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Method of calculation of electromagnetic torque and energy losses of three-phase induction motors when powered by a regulated single-phase voltage

Introduction. *Single-phase power supply of induction motors is used in public utilities, in microclimate control systems for remote agricultural consumers, in water supply and pipeline transport systems, etc. In practice, there is the use of induction motors with three-phase stator winding in the conditions of single-phase power supply. Starting and operating capacitors are used to enable their operation when powered by a single-phase network.* ***Problem.*** *There are many fairly accurate methods for calculating the characteristics of an induction motor in asymmetric, including single-phase, modes of operation, but they are based on differential equations, which does not allow to obtain analytical expressions for preliminary analysis and synthesis of such systems.* ***Goal.*** *The purpose of this article is to develop the analytical method of definition of electromagnetic torque and energy losses of voltage-regulated three-phase induction motors working according to the scheme of single-phase inclusion with the phase-shifting capacitor.* ***Methodology.*** *The method is based on the theory of symmetric components and analysis of replacement schemes of induction machine in motor and generator modes.* ***Results.*** *The analysis of the obtained data shows that at a constant value of the phase-shifting capacitor capacity induction motor working according to the scheme of single-phase inclusion has a minimum of losses at one value of slip at different values of supply voltage. Therefore, if you keep this slip constant when the load changes, you can achieve a mode of minimizing losses at a constant value of the capacity, optimal for this slip. This shows that the thyristor voltage regulator can be used as an energy-saving element under variable load, while the capacitance of the phase-shifting capacitor can remain constant when changing the load in a wide range provided that this slip is stabilized.* ***Originality.*** *The developed method allows to obtain analytical expressions for comparative analysis of electromagnetic torque and energy losses of three-phase induction motors powered by a single-phase network at different values of the capacity of the phase-shifting capacitor, supply voltage for different variants of schemes for including three-phase induction motors in a single-phase network.* ***Practical value.*** *Based on the developed analytical method, the optimal parameters of phase-shifting capacitors and rational schemes for including three-phase induction motors in a single-phase network can be determined.* References 25, figures 3.

Key words: **induction motor, single-phase supply, voltage regulator, method of symmetric components, phase-shifting capacitor.**

Розроблено аналітичну методику розрахунку електромагнітного моменту та втрат енергії регульованих за напругою трифазних асинхронних двигунів при живленні від однофазної мережі за схемою з фазозсуваючим конденсатором. В основу методики покладено метод симетричних складових та аналіз схем заміщення асинхронної машини у двигунному та генераторному режимах роботи. На основі цієї методики можуть бути визначені оптимальні параметри фазозсуваючих конденсаторів та вибрані раціональні схеми включення трифазних асинхронних двигунів в однофазну мережу з регульованою напругою. Показано, що регулятор напруги може бути використаний як енергозберігаючий елемент при однофазному живленні трифазних асинхронних двигунів та його застосування дозволяє використовувати постійну ємність фазозсуваючого конденсатора при зміні навантаження у широких межах. Бібл. 25, рис. 3.

Ключові слова: **асинхронний двигун, однофазне живлення, регулятор напруги, метод симетричних складових, фазозсуваючий конденсатор.**

Introduction. Single-phase power supply of induction motors (IMs) is used in household and communal economy [1], in microclimate regulation systems of agricultural consumers [2], in water supply and pipeline transport systems [3]. In practice, the use of induction motors with a three-phase stator winding is observed under conditions of single-phase power supply [4, 5]. For the possibility of their operation when powered from a single-phase network, starting and working capacitors are used [6, 7]. The use of voltage-regulated electric drives based on three-phase induction motors makes it possible to meet the technological and energy-saving requirements of many consumers [8, 9], to facilitate start-up conditions [10], and to increase the energy efficiency of technological units by taking into account the nature of load changes in the algorithm for regulating closed-loop electric drive systems [11].

There are many fairly accurate methods for calculating [4-7, 12, 13] the characteristics of an induction motor in asymmetric, including single-phase, modes of operation, but they are based on differential equations, which does not allow obtaining analytical expressions for the preliminary selection of the capacity of the phase-shifting capacitor and comparative analysis of possible variants of connection schemes.

The goal of the article is to develop an analytical method for determining the electromagnetic torque and energy losses of voltage-regulated three-phase induction motors operating according to the single-phase circuit with a phase-shifting capacitor.

Object of study. Analytical expressions for calculating the electromagnetic torque and energy losses of a voltage-regulated three-phase induction motor with single-phase power supply will be considered using the example of the Steinmetz scheme (Fig. 1).

Regulation of the motor according to the voltage in this scheme takes place with the help of a thyristor voltage regulator (TVR). Let's note that the method developed in this article is based on the assumption that only the first harmonic component of the voltage is present at the output of the TVR, therefore it can be applied to any type of voltage regulator [14, 15]. Moreover, the voltage regulator can be considered similarly to three-phase systems as an energy-saving element [8]. Here, it should be taken into account that the used technique does not take into account losses from higher harmonics of the current generated by the thyristor regulator, therefore the effective effect of energy saving will be smaller at low loads [16].

