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INSTANTANEOUS POWER OF A DOUBLY FED INDUCTION GENERATOR WITH THE UNBALANCED STATOR WINDINGS

Doubly fed induction generators have become widespread in generation systems in which maintaining the rotor speed cannot be fully performed by adjusting the drive mechanism.

Purpose. Establishing instantaneous power of a doubly fed induction generator in an autonomous system with a nonlinear load under the condition of changing the machine stator windings' electrical parameters.

Methodology. As a result, of the known studies analysis, the presence of technical solutions that provide control of the generator rotor current even under conditions of nonlinear or asymmetric load was established. Using the known provisions of the electrical engineering theory and the electric machines theory using the instantaneous power balance principles, the balance equations for a three-phase double feed induction generator were determined.

Findings. A model was synthesized for studying the processes of power components distribution of the equivalent circuit elements of a doubly fed induction generator in a visual programming package. The specified model allows simulating the modes of the machine with linear and nonlinear generator loading and asymmetry of the stator windings' electrical parameters. Under the conditions of conducting experiments, a significant change was noted in the electromagnetic power spectrum of a phase rotor windings under conditions of asymmetry, which is characterized by the presence of power harmonics with a 50 Hz frequency, which corresponds to the interaction of the rotor phases' direct current with the alternating voltage components of the rotor circuit's corresponding element.

Originality. During the study under the condition of asymmetry of the stator windings' electrical parameters, it was established that the electromagnetic power harmonics of the stator windings' phases have values that exceed the nominal power of the machine by a magnitude order and, being formed into the total power of the three phases, mutually compensate each other. Moreover, the level of these harmonics is sensitive to the nature of the asymmetry at a frequency of 100 Hz. In the power of three phases of elements of a doubly fed induction generator under the experiment conditions, constant components dominate, the level of which for the stator circuit is sensitive to the nature of the electrical parameters' asymmetry of the stator windings and leads to changes by more than 2.3 % for the stator windings electromagnetic power and 2.2 % for the mechanical power.

Practical value. The obtained results can be used in the future to improve the systems for the mode parameters control of a doubly fed induction generator to energy performance increase of the complex.

Keywords: *electric power, instantaneous power, power harmonics, doubly fed induction generator*

Introduction. The general distribution of alternative energy sources together with the solution of the problems of forming additional electric energy distributed sources poses a number of additional tasks arising during operation [1]. This is continuous monitoring of the electric power balance, both active and reactive in nature, which is associated with the stability of voltage by frequency and effective value [2]. The designated tasks are closely related to the electric energy quality problem in conditions of asymmetry and non-sinusoidality of current and/or voltage. A certain feature of the distributed sources functioning is their operating mode – in parallel with the main network with the ability to generate excess energy, or autonomously for a load of limited power. In the latter case, the issue of stabilizing the frequency of alternating current becomes extremely important [3].

In the case of using wind power plants, one of the critical tasks of rational electric energy generation is to maintain the frequency of the electromagnetic field of the stator and maintain the required electromagnetic torque in conditions of a changing flow of the primary energy carrier – wind [4]. One of the options for solving this problem is the use of electrical complexes based on asynchronous generators with a phase rotor. In this case, ensuring the quality of electricity remains associated with the modes of the electric machine, which in turn depend on the operation of the control systems, the state of the electric machine and the nature of the load [5].

Literature review. Wind power is a rapidly growing source of renewable energy use worldwide. The doubly fed induction generator used in wind turbines provides active and reactive power flow, dynamic and static energy support [6]. The authors of the study propose to apply the control system to regulate the deviations of the grid voltage amplitude and frequency in accordance with the rules established for the intelligent grid controller of the utility company. The considered microgrid voltage amplitude under load fluctuations is improved by regulating the doubly fed induction generator reactive power. Additional attention is also paid to the calculating methods of the electric grid stability in the environment of consumers with a certain proportion of induction machines, paying special attention to the sources with induction generators for the stability of voltage and frequency maintenance [7]. By dividing the sources with induction machines into four types, equivalent circuits of each type are derived in the normal state and instability, respectively. Based on the electric network Thevenin equivalent impedance and the connected device equivalent impedance, a definition and calculation method for the reliability of voltage maintenance are given. Based on the frequency change initial rate and the established frequency deviations of power system, any node at the maximum expected increase in active power, the corresponding inertia rise coefficient and the established frequency decrease coefficient are determined, respectively, to describe the contribution of asynchronous machine sources to the power system frequency stability maintenance. Doubly fed induction generators [8] are also used in the frequency control system using voltage dip compensation circuits with a fixed energy performance indicator. The authors propose an improved generator frequency decrease control circuit that can both compensate for the frequency increase and limit the maximum frequency change rate during regulation, even with a change in wind speed.

The article presents a separate direct control of the power of a doubly fed induction generator connected to an unbalanced power system implemented in a stationary orthogonal system associated with the stator voltage [9]. The control allows maintaining a constant electromagnetic torque, regardless of the stator connection to an asymmetric power system. The control principle does not require decomposition of the signal into positive and negative sequences, which reduces its complexity and measurement requirements. In [10], a flexible compensation strategy is proposed for parallel-connected doubly fed induction generators connected to an asymmetric network of limited power. The strategy proposed by the authors has two main advantages: the voltage unbalance coefficient at the point of common connection can be continuously monitored, as a result of which a flexible compromise can be achieved between the generator's asymmetrical output current and the symmetrical voltage. In this case, the negative current sequence required for compensation can be divided between the parallel-operating generator and its converter on the network side. In this case, the converter is assigned additional functions, in addition to stabilizing the voltage in the intermediate DC voltage circle. Similar solutions are proposed for matching the direct power control circuit of the rotor side converter [11] and the grid side converter of an induction generator with a phase rotor under asymmetrical grid voltage conditions. To eliminate the connection between the phase automatic frequency adjustment circuit and the local asymmetrical grid, a virtual phase angle is used instead of the actual one. In the case of asymmetrical grid, the rotor side converter is controlled taking into account the task of reducing electromagnetic torque pulsations. For this purpose, a resonant controller with frequency isolation between the parameters of the positive and negative sequence of the same frequency is used. These sequences are used in the matched direct power control circuit to avoid complex calculations of the power compensation components.

