Features of the Functioning of Asynchronous Motors in Autonomous Systems

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Abstract— **Currently, in various sectors of economic activity, in particular the courts of the transport industry, widely used power system three-phase alternating current frequency of 50 Hz (less often - with a frequency of 60 Hz), whose characteristic feature is their autonomy and commensurability in the power unit of a separate receivers and sources of electrical energy. The main sources of electrical energy are three-phase synchronous generators, and the receivers of electrical energy are three-phase asynchronous motors of marine electric drives, the operating modes of which have a direct impact on the quality of marine electrical energy and the amount of losses. The article considers the main variants of possible modes of operation of three-phase AC electric drives in autonomous electric power systems.**

Keywords— Autonomous electric power system, static unbalanced modes of operation, three-phase alternating current, asynchronous electric motor, electric drive.

I. INTRODUCTION (*HEADING 1*)

Static operating modes are the main operating modes of asynchronous motors of three-phase alternating current as part of electric drives, which can be considered as special cases of transient modes with a quasi-constant angular velocity of the rotor ωr (ωr = const) and the absence of a dynamic moment Md (Md = 0) [1]. Static modes can be conditionally grouped into two main groups – symmetric and non-symmetric. The main conditions of the established symmetric modes of operation of electric motors are the equality of the corresponding parameters and variables of all three phases of the asynchronous motor. In these cases, all electrical quantities contain components only of a direct sequence.

Electric motors in autonomous electric power systems operate, as a rule, in quasi-symmetric or asymmetric static modes, the reasons for which are of a diverse qualitative and quantitative nature [2]. In electric motors, such modes occur, for example, when there is an uneven distribution of loads between the phases of a three-phase ship network. In these modes, asynchronous motors operate with increased losses, increased heating of the windings, and, accordingly, with a reduced service life. Therefore, it is of interest to study these modes and the causes of their occurrence.

II. ANALYSIS OF THE CAUSES OF ASYMMETRIC MODES OF OPERATION OF ASYNCHRONOUS MOTORS

At symmetric phase voltages of the network, the reasons for the asymmetric operating modes of asynchronous motors include technological deviations of structurally designed electric motors, operating modes due to specific mechanical and climatic loads [1], which lead, among other things, to uneven wear of bearings, changes in the forces in the connecting and switching contacts. The causes of asymmetric non-standard modes also include malfunctions of the stator and rotor windings that occur during the operation of electric motors. A number of papers, including [3, 4, 5], have been devoted to the study of such regimes with varying degrees of detail.

Other types of non-standard modes (simultaneous stator and rotor asymmetry, short-circuit of the stator windings, damage to the rotor windings, etc.) have been published in [6, 7, 8, etc.].

In order to increase the reliability of the operated electric drives in autonomous electric power systems, a number of scientific and technical solutions are currently proposed [9, 10], including combined (hybrid) control systems [11, 12].

When using combined control systems, including the technical implementation of the developed method presented in [13], in addition to the above reasons, the occurrence of asymmetric power supply modes of the stator windings is possible, due to the specific operational features of power semiconductor devices.

Table 1 shows, as an example, the relationships between failures in the form of breaks and short circuits of semiconductor devices (diodes and triodes), presented in [14].

TABLE I RELATIONS BETWEEN FAILURES OF SEMICONDUCTOR DEVICES AT DIFFERENT LOAD FACTORS k_l

№	Type element	Type failures	Values k_l		
			0,0…0,3	0,3…0,7	0,7…1,0
1	2	3	4	5	6
2	Diodes	Break circuit	0,75	0,75…0,95	0,55
		Short circuit	0,25	0,25…0,05	0,45
3	Triodes	Break circuit	0,00…0,20	0,20…0,05	0,00…0,05
		Short circuit	1,00…0,80	0,80…0,95	1,00…0,95

In Table 1, k_l is the load factor, which represents the ratio of the actual load parameter to its nominal value.

When operating in key modes, in contrast to their operation in parameter control modes, the probability of failure of individual power semiconductor devices increases due to the values of the transient mode currents that significantly exceed their steady-state values. So, for example, the starting current of electric motors exceeds the rated current values up to ten times, and in cases of reversals and repeated inclusions of asynchronous motors in the network-up to 18 times. During disconnections, the most severe operating conditions of power semiconductor devices occur in cases of braked asynchronous motors, when the switched currents reach sevenfold values [3].

