reflected in the diagram.

3. By analysing the instantaneous electric power of the induction motor under the conditions set out in item 2 using wavelet transform, the power spectrum components caused by vibration moment on the motor shaft and having frequencies lower than the stator voltage and current frequencies are detected.

4. The instantaneous power of the stator was determined as a result of a physical experiment on a laboratory installation with the induction motor with a short-circuited rotor based on phase voltages and currents, whose wavelet transformation using virtual tool developed in LabVIEW package allowed confirming the conclusion obtained in item 3. The main frequency of stator instantaneous power fluctuations was 25 Hz in mathematical modelling, and in case of experiment in the range of 17–32 Hz.

5. The obtained results are a prerequisite for further development of the theory of instantaneous power as a factor that reflects the phenomena in energy conversion and transmission elements, especially subject to availability of information about instantaneous power at input and output of the system element.

References.

1. Shreyner, R., Yemelianov, A., & Medvedev, A. (2010). Energy saving resources in intermittent modes of operation of a frequency-controlled asynchronous electric drive. *Innovative technologies in the field of energy saving: materials of the regional scientific-practical conference of students*, 79-86.

2. Pugachov, A. (2015). Minimization of power losses in an electric drive with a scalar induction motor control system. *Cherepovets State University Bulletin*, (3), 32-37.

3. Minervini, M., Mognaschi, M.E., Di Barba, P., & Frosini, L. (2021). Convolutional neural networks for automated rolling bearing diagnostics in induction motors based on electromagnetic signals. *Applied Sciences (Switzerland), 11*(17), 7878. https://doi.org/10.3390/app11177878.

4. Koura, M.B., Boudinar, A.H., Aimer, A.F., & Khodja, M.-el-A. (2021). Induction Motor Bearing Faults Diagnosis Using Stator Current and Vibration Analysis. *Periodica Polytechnica Electrical Engineering and Computer Science*, *65*(4), 344-35. https://doi.org/10.3311/PPee.17284.

5. Petrushin, V.S., & Yenoktaev, R.N. (2014). Design Range Criteria for the Development of Variable Induction Motors. *Electrical Engineering & Electromechanics*, *5*, 33-36.

6. Aarniovuori, L., Niemelä, M., Pyrhönen, J., Cao, W., & Agamloh, E.B. (2018). Loss Components and Performance of Modern Induction Motors. *Proceedings of the XIII International Conference on Electrical Machines (ICEM).* https://doi.org/10.1109/ICELMACH.2018.8507189.

7. Chenchevoi, V., Kuznetsov, V., Kuznetsov, V., Chencheva, O., Zachepa, I., Chornyi, O., Kovzel, M., ..., & Levchenko, S. (2021). Development of mathematical models of energy conversion processes in an induction motor supplied from an autonomous induction generator with parametric non-symmetry. *Eastern-European Journal of Enterprise Technologies*, *4*(8(112)), 67-82. https://doi.org/10.15587/1729-4061.2021.239146.

8. Chumachova, A., & Kalinov, A. (2012). Compensation of the induction motor parametric asymmetry by means of the frequency-controlled electric drive. *Technical Electrodynamics*, (3), 87-88.

9. Zagirnyak, M., Kalinov, A., Melnikov, V., & Kochurov, I. (2015). Correction of the Operating Modes of an Induction Motor with Asymmetrical Stator Windings at Vector Control. *Proceedings of the International Conference on Electrical Drives and Power Electronics (EDPE)*, 259-265. https://doi.org/10.1109/EDPE.2015.7325303.

10. Nozhenko, V., Bialobrzheskyi, O., & Rodkin, D. (2021). Revealing the Impact of Electromechanical Complex Mechanical Vibrations on Electrical Instantaneous Power. *Proceedings of the 2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek)*, 486-489. https://doi.org/10.1109/KhPIWeek53812.2021.9570031.

11. Gavrelets, G., & Rodkin, D. (2016). Simulation of oscillatory processes in vibration isolation of the electromechanical equipment. *Electromechanical and energy saving systems*, *4*(36), 44-52.

12. Bratash, O., & Kalinov, A. (2010). Research of vibration power of induction motor. *Electromechanical and energy saving systems*, *4*(12), 28-33.

13. Daoud, M., & Iqbal, A. (2021). Vector control of dual 3-ϕ induction machine-based flywheel energy storage system using fuzzy logic controllers. *AI and Machine Learning Paradigms for Health Monitoring System, 86*, 339-349. https://doi.org/10.1007/978-981-33-4412-9_20.