Taking into account saturation in certain modes of a doubly fed induction generator, according to researchers [12], is important for the correct modeling of doubly fed induction generators when conducting harmonic analysis in power systems. This is especially important for low-order current harmonics, which are commonly encountered in modern power systems. Analytically, the authors determine equivalent harmonic resistances using impedance matrices. By integrating this model with the model of a doubly fed induction generator, a general harmonic model is demonstrated that can be calculated using known methods of circuit analysis.

The electrical power quality in low-voltage networks of limited capacity is of interest to researchers with an emphasis on the higher harmonic currents generation [13]. The authors investigated the harmonic currents characteristics created by combinations of devices commonly used in non-linear loads of commercial and residential properties. As a result of experimental tests, it was shown that harmonic currents created by several non-linear loads sometimes tend to reduce the current total harmonic distortion factor. It was found that the changes in the harmonic content caused by the effects of addition and/or curvature of the total current consumed from the network by the non-linear load should be a key factor in the study of pollution by higher frequencies harmonic currents. A new control topology for reducing the stator current harmonics of a doubly fed induction generator under the network voltage harmonic content condition, with an emphasis on reducing the electromagnetic torque's alternating components is proposed in [14]. The proposed controller provides harmonic vector control capable of reducing any desired current harmonic. The authors note that the fifth, seventh, eleventh and thirteenth components of the grid voltage cause harmonic components of the same order in the generator, but with a higher harmonic relative amplitude due to the high series impedance stator. The proposed control does not require harmonic filters to assess the harmonics content present in the stator current caused by the grid. Thus, improving the quality indicators of electrical energy in electrical complexes with a doubly fed induction generator is relevant, while the effect of changing machine electrical parameters on energy processes in the higher harmonics presence of current and voltage is important.

The work purpose. Research on doubly fed induction generator instantaneous power in autonomous system with nonlinear load under conditions of machine stator windings' electrical parameters change.

Main material and study results. Most researchers focus their efforts on improving the control systems of power converters of a generating plant based on a doubly fed induction generator [8, 11]. The control systems of converters, both on the rotor side and on the grid side, are built according to the principles of vector control [15], using the Park and Clarke coordinate transformation, based on the assumptions of a symmetrical system of electrical parameters of the machine.

One of the main problems, arising in constructing a model of an asynchronous machine, is the choice of a coordinate system in which electromagnetic processes are considered. However, the choice of one or another coordinate system should not affect the real physical processes occurring in an electric machine, but should only be a method of mathematical interpretation. Depending on the problem being solved, mathematical models are used in the natural coordinates of the machine, in fixed or rotating with a certain frequency orthogonal coordinates, in polar coordinates. The presence of periodic coefficients in front of the variable equations of a three-phase machine forced us to look for ways to simplify the system of differential equations in order to obtain equations with constant coefficients. In this case, it is assumed that the system of equations written relative to new variables describes an idealized asynchronous machine for which voltages, currents and flux linkages are related to voltages, currents and flux linkages of a real asynchronous machine. Since the differential equations of an idealized asynchronous machine contain periodic coefficients, it can be assumed that the rotor of such a machine is fixed relative to the stator. Indeed, periodic coefficients appear as a result of changing the mutual arrangement of the stator and rotor windings, which complicates the calculation process. Then it is assumed that the idealized input two-phase machine is equivalent to a three-phase real machine in magnetizing forces created by both stator winding currents and rotor currents. The stator and rotor windings are stationary relative to each other and are located along the axes of the coordinate system, and both axes in this case can rotate in space at an arbitrary speed.

However, in real operating conditions of electric machines, especially during long-term operation, processes occur that lead to deviation of the machine electrical parameters from the initial ones [16, 17]. It is noted that the main types of damage to key components that affect the reliability of the equipment are various damage to bearings, stator and rotor windings and rubbing contact elements. The condition of these units during operation is affected by some factors that indicate the occurrence and development of defects. For example, for brush and bearing units, this is their temperature and vibration, as well as the rotor speed; for stator or rotor windings, this is temperature and vibration caused by asymmetry. For slip rings, vibration is important, which leads to the nature of the fit, and the current density under the brush. Despite the variety of damages, their impact on reliability is mostly due to the deterioration of thermal and vibration processes. Also, given the randomness and variety of damage, for a broader analysis of vibration, the need for a separate assessment of mechanical and electromagnetic factors is confirmed. The specified damages and the deviations of the machine's electrical parameters caused by them, together with the influence of the load from the stator, can lead to an increase in the previously indicated impact. Probably, such an effect can have both quantitative and qualitative changes. In this case, it is rational to use a generalizing parameter for analysis – instantaneous power [18], the balance of which in an arbitrary closed system is beyond doubt.

The use of voltage and current representation as periodic polyharmonic functions when considering periodic non-sinusoidal currents and voltages is a common technique. This allows formulating the energy balance equation for both the energy source and all elements of the circuit or system. Decomposition of instantaneous power into harmonic frequency components allows forming a set of energy balance equations. To calculate the power components caused by current and voltage harmonics, in addition to active and reactive power, the power characterizing distortion is used. This option for determining the components of electrical power implies its division into components depending on the numbers and combination of current and voltage harmonics. Additionally, when characterizing instantaneous power, in addition to the active and reactive components, its root-mean-square norm is used.