Studies of asymmetric non-standard operating modes of asynchronous motors due to failures of power semiconductor devices and their analysis allow us to assess the danger of such modes for the remaining power semiconductor devices, asynchronous motors and marine electric drives in general.

There are three main types of asymmetric modes: intraphase, interphase, and general [15].

In the case of intra-phase asymmetries, due to the different opening angles of the counter-parallel connected thyristors, the same absolute value for all phases of the mismatch angle $\Delta\alpha$ is observed. In cases of phase-to-phase asymmetries, $\Delta\alpha = 0$, but the opening angles of power semiconductor devices of different phases will differ. General asymmetries are caused by the presence of $\Delta\alpha = 0$ and differences in the opening angles of thyristors of different phases.

The results of analytical studies, in particular of the three – phase system «thyristor switch-active-inductive load», given in [16], show that with intra-phase asymmetry in the output voltage, there is no constant component and harmonics that are multiples of three. In cases where there is an inter-phase asymmetry, there is no constant voltage component and even harmonics. With general asymmetry, the output voltage contains both a constant component and the full spectrum of higher harmonics.

Thus, all cases of such asymmetries lead to distortion of the forms of stress curves to non-sinusoidal ones.

III. Mathematical model of an asynchronous motor

Taking into account the accepted assumptions and conventions [17], the phase currents of the direct sequence stator in the complex form have the form

$$\left.\begin{aligned} i_{sdA} &= \mathrm{Re}\tilde{I}_{sdA} = 0{,}5(\tilde{I}_{sdA} + \tilde{I}^*_{sdA}); \\ i_{sdB} &= \mathrm{Re}\tilde{I}_{sdA}\underline{a}^2 = 0{,}5\left(\tilde{I}_{sdA}\underline{a}^2 + \tilde{I}^*_{sdA}\underline{a}\right); \\ i_{sdC} &= \mathrm{Re}\tilde{I}_{sdA}\underline{a} = 0{,}5\left(\tilde{I}_{sdA}\underline{a} + \tilde{I}^*_{sdA}\underline{a}^2\right). \end{aligned}\right\} \quad (1)$$

In (1) $\tilde{I}_{sdA}$, $\tilde{I}^*_{sdA}$ – complex and conjugate complex functions of the direct sequence current of phase A; $\underline{a}$, $\underline{a}^2$ – single complexes that indicate the directions of the phase axes in a three-phase coordinate system.

The complex function of the current $\tilde{I}_{sdA}$ in (1) is expressed by the dependence

$$\tilde{I}_{sdA} = \dot{I}_{sdA}\mathrm{e}^{j\omega_0 t}, \quad (2)$$

in which

$$\dot{I}_{sdA} = I_{sdm}\mathrm{e}^{j\beta_A} \quad (3)$$

– the complex amplitude of the current of the direct sequence of the stator phase A, in which β_A is the phase angle for the current of the stator phase A.

The single complexes $\underline{a}$ and $\underline{a}^2$ in (1) have the form

$$\underline{a} = \mathrm{e}^{j\frac{2\pi}{3}};\ \underline{a}^2 = \mathrm{e}^{j\frac{4\pi}{3}}. \quad (4)$$

The resulting complex function of the stator current $\tilde{I}_{snp}$ through the instantaneous values of the phase currents i_{sdA} i_{sdB} and i_{sdC} is expressed as

$$\tilde{I}_{sd} = \tfrac{2}{3}\left(i_{sdA} + i_{sdB}\underline{a} + i_{sdC}\underline{a}^2\right). \quad (5)$$

Equation (5), taking into account (1), in the orthogonal coordinate system α, β is represented in the following transformed form

$$\tilde{I}_{sd\alpha\beta} = \left(\tilde{I}_{sdA}(1 + \underline{a}^3 + \underline{a}^3) + \tilde{I}^*_{sdA}(1 + \underline{a}^2 + \underline{a})\right)/3, \quad (6)$$

whence the resulting complex is represented as

$$\tilde{I}_{sd\alpha\beta} = \tilde{I}_{sdA} = \dot{I}_{sdm}\mathrm{e}^{j\omega_0 t}. \quad (7)$$

In a similar way, the resulting complexes of flux linkage $\tilde{\Psi}_{sd\alpha\beta}$ and stator voltage $\tilde{U}_{sd\alpha\beta}$ of the asynchronous motor are expressed in the axes α, β:

$$\tilde{\Psi}_{sd\alpha\beta} = \tilde{\Psi}_{sdA} = \Psi_{sdm}\mathrm{e}^{(j\phi_A + j\omega_0 t)}; \quad (8)$$

$$\tilde{U}_{sd\alpha\beta} = \tilde{U}_{sdA} = U_{sdm}\mathrm{e}^{(j\varphi_A + j\omega_0 t)}, \quad (9)$$

where ϕ_A and φ_A are the phase angles for the voltage and flux linkage of the stator phase A, respectively.