14. Shreyner, R., Kalygin, A., & Krivoviaz, V. (2012). *AC drives based on PWM direct frequency converters*: *monograph*. Yekaterinburg: RGPPU.

15. Zagirnyak, M., Prus, V., & Somka, O. (2019). The methods for accounting the degree of electric machines aging in the assessment of their reliability. *Proceedings of the International Conference on Modern Electrical and Energy Systems (MEES),* 194-197. https://doi.org/10.1109/MEES.2019.8896468.

16. Blekhman, I.I. (2013). *Theory of vibration processes and devices. Vibration mechanics and vibration technology*. St. Petersburg: Ore & Metals. ISBN: 978-5-98191-074-6.

17. Rodkin, D., Nozhenko, V., Bohatyrov, K., & Chenchevoi, V. (2017). Electric drive operation modes of above resonance vibration machine. *Proceedings of the 2017 IEEE International conference on Modern Electrical and Energy Systems (MEES)*, 140-143. https://doi.org/10.1109/MEES.2017.8248872.

18. Arfaoui, S., Mabrouk, A.B., & Cattani, C. (2021). *Wavelet Analysis. Basic Concepts and Applications*. New York: Chapman and Hall/CRC. https://doi.org/10.1201/9781003096924.

19. Todorov, O., Bialobrzheskyi, O., Reva, I., & Bezzub, M. (2021). Abruptly changing load timediagram analysis of transformer substation using wavelet transform. *Proceedings of the 2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek)*, 396-400. https://doi.org/10.1109/KhPIWeek53812.2021.9570080.

Вплив неспіввісності з’єднання валів електричних машин на характер електричної потужності асинхронного двигуна

О. В. Бялобржеський[*], *В. Ю. Ноженко*, *О. В. Тодоров*

Кременчуцький національний університет імені Михайла Остроградського, м. Кременчук, Україна

[*] Автор-кореспондент e-mail: seemal@kdu.edu.ua

Мета. Виявлення складових потужності вібрації, викликаної неспіввісністю з’єднання валів електричних машин у миттєвій потужності асинхронного двигуна.

Методика. Аналітично визначені складові потужності асинхронного двигуна з урахуванням потужності, що спричинена коливаннями моменту на валу. На підставі цього з використанням методів математичного моделювання в середовищі візуального програмування складена відома модель трифазного асинхронного дви-

гуна з короткозамкненим ротором. Додатково введено елементи та зв'язки, що реалізують формування моменту, зумовленого неврівноваженістю обертових мас. Із використанням Фурье-перетворення електричної потужності асинхронного двигуна визначено її дискретний спектр. Проведене експериментальне дослідження електричної потужності асинхронного двигуна з короткозамкненим ротором, в аналогічних модельним умовах, на лабораторному обладнані. Використанням віртуального приладу, синтезованого в пакеті LabVIEW, виконаний вейвлет-аналіз електричної потужності статора двигуна лабораторного електротехнічного комплексу.

Результати. Отримані диференційні рівняння асинхронного двигуна з короткозамкненим ротором у системі координат *abc*, що відбивають розподіл миттєвої потужності в машині з урахуванням вібраційного моменту. У результаті моделювання за зазначеними рівняннями асинхронної машини, в умовах повної симетрії параметрів схеми й режиму з ексцентриситетом обертових мас, виявлені низькочастотні коливання електричної потужності статора з частотою 25 Гц. Аналогічні результати отримані в результаті вейвлет-аналізу електричної потужності асинхронного двигуна лабораторного електротехнічного комплексу.

Наукова новизна. Обґрунтована раціональність використання миттєвої електричної потужності статора асинхронного двигуна для виявлення вібрації, викликаної неспіввісністю з'єднання його валу з валом іншої машини, що дозволяє виявляти вібрації без складних методів вимірювання вібраційного зміщення та його похідних.

Практична значимість. Виявлення вібрації шляхом вимірювання електричних параметрів статорного кола асинхронного двигуна й визначення коливань його миттєвої потужності без використання спеціалізованого обладнання суттєво спрощує процедуру вібродіагностики на її перших етапах.

Ключові слова: *асинхронний двигун, неспіввісність валів, електрична потужність, механічні вібрації*

The manuscript was submitted 21.11.21.