Let us consider the general equations of instantaneous power of a doubly fed induction generator due to the nature of its transformation in the machine (Fig. 1). To do this, we will separate the instantaneous power balance of the stator, rotor and mechanical part. The balance of mechanical part power looks like this

$$p_{m.} = p_{m.d.} - p_{in.} - p_{m.l.}, \quad (1)$$

where $p_{m.}$ is the generator mechanical power; $p_{m.d.}$ is the drive mechanism power; $p_{in.}$ is the power is due to the rotating masses inertia; $p_{m.l}$ is the generator mechanical loss power.

The rotor circuit power balance

$$p_{em.r} = p_r - p_{Rr} - p_{L\sigma r} - p_{\mu.r}, \quad (2)$$

where $p_{em.r}$ is the electromagnetic rotor power; p_r is the rotor's total electric power (from external source); p_{Rr} is the rotor windings' active resistance power; $p_{L\sigma r}$ is the rotor windings' electromagnetic power dissipation; $p_{\mu.r}$ is the power loss in rotor steel.

The stator circuit power balance is

$$p_s = p_m + p_{em.r} - p_{Rs} - p_{L\sigma s} - p_{\mu.s}, \quad (3)$$

where $p_{s.}$ is the power generated by the machine; p_{Rs} is the stator windings' active resistance power; $p_{L\sigma s}$ is the stator windings' electromagnetic power dissipation; $p_{\mu.s}$ is the power loss in stator steel.

In view of the fairly generalized form of the power balance (Fig. 2, *a*), we will carry out further reasoning based on the diagram shown in Fig. 2, *b*. The following notations in the figure are used: u_A, u_B, u_C are stator phase

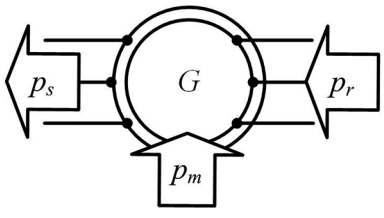

Fig. 1. Generalized diagram of a double fed induction generator

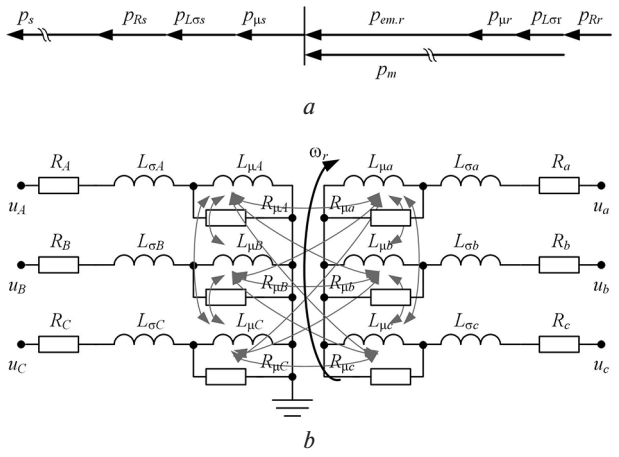

Fig. 2. Doubly fed induction generator with a phase rotor: a – power balance diagram; b – equivalent circuit

voltages; i_A, i_B, i_C are stator phase currents; u_a, u_b, u_c are rotor phase voltages; i_a, i_b, i_c are rotor phase currents; R_A, R_B, R_C are stator phase windings' active resistances; R_a, R_b, R_c are rotor phase windings' active resistances; $L_{\sigma A}$, $L_{\sigma B}$, $L_{\sigma C}$ are stator phase windings' leakage inductance; $L_{\sigma a}$, $L_{\sigma b}$, $L_{\sigma c}$ are rotor phase windings' leakage inductance; $L_{\mu A}$, $L_{\mu B}$, $L_{\mu C}$ are stator phase magnetizing inductance; $L_{\mu a}$, $L_{\mu b}$, $L_{\mu c}$ are rotor phase magnetizing inductance; $R_{\mu A}$, $R_{\mu B}$, $R_{\mu C}$ are equivalent resistance of losses in steel along stator phases; $R_{\mu a}$, $R_{\mu b}$, $R_{\mu c}$ are equivalent resistance of losses in steel along rotor phases.

In this case, we will assume that the electromagnetic system has no saturation, and the magnetization characteristic is linear [19]. In addition, due to the low frequency of the rotor flux, we neglect the power loss in the rotor steel. Mechanical losses, or more precisely, the moment of resistance causing the specified losses, have a linear dependence on the rotation frequency [20]. We will assume that the generator stator windings' zero terminal for powering consumers will be grounded in further discussions.

Then the drive mechanism mechanical power is

$$p_{m.d.} = M_{m.d.}\omega_r, \tag{4}$$

where $M_{m.d.}$ is mechanical torque; ω_r is rotor rotation angular frequency, excluding the power due to the rotating masses inertia and the power of the generator's mechanical losses

$$p_{in.} + p_{m.l.} = J\frac{d\omega_r}{dt}\omega_r + k_{fr}\omega_r^2, \tag{5}$$

where J is rotating masses' moment of inertia; k_{fr} is mechanical loss coefficient, transmitted to the generator stator circuits.