The frequency of the current in the rotor circuit f_r of the asynchronous motor is defined as

$$f_r = f_c\left(\frac{\omega_0 - \omega_r}{\omega_0}\right) = f_c s, \quad (10)$$

where s is the slip of the electric motor.

In this case, the values of the direct sequence of the rotor change with an angular velocity ω_{rd} equal to ω_0s The resulting complexes of the rotor in the d, q axes have the following form:

$$\tilde{I}_{rddq} = \tilde{I}_{rda} = \dot{I}_{rdm}\mathrm{e}^{j\omega_{rd} t}; \quad (11)$$

$$\tilde{\Psi}_{rddq} = \tilde{\Psi}_{rda} = \dot{\Psi}_{rdm}\mathrm{e}^{j\omega_{rd} t}; \quad (12)$$

$$\tilde{U}_{rddq} = \tilde{U}_{rda} = \dot{U}_{rdm}\mathrm{e}^{j\omega_{rd} t}, \quad (13)$$

where

$$\dot{I}_{rdm} = I_{rdm}\mathrm{e}^{j\beta_A} \quad (14)$$

– the complex amplitude of current direct sequence phase A rotor in which β_A – phase angle for phase current A

$$\dot{\Psi}_{rdm} = \Psi_{rdm}\mathrm{e}^{j\phi_A} \quad (15)$$

– complex amplitude of the flux linkage of direct sequence of rotor phase A, in which ϕ_A is the phase angle for the flow coupling of phase A;

$$\dot{U}_{rdm} = U_{rdm}\mathrm{e}^{j\varphi_A} \quad (16)$$

– the complex amplitude of the direct sequence voltage of the phase A of the rotor, in which ϕ_A is the phase angle for the voltage of phase A.

To convert the obtained forms of records into steady-state equations for a three-phase coordinate system, the equations of the electric equilibria of the stator and rotor in the axes rotating with speed ω_0 are used:

$$\tilde{U}_s = R_s\tilde{I}_s + \frac{d\tilde{\Psi}_s}{dt} + j\omega_0\tilde{\Psi}_s; \quad (17)$$

$$\tilde{U}_r = R_r\tilde{I}_r + \frac{d\tilde{\Psi}_r}{dt} + j\omega_0 s\tilde{\Psi}_r. \quad (18)$$

Having expressed in (17) and (18) the complex functions by the obtained dependences, after some transformations, a system of equations for three-phase AM, reduced to transformers, is derived:

$$\left.\begin{aligned} \dot{U}_s &= \dot{I}_s\left(R_s + j\omega_s L_{s\sigma}\right) + j\omega_s L_{srm}\dot{I}_m; \\ \dot{U}_r &= \left(\dot{I}_r\left(\frac{R_r}{s} + j\omega_r L_{r\sigma}\right) + j\omega_r L_{srm}\dot{I}_m\right)s = 0. \end{aligned}\right\} \quad (19)$$

In (19) ω_s – arbitrary angular velocity of the axes; L_{srm} – the main mutual inductance between the stator phase and the rotor phases.

IV. Asymmetric static modes of operation of an asynchronous motor

In analytical studies of such asymmetric modes, the method of symmetric components is widely used. The system of asymmetrical primary voltages ($\dot{U}_{sA}, \dot{U}_{sB}, \dot{U}_{sC}$) can be represented as the sum of the components of the direct sequence ($\dot{U}_{sdA}$, $\dot{U}_{sdB}$, $\dot{U}_{sdC}$) and reverse sequence ($\dot{U}_{srA}$, $\dot{U}_{srB}$, $\dot{U}_{srC}$).

The components of the stator voltage of the direct and reverse sequences for phase *A*, for example, have the form:

$$\left.\begin{aligned} \dot{U}_{sdA} = \dot{U}_{sd} &= \left(\dot{U}_{sA} + \dot{U}_{sB}\underline{a} + \dot{U}_{sC}\underline{a}^2\right)/3; \\ \dot{U}_{srA} = \dot{U}_{sr} &= \left(\dot{U}_{sA} + \dot{U}_{sB}\underline{a}^2 + \dot{U}_{sC}\underline{a}\right)/3, \end{aligned}\right\} \quad (20)$$

where $\underline{a}$, $\underline{a}^2$ are single complexes (4).

The components of the stator phase current of the direct and reverse sequences, taking into account the asynchronous motor substitution scheme [17], are expressed by analytical dependencies

$$\left.\begin{aligned} \dot{I}_{sd} &= \frac{\dot{U}_{sd}}{(R_s + jX_{s\sigma}) + \left(Z_m^{-1} + Z_{rd}^{-1}\right)^{-1}}; \\ \dot{I}_{sr} &= \frac{\dot{U}_{sr}}{(R_s + jX_{s\sigma}) + \left(Z_m^{-1} + Z_{rr}^{-1}\right)^{-1}}, \end{aligned}\right\} \quad (21)$$

where $X_{s\sigma}$ –inductive scattering resistance of the stator winding of an asynchronous motor;
Z_m – complex resistance of the magnetizing circuit; Z_{rd}, Z_{rr} – the components of the resistance of an equivalent stationary rotor for currents of direct and reverse sequences, respectively.

The components Z_{rd} and Z_{rr} are defined as

$$Z_{rd} = \frac{R_r^/}{s} + jX_{r\sigma}^/, \quad (22)$$

$$Z_{rr} = \frac{R_r^/}{2-s} + jX_{r\sigma}^/. \quad (23)$$

The frequency of the rotor currents of the reverse sequence f_{rr}, expressed by the dependence

$$f_{rr} = (2 - s)f_s, \quad (24)$$

is much higher than the frequency f_{rd} of the direct sequence rotor currents determined by (10), and the effect of displacing the reverse sequence currents is much greater than the direct sequence currents.

Taking into account the substitution scheme [2], the phase currents of the stator of an asynchronous motor are represented as:

$$\left.\begin{aligned} \dot{I}_{sA} &= \dot{I}_{sd} + \dot{I}_{sr}; \\ \dot{I}_{sB} &= \dot{I}_{sd}\underline{a}^2 + \dot{I}_{sr}\underline{a}; \\ \dot{I}_{sC} &= \dot{I}_{sd}\underline{a} + \dot{I}_{sr}\underline{a}^2. \end{aligned}\right\} \quad (25)$$

With the distortion of the stator voltage, for example, by 4% ((U_{sr} / U_{sd}) = 0,04), the distortion of the stator current is 20% ((I_{sr} / I_{sd}) = 0,2). In this case, in one of the phases, the current in relative units can be 1,2, and the losses – 1,44 [2].

The torque *M* of a three-phase asynchronous motor with distortions of the symmetry of stator voltages is expressed as

$$M = M_d + M_r, \quad (26)$$

where M_d, M_r are the components of the moment of the direct and reverse sequences, respectively.

$$M_d = \frac{m_s U_{sd}^2 R_r^/}{s\omega_0\left(\left(R_s + \frac{R_r^/}{s}\right)^2 + \left(X_{s\sigma} + X_{r\sigma}^/\right)^2\right)}; \quad (27)$$

$$M_r = \frac{m_s U_{sr}^2 R_r^/}{(2-s)\omega_0\left(\left(R_s + \frac{R_r^/}{2-s}\right)^2 + \left(X_{s\sigma} + X_{r\sigma}^/\right)^2\right)}, \quad (28)$$

where m_s – the number of phases of the stator winding; $R_r^/$, $X_{r\sigma}^/$ – reduced active and inductive resistance of leakage of the asynchronous motor rotor winding, respectively.

To preserve the resulting torque M with asymmetry stator voltages, it is necessary to increase the component M_d by a value M_r , which leads to an increase in slip *s* by about $M_d/(M_d - |M_r|)$ times, an increase in losses and a deterioration in the efficiency of three-phase asynchronous motors.

Assuming that for a given slip s, the parameters of an asynchronous motor do not depend on voltage and current, the motor powered by a non-sinusoidal three-phase voltage, based on the superposition principle, is equivalent in the first approximation to a system that includes several conventional electric motors located on a single shaft. Each conventional motor powered by a separate harmonic ν corresponds to its own replacement circuit [15, 18], and both the inductive and active resistances of the rotor circuits depend on the b-th harmonic. An equivalent L-shaped phase replacement circuit of a three-phase asynchronous motor for the ν -th harmonic of the voltage $U_{s\nu}$ is given in [2].