Power is supplied to the rotor electrical circuits of generator

$$p_r = u_a i_a + u_b i_b + u_c i_c. \tag{6}$$

Part of the specified power is spent a power of the rotor windings active resistance

$$p_{Rr} = (R_a i_a^2 + R_b i_b^2 + R_c i_c^2). \tag{7}$$

Part of the power of the rotor's electrical circuits covers the power of rotor windings' leakage inductance

$$p_{L\sigma r} = -L_{\sigma a}\frac{di_a}{dt}i_a - L_{\sigma b}\frac{di_b}{dt}i_b - L_{\sigma c}\frac{di_c}{dt}i_c. \tag{8}$$

The resulting power is transferred to the machine stator's electromagnetic system via the rotor's electromagnetic power $p_{em.r}$. According to the stator power balance equation (3), taking into account the mechanical power p_m, part of the power goes to cover the power loss in the stator steel

$$p_{\mu s} = (R_{\mu A} i_{\mu A}^2 + R_{\mu B} i_{\mu B}^2 + R_{\mu C} i_{\mu C}^2), \tag{9}$$

coverage of stator windings' electromagnetic leakage power is

$$p_{L\sigma s} = -L_{\sigma A}\frac{di_A}{dt}i_A - L_{\sigma B}\frac{di_B}{dt}i_B - L_{\sigma C}\frac{di_C}{dt}i_C, \tag{10}$$

coverage of the stator windings active resistance power is

$$p_{Rs} = (R_A i_A^2 + R_B i_B^2 + R_C i_C^2). \tag{11}$$

The resulting stator electrical power p_s generated by the machine is formed in accordance with the balance equation (3).

Considering the complexity of further analytical expressions for a three-phase doubly fed induction generator, we will generally use modeling tools. For this purpose, we will use the model given in [21] (Fig. 3). In accordance with the concept outlined in [21], an asynchronous generator with a phase rotor is represented by three blocks (Stator, Rotor, Mechanical), which reproduce the corresponding submodels of the machine stator, rotor and mechanical part. Additionally, converters of the stator voltage signal type (CVS) are used for each phase to connect to the load power circuits. This is due to the features of the visual programming package modeling. At the same time, additional blocks (CM) are introduced to measure the load/stator current. In general, this represents the input parameters organized by the rotor voltage ports (Vabc, r) and rotor speed (Rotor speed). Power ports (*A*, *B*, *C*) are used to connect the power elements of the load. To control the machine mode parameters, the output data ports are organized: stator current (Iabc, s); rotor current (Iabc, r); rotor speed (ω_r); mechanical and electromagnetic torque (T_e, T_m). The specified model is organized using a specialized "mask" block – this is a customizable user interface for the block that hides the subsystem contents, making it visible to the user as an atomic block with its own icon and dialog box for parameters. The specified technique is performed in Fig. 4, in which the model of Fig. 3 is represented by a module (Three-phase DFIG).

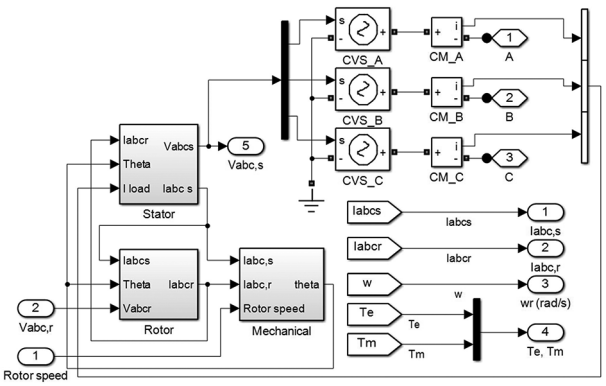

Fig. 3. The double fed induction generator model and stator current matching

To perform the operating modes study of the doubly fed induction generator, nonlinear and linear load units (Harmonic load, Linear load) are included in the power section, the connection period of which is controlled by the corresponding switches (Breaker). Calculation of the machine power components (1–11) is performed in the subsystem (Measurement Unit). For operational machine mode monitoring, frequency measurement units (PLL 3ph), positive sequence active and reactive power (Power Positive Sequence), and units for measuring the stator current and voltage symmetrical components (Sequence Analyzer) are introduced. The initial data from the specified measuring units are displayed on the displays.

Blocks (Sequence Analyzer) are used to monitor the positive, negative and zero sequences of voltage and current components. This block implements the definition of the current or voltage module and phase shift of the positive, negative and zero sequences, which are selected optionally. The order of calculating the specified parameters is implemented as follows. The parameter is calculated in complex form based on the time function for each phase

$$\dot{F} = a + jb = \frac{2}{T}\int_0^T f(t)e^{-j\omega t}dt = \\ = \mathrm{Re}\left(\frac{2}{T}\int_0^T f(t)e^{-j\omega t}dt\right) + j\,\mathrm{Im}\left(\frac{2}{T}\int_0^T f(t)e^{-j\omega t}dt\right), \quad (12)$$

where $f(t)$ is a parameter in time function; ω is angular frequency; $T = 2\pi/\omega$ is a period of function. Determine the amplitude and initial phase

$$F = \sqrt{a^2 + b^2}; \quad \psi_F = \mathrm{arctg}\frac{b}{a}. \quad (13)$$

Using the phase shift operator in complex form, the components of the positive, negative and zero sequences are determined

$$\begin{cases} \dot{F}_1 = 1/3\left(F_A e^{j\psi_{F.A}} + F_B e^{j\psi_{F.B}} e^{j2\pi/3} + F_C e^{j\psi_{F.C}} e^{j4\pi/3}\right) \\ \dot{F}_2 = 1/3\left(F_A e^{j\psi_{F.A}} + F_B e^{j\psi_{F.B}} e^{j4\pi/3} + F_C e^{j\psi_{F.C}} e^{j2\pi/3}\right). \\ \dot{F}_0 = 1/3\left(F_A e^{j\psi_{F.A}} + F_B e^{j\psi_{F.B}} + F_C e^{j\psi_{F.C}}\right) \end{cases} \quad (14)$$

The experiments were performed for a machine with the following parameters: power 75 kW; stator voltage 220 V; frequency 50 Hz; the number of pole pairs 4; stator current 140 A; magnetizing inductance 0.1 H; stator leakage inductance 2 mH; rotor leakage inductance 0.7 mH; active resistance of the stator and rotor winding 0.435, 0.816 Ohm; rotor moment of inertia 0.089 kg m^2. The following generator mode parameters are set: rotor voltage 36 V, rotor rotation angular frequency 79 rad/s. The rotation frequency is maintained constant. A load with a power of 20 kW is connected to the machine stator. At the moment of time 0.1 s, a non-linear load is connected in the form of two current harmonics 5^{th} and 7^{th} with an effective current value of 6.6 A. At 0.15 s, the active linear load is additionally increased by 10 kW.

Let us consider the influence of the winding parameter asymmetry on the machine mode parameters. In this case, we will assume that the winding parameter asymmetry is caused by a turn-to-turn short circuit [22]. In this case, a certain distribution of the machine electrical and electromagnetic parameters occurs. First, let us consider the electrical equations of the damaged phase, assuming that it arose in the stator. The total number of stator winding turns (w_{PH}). As a result of such a short circuit, a ratio of the remaining turns in the main circuit

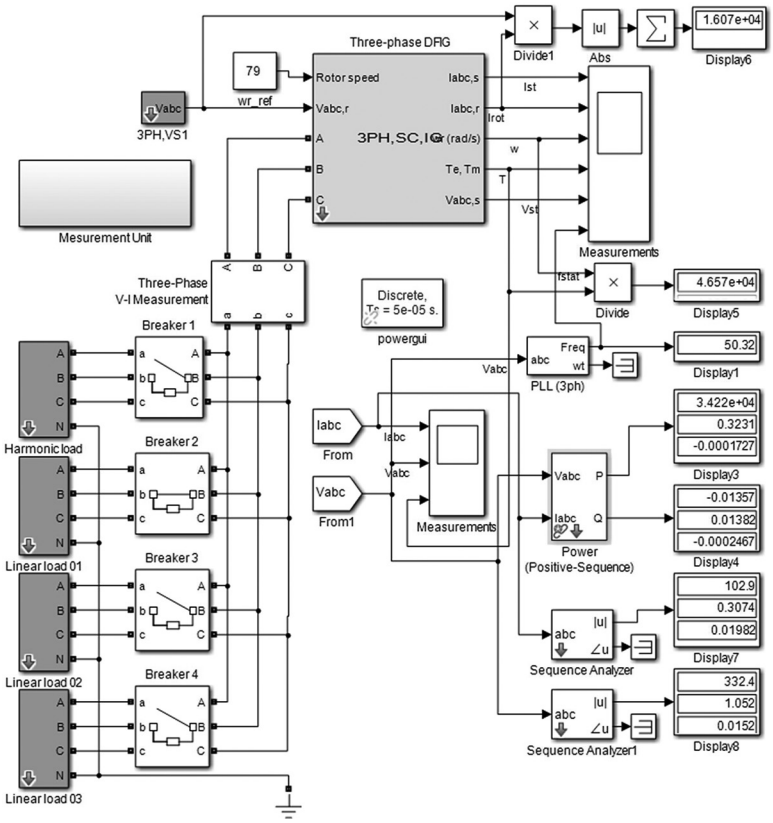

Fig. 4. The electric power system model of a doubly fed induction generator and different types of load

(w'_{PH}) and in the external circuit of short-circuited turns (w''_{PH}) arises. Taking this into account, it is advisable to use the parameters of the damaged and undamaged windings, for example, for winding active resistance

$$R'' = R\frac{w''_{PH}}{w_{PH}};$$
$$R' = R\frac{w'_{PH}}{w_{PH}} = R\frac{w_{PH} - w''_{PH}}{w_{PH}} = R\left(1 - \frac{w''_{PH}}{w_{PH}}\right), \quad (15)$$

where R is total winding resistance; R' is undamaged part resistance of the winding turns; R'' is damaged part resistance of the winding turns. Assuming the probable presence of turn-to-turn short circuits in the stator winding, the system of differential equations according to Kirchhoff's second law [22] for one of the phases will look like

$$-(w_s - w''_s)\frac{d\Phi_s}{dt} = u_s + L_{\sigma s}\frac{w_s - w''_s}{w_s}\frac{di_s}{dt} + R_s\frac{w_s - w''_s}{w_s}i_s; \quad (16)$$

$$0 = w''_s\frac{d\Phi_s}{dt} + L_{\sigma s}\frac{w''_s}{w_s}\frac{di''_s}{dt} + R_s\frac{w''_s}{w_s}i''_s, \quad (17)$$

where u_s is stator phase voltage; i_s is undamaged part windings stator phase current; i''_s is damaged part windings stator phase current; $L_{\sigma s}$ is stator winding phase leakage inductance; Φ is magnetic flux; w''_s is the number of stator winding phase damaged turns; R_s is stator winding phase resistance.

Three experiments were conducted: the stator windings are symmetrical (Exp1); the stator phase A winding has a 2 % decrease in active resistance and inductance (Exp2); in addition, the stator phase winding B has a 2 % decrease in active resistance and inductance (Exp3). Accordingly, Fig. 5 shows the time diagrams of the stator current, stator voltage and drive mechanism torque. The effect of the asymmetry nature is observed in all three diagrams for each of the experiments. Changes are especially pronounced in the mechanical torque diagram. Some changes can also be observed in the voltage and current diagrams. Given the complexity of visual analysis of the time diagrams, we will use well-known indicators: the total harmonic distortion factor and the unbalance factor for voltage and current [23]. Summary data are presented in Table 1.