The electromagnetic moment of the ν-th harmonic M_ν can be expressed by the following equation

$$M_\nu = \frac{m_s U_{s\nu}^2 (1+g_\nu s_\nu)}{\sigma^2 R_{rn}^{/} s_\nu \omega_0 \nu \left(\left(\frac{R_s}{\sigma R_{rn}^{/}} + g_\nu + \frac{1}{s_\nu} \right)^2 + \left(\frac{X_{shcn}}{\sigma^2 R_{rn}^{/}} \right)^2 \nu^2 \varepsilon_\nu^2 \right)}, \quad (29)$$

where g_ν is the calculated coefficient for the ν -th harmonic; s_ν – slip for the th harmonic of the direct and reverse fields; σ – scattering coefficient; $R_{rn}^{/}$, X_{shcn} – the reduced nominal active resistance of the rotor winding and the inductive resistance of the short circuit in the nominal mode; ε_ν – the relative value of the inductive resistance.

The analysis of the mechanical characteristics of the electric drive of the "thyristor switch – asynchronous motor" system in quasi-steady-state modes, obtained analytically under known assumptions, allows us to conclude that with intra-phase asymmetries, the electromagnetic moment of the electric motor *M* will be determined as

$$M = \sum M_{\nu d}, \quad (30)$$

that is, the distortion of the resulting torque curve is minimal.

In formula (30) $\sum M_{\nu d}$ – the resulting moment of the ν -th harmonics of the direct sequence fields.

In cases of phase-to-phase unbalances

$$M = \sum M_{\nu 1d} + \sum M_{\nu 1r}, \quad (31)$$

where $\sum M_{\nu 1d}$, $\sum M_{\nu 1r}$ – the resulting moments of the odd harmonics of the fields of the direct and reverse sequences, respectively.

If the asymmetries are general, then

$$\mathrm{M} = \sum M_{\nu d} + \sum M_{\nu r} + M_c, \quad (32)$$

where $\sum M_{\nu r}$ – the resulting moment of the ν-th harmonics of the fields of the reverse sequence; M_c – constant component of the moment.

Forms of mechanical characteristics of an asynchronous motor $\omega_r = f(M)$ with general asymmetries have significant distortions.

The components of the moments of the direct and reverse sequences in formulas (30) ... (32) are determined by expression (29), and the constant component of the torque in (32) is determined by the values of the constant component of the current.

V. Analysis of the causes of abnormal operating modes of an adjustable asynchronous electric drive

Depending on the type of asymmetry and the degree of its manifestation, the non-standard operating modes of the asynchronous motor can be conditionally grouped into four groups.

The modes of the first group occur when technological asymmetries or minor misalignments of the semiconductor switch during operation [19]. Such operating modes can be classified as quasi-normal.

The second group of abnormal modes includes asymmetric modes that arise during misalignments or partial failures of the control system, which, disrupting the normal functioning of the electric drive, do not lead to a complete loss of controllability of the electric drive.

The third group includes special modes that occur due to breakdowns of one or more power semiconductor devices [20]. Due to the absence of a constant component and even harmonics of the current, overloads and distortions of the variables are insignificant.

Special modes of operation of the fourth group are associated with the complete closure of one or more power semiconductor devices. They represent the greatest danger to the induction motor and the electric drive as a whole in connection with a high probability of the presence of the DC component of the torque M_c (32), the presence of which simultaneously with the motor mode creates a dynamic braking mode of the electric motor. The M_c component, as a rule, introduces the greatest distortion in the mechanical characteristics of an asynchronous motor, since its values are directly proportional to the values of the constant current component, which is limited only by the active resistances of the motor windings. The remaining serviceable power semiconductor devices will operate in more current-loaded modes under conditions of approximate equalities of the moment of resistance M_c on the motor shaft before and after the occurrence of asymmetric modes. A more detailed description of such modes is given in [15].

VI. Conclusion

Thus, based on the above, at present, it is relevant to study the asymmetric modes of operation of asynchronous motors as part of an electric drive in autonomous electric power systems, due to the requirements of adequate reproduction of the shapes and values of the voltage and current curves of an asynchronous motor, in order to quantify their impact on the electric motor itself and the remaining serviceable power semiconductor devices.

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