Analysis of the data in Table 1 shows that the nature of the unbalance affects not only the asymmetry factors for the zero (K_0) and negative (K_2) sequences, but also the total harmonic distortion coefficient (THD), which is set constant for all experiments on the load side. And if the total harmonic distortion factor increases for voltage, for example in phase A, then this parameter decreases for current.

It should be noted, that the rotor is powered by direct current to form a constant rotor flux. During the experiments, at the time of 0.15 s, the rotor current (voltage) increases to maintain the level of the stator voltage effective value, generated by the machine.

Considering that in the modes of the model under study the unbalance indicators change, which, as shown above, affect the non-sinusoidality indicators, let us consider how this affects the power of the machine active elements. The results of calculating the power amplitudes using the procedure of FFT analysis visual programming package for instantaneous powers (1–11) for each phase

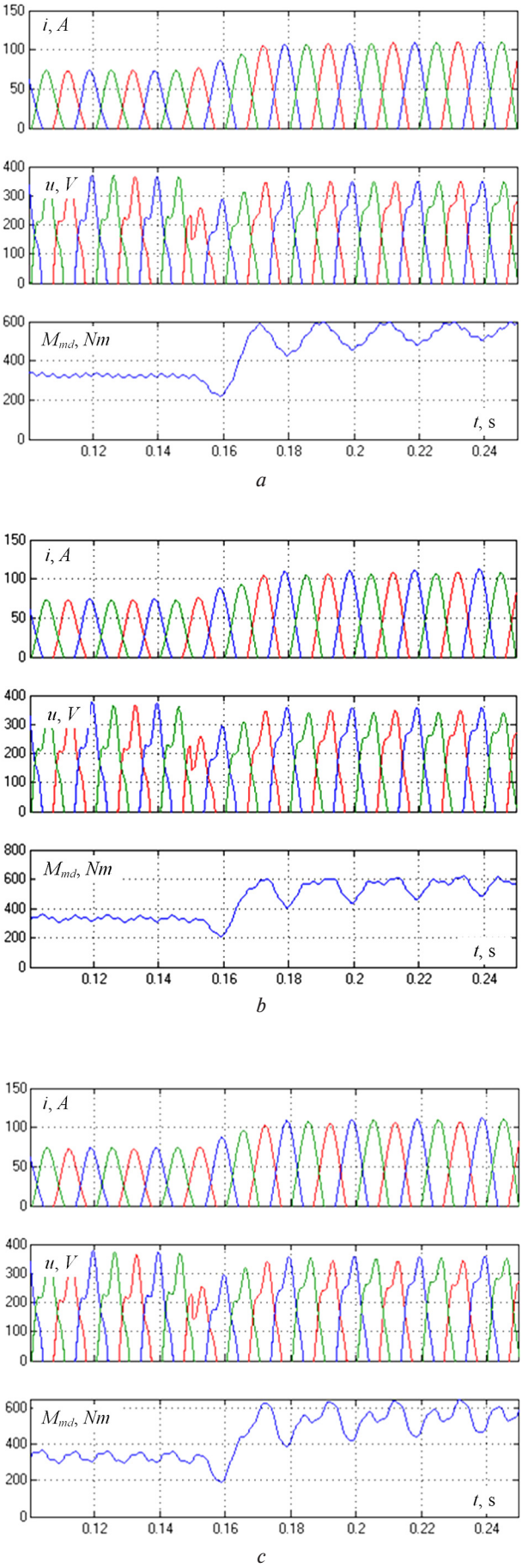

Fig. 5. The stator current, stator voltage and mechanical torque time diagrams:
a – Exp1; b – Exp2; c – Exp3

Table 1

The stator phase current and voltage distortions

	Exp1	Exp2	Exp3
THD_{ia},%	6.87	6.77	6.64
THD_{ib},%	6.93	6.58	6.39
THD_{ic},%	7.60	7.51	7.00
THD_{ua},%	10.55	10.85	11.19
THD_{ub},%	10.07	10.02	10.25
THDuc,%	10.27	10.61	10.45
K_{0i},%	0.02	2.87	2.81
K_{2i},%	0.30	0.26	1.57
K_{0u},%	0.00	2.85	2.83
K_{2u},%	0.32	0.24	0.24

relative to the network voltage frequency of 50 Hz are summarized in Fig. 6 for the stator circuit and the rotor circuit.

A comparative analysis of the obtained results shows the following. The total power of the stator windings (Fig. 6) includes power harmonics that change with a frequency of 0, 100, 200, 300 Hz, which corresponds to the instantaneous power existing theory [24]. Harmonics of higher frequencies are absent despite the fact that there is a current of the fifth harmonic in the load, but this current is not transmitted to the stator of the machine, but closes on other elements of the load. Depending on the unbalance nature, an increase in the amplitudes of the power in the corresponding phases occurs. In the case of the stator winding phases power, this is clearly visible at frequencies of 0 and 100 Hz (which corresponds to the fundamental voltage frequency of 50 Hz). At frequencies of 200 and 300 Hz, significant changes are not noted.

Particular attention should be paid to the pulsations of the stator flux linkage power of the windings in phases [25], the level of which is several times higher than the rated machine power. In this case, the power harmonic at a frequency of 100 Hz stands out clearly. Depending on the nature of the experiment, the level of the specified power in the machine phases changes. A similar picture is observed in the distribution of harmonics of the electromagnetic scattering power of the stator windings, with the exception of the constant component.

The power of the stator winding phases' active resistance changes depending on the nature of the machine stator winding parameters unbalance. Due to the fact that the specified power is exclusively active, it is necessary to pay attention to the fact that the power at a frequency of 100 Hz differs from the constant component of 0 Hz power in level. Probably, this is caused by the influence of the power components formed by harmonics of current and voltage of different frequencies, which in well-known studies were called "non-canonical" and "pseudo-canonical" [24]. Using the example of the power of the stator windings active resistance, this means that the change in the amplitude of the power with a frequency of 0 and 100 Hz is caused by the action of voltages and currents with frequencies of $0 = 50 - 50 = 150 - 150$ and, accordingly, $100 = 50 + 50 = 150 - 50 = |50 - 150| = 250 - 150 = |150 - 250|$.

Particular attention should be paid to the harmonics level of the machine stator windings' electromagnetic power, which are an order of magnitude higher than the level of power generated by the machine. The rotor circuit elements power differs in nature from the power of the stator circuit. First of all, due to the fact that a direct current of the rotor circuit is formed from an external voltage source, distributed among the phases in such a way as to form a rotor field that will ensure adhesion of the rotor to the stator at zero slip. That is, the currents in the rotor phases have a significant constant component and are distributed among the phases in such a way as to create the maximum magnetic flux. Accordingly, the power of the rotor winding phases in all cases has an exclusively constant component with a corresponding distribution among the phases. The power spectrum of the electromagnetic phases of the rotor windings changes significantly under unbalance conditions. The existing power harmonics with a frequency of 50 Hz correspond to the action of direct current with variable components of the corresponding element voltage. The introduction of unbalance in two phases of the stator windings leads to an increase in the level of harmonics of the rotor windings electromagnetic power at frequencies of 100 and 200 Hz. The power loss in the rotor windings phases is characterized by the dominance of an exclusively constant component, the level of which does not depend on the unbalance nature of the stator winding phases electrical parameters.

Table 2 shows the distribution of the three phases total power of the machine elements by harmonics. To improve the perception of the power harmonics distribution in the corresponding experiments, their absolute value is listed relative to the machine declared power above and is given in Table 2 as a percentage (%). Let us analyze each power sequentially in the order given in Table 2. The total stator power in all three experiments has a constant component, which increases insignificantly with increasing unbalance. The components with frequencies of 100 and 200 Hz present in the corresponding phase power compensate each other to a level not exceeding 0.3 %. In contrast, the power harmonic with a frequency of 50 Hz is not compensated, which is the most pronounced in the second experiment and amounts to 1.3 %. A significant value at the level of 6.4 % is the power harmonic with a frequency of 300 Hz, the level of which does not change in all experiments. The constant component of the electromagnetic power of the stator relative to the first experiment increases by 2.3 % in the second, and decreases by 1.2 % in the third. The specified power harmonic with a frequency of 50 Hz makes up more than 3 %, without changing significantly during the experiments. The specified power harmonic with a frequency of 100 Hz changes significantly in the second and third experiments to 6.6 %.

The power harmonic with a frequency of 300 Hz in all experiments does not exceed 2.6 %. The harmonic of the electromagnetic scattering power of the stator windings with a frequency of 50 Hz coincides in level and nature with the corresponding harmonic of the stator electromagnetic power. A similar analogy is observed at a frequency of 300 Hz, but in this case the value of the power harmonic remains at the level of 3.9 %. The power of the stator windings' active resistance does not change significantly in the experiments and differs only in the constant component not exceeding 9.2 %.

The total electric power of the rotor does not change significantly in the experiments, as well as the active re-

Fig. 6. Power spectra diagrams of stator elements by phases for three experiments

sistance power of the rotor windings at the level of 1.7 %. Certain changes are observed in the harmonics of the electromagnetic power and rotor windings scattering at a frequency of 100 Hz. It should be noted that there are harmonics of the specified powers at a frequency of 50 Hz with a level of 3.3 %, which does not change dur-

Table 2

The power harmonics summary data

	f, Hz	0	50	100	150	200	250	300
p_s, *VA*	Exp1	67.6	0.9	0.3	0.2	0.1	0.1	6.4
	Exp2	68.0	1.3	0.2	0.2	0.3	0.1	6.4
	Exp3	68.7	0.9	0.3	0.2	0.2	0.1	6.4
$p_{em.s}$, *VA*	Exp1	86.4	3.4	0.4	0.3	0.2	0.2	2.5
	Exp2	88.7	3.5	6.4	0.3	0.8	0.2	2.6
	Exp3	87.5	3.4	6.6	0.4	0.9	0.2	2.6
$p_{L\sigma s}$, *VA*	Exp1	9.7	3.3	0.2	0.1	0.1	0.1	3.9
	Exp2	11.6	3.4	6.6	0.1	0.5	0.1	3.9
	Exp3	9.6	3.3	7.0	0.2	0.8	0.1	3.9
p_{Rs}, *VA*	Exp1	9.2	0.1	0.0	0.0	0.0	0.0	0.1
	Exp2	9.1	0.1	0.1	0.0	0.1	0.0	0.1
	Exp3	9.2	0.1	0.1	0.0	0.0	0.0	0.1
p_r, *VA*	Exp1	21.2	0.0	0.0	0.0	0.0	0.0	0.0
	Exp2	21.2	0.0	0.1	0.0	0.0	0.0	0.0
	Exp3	21.3	0.0	0.0	0.0	0.0	0.0	0.0
$p_{em.r}$, *VA*	Exp1	1.7	3.3	0.1	0.1	0.1	0.0	3.7
	Exp2	1.7	3.3	1.7	0.1	0.3	0.0	3.7
	Exp3	1.7	3.3	1.9	0.1	0.6	0.0	3.8
$p_{L\sigma s}$, *VA*	Exp1	1.8	3.3	0.2	0.1	0.1	0.0	3.7
	Exp2	1.8	3.3	1.7	0.1	0.3	0.0	3.7
	Exp3	1.8	3.3	1.8	0.1	0.6	0.1	3.8
p_{Rr}, *VA*	Exp1	17.7	0.0	0.1	0.0	0.0	0.0	0.0
	Exp2	17.7	0.0	0.1	0.0	0.0	0.0	0.0
	Exp3	17.9	0.0	0.1	0.0	0.0	0.0	0.0
p_m, *VA*	Exp1	76.8	6.5	0.6	0.4	0.3	0.2	1.1
	Exp2	79.0	6.5	5.1	0.4	0.6	0.2	1.1
	Exp3	77.8	6.5	8.4	0.5	0.5	0.3	1.1

ing the experiments. The active resistance power of the rotor windings changes insignificantly – harmonics of 0 Hz at the level of 17.7–17.9 %. Significant changes are observed in the harmonics of mechanical power with frequencies of 0, 150 Hz in the range of 76.8–79.0 % and 0.6–8.4 %, respectively. A sufficiently significant harmonic of the specified power with a frequency of 50 Hz is maintained in all experiments at the level of 6.5 %. The harmonic of the mechanical power with a frequency of 300 Hz is more than 1 %.

Conclusions and directions for further research. Based on the equivalent circuit of a three-phase doubly fed induction generator, an equation is formulated for the balance of mechanical power, rotor power and stator power, which, on the one hand, provide a generalized idea of the power distribution in the elements of the machine equivalent circuit; on the other hand, these equations are disclosed for phase circuits, allowing us to study the power distribution.

A model for studying the processes of power components distribution of three-phase doubly fed induction generator elements is developed in a visual programming package. This model allows us to simulate linear and nonlinear generator loads and asymmetry of stator windings' electrical parameters.

During the study, it was found that the harmonics of the electromagnetic power in stator windings phases have values that exceed the machine rated power by an order of magnitude and, forming a total power of three phases, mutually compensate. Moreover, the level of these harmonics is sensitive to the nature of the asymmetry at a frequency of 100 Hz.

During the experiments, a significant change in the spectrum of the electromagnetic power in rotor windings phases was noted with unbalance, which is characterized by the presence of power harmonics with a frequency of 50 Hz, which corresponds to the direct current interaction with alternating components of the voltage of the rotor circuit corresponding element.

In the three phases total power of the three-phase doubly fed induction generator elements under the experimental conditions, harmonics with a frequency of 0 Hz dominate, the level of which for the stator circuit is sensitive to the unbalance nature of the stator electrical parameters and leads to changes by more than 2.3 % for the stator windings' electromagnetic power and 2.2 % for the mechanical power.

Using the obtained results in the control systems development for three-phase doubly fed induction generator will improve their energy performance under nonlinear load.

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Миттєва потужність асинхронного генератора із фазним ротором при несиметрії обмоток статора

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Асинхронні генератори із фазним ротором знайшли розповсюдження в системах генерації, в яких підтримка частоти обертання ротора не може бути вирішена в повній мірі шляхом регулювання приводного механізму.

Мета. Встановлення миттєвої потужності асинхронного генератора із фазним ротором в автономній системі з нелінійним навантаженням за умови зміни електричних параметрів обмоток статора машини.

Методика. У результаті аналізу відомих досліджень встановлена наявність технічних рішень, що забезпечують регулювання струму ротора генератора навіть в умовах нелінійного або несиметричного навантаження. Із використанням відомих положень теорії електротехніки й теорії електричних машин із використанням принципів балансу миттєвої потужності визначені рівняння балансу для трифазної асинхронної машини із фазним ротором.

Результати. Синтезована модель для дослідження процесів розподілу компонент потужностей елементів схеми заміщення асинхронного генератора із фазним ротором у пакеті візуального програмування. Зазначена модель дозволяє імітувати режими машини з лінійним і нелінійним навантаження генератора та несиметрію електричних параметрів обмоток статора. За умови проведення експериментів, відмічена суттєва зміна спектру потужності електромагнітної фази обмоток ротора за умов несиметрії, яка характеризується наявністю гармонік потужності частотою 50 Гц, що відповідає взаємодії постійного струму фаз ротора зі змінними складовими напруги відповідного елемента роторного кола.

Наукова новизна. У ході проведення дослідження, за умови несиметрії електричних параметрів обмоток статора, встановлено, що гармоніки потужності електромагнітної фази обмоток статора мають значення, які на порядок перевищують номінальну потужність машини та, формуючись у загальну потужність трьох фаз, взаємокомпенсуються. При чому рівень цих гармонік чутливий до характеру несиметрії на частоті 100 Гц. У потужності трьох фаз елементів асинхронного генератора із фазним ротором за умов проведених експериментів домінують постійні складові, рівень яких для кола статора чутливий до характеру несиметрії електричних параметрів обмоток статора й призводить до змін більш ніж на 2,3 % для електромагнітної потужності обмоток статора та 2,2 % для механічної потужності.

Практична значимість. Отримані результати в подальшому можуть бути використані для удосконалення систем регулювання параметрів режиму асинхронного генератора із фазним ротором для підвищення енергетичних показників комплексу.

Ключові слова: *електрична потужність, миттєва потужність, гармоніки потужності, асинхронний генератор*

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