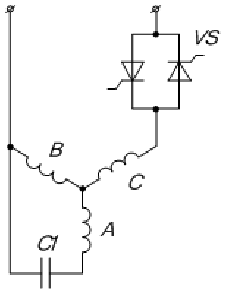

Fig. 1. Scheme of connection of a voltage-regulated three-phase motor in a single-phase network

This technique is proposed for a preliminary search analysis of electromagnetic torque values and energy losses of an induction motor powered by a single-phase network according to a scheme with a thyristor voltage regulator and a phase-shifting capacitor. For more accurate studies, it is necessary to use models that take into account the influence of non-sinusoidal and asymmetric on the motor parameters [17-20].

General relationships in the induction motor in single-phase mode of operation. To analyze the operation of an induction motor in single-phase mode, we will use the method of symmetrical components. The basis of the calculation will be the characteristics of IM in the symmetrical three-phase mode of operation. Here, we introduce the notation: M_1, I_1, Z_1, φ_1 are respectively, the dependence on the torque slip, current, module, and argument of the total resistance of the IM replacement circuit in the symmetrical motor mode, and M_2, I_2, Z_2, φ_2 are the same dependencies in the symmetrical generator mode.

The Kirchhoff equations for the circuit in Fig. 1 will be the following:

$$\underline{U}_C - \underline{U}_B = \underline{U}\,; \tag{1}$$

$$\underline{U}_A - \underline{U}_B = jX_{C1}\underline{I}_A, \tag{2}$$

where $\underline{U}$ is the complex value of the IM supply voltage, which is the output voltage of the TVR; $\underline{U}_A, \underline{U}_B, \underline{U}_C$ are the complex values of stator phase voltages; $jX_{C1}\underline{I}_A$ is the complex value of the voltage on the phase-shifting capacitor, where $X_{C1} = 1/(\omega \cdot C1)$.

Let's introduce the components of voltages and currents of forward (marked by index p), reverse (n) and zero (0) sequences:

$$\underline{U}_A = \underline{U}_p + \underline{U}_n + \underline{U}_0\,; \tag{3}$$

$$\underline{U}_B = \underline{U}_p a + \underline{U}_n a^2 + \underline{U}_0\,; \tag{4}$$

$$\underline{U}_C = \underline{U}_p a^2 + \underline{U}_n a + \underline{U}_0\,; \tag{5}$$

$$\underline{I}_A = \underline{I}_p + \underline{I}_n + \underline{I}_0\,, \tag{6}$$

where $\underline{U}_p, \underline{U}_n, \underline{U}_0$ are the complex values of forward, reverse and zero sequence voltages; $a = e^{-j\frac{2\pi}{3}}$ is the rotary multiplier; $\underline{I}_p = \dfrac{\underline{U}_p}{\underline{Z}_1}, \underline{I}_n = \dfrac{\underline{U}_n}{\underline{Z}_2}, \underline{I}_0 = \dfrac{\underline{U}_0}{\underline{Z}_0}$ are the complex values of currents of direct and reverse sequences.

Note that for the scheme in Fig. 1 zero sequence is absent due to the absence of a neutral wire.

Here $\underline{Z}_1, \underline{Z}_2$ are the complex resistances according to the parameters of the substitution schemes, respectively, of the forward and reverse sequences:

$$\underline{Z}_1 = Z_1(\cos\varphi_1 + j\sin\varphi_1)\,; \tag{7}$$

$$\underline{Z}_2 = Z_2(\cos\varphi_2 + j\sin\varphi_2), \tag{8}$$

where $Z_1, Z_2, \varphi_1, \varphi_2$ are the modules and phases of complex resistances of forward and reverse sequences

Substituting (3)–(6) into (1), (2), we obtain:

$$\left(\underline{U}_p - \underline{U}_n\right)\left(a^2 - a\right) = \underline{U}\,; \tag{9}$$

$$\underline{U}_p\left(1 - a - \frac{jX_{C1}}{\underline{Z}_1}\right) + \underline{U}_n\left(1 - a^2 - \frac{jX_{C1}}{\underline{Z}_2}\right) = 0\,. \tag{10}$$

Let's introduce the basic values X_{C_0} for capacitive resistance:

$$X_{C_0} = \frac{\sqrt{3}U}{I_1} = \sqrt{3}Z_1\,, \tag{11}$$

where U and I_1 are the phase values of voltage and current in symmetrical motor mode.

Also we introduce the relative value of the capacity:

$$x = \frac{X_{C_0}}{X_{C1}} = \frac{1/\omega C_0}{1/\omega C_1} = \frac{C1}{C_0} \tag{12}$$

and the coefficient equal to the ratio of the currents of the anti-switching and motor modes with symmetrical power supply:

$$k_i = \frac{U/Z_2}{U/Z_1} = \frac{Z_1}{Z_2}\,. \tag{13}$$

After carrying out a series of transformations, we obtain expressions for the forward and reverse sequence voltages:

$$\underline{U}_p = \frac{\underline{U}\left[\frac{\sqrt{3}}{2}x - k_i\sin\varphi_2 - j\left(\frac{1}{2}x + k_i\cos\varphi_2\right)\right]}{\sqrt{3}\left\{\cos\varphi_1 + k_i\cos\varphi_2 + j[\sqrt{3}x - (\sin\varphi_1 + k_i\sin\varphi_2)]\right\}}\,; \tag{14}$$

$$\underline{U}_n = \frac{-\underline{U}\left[\frac{\sqrt{3}}{2}x - \sin\varphi_1 + j\left(\frac{1}{2}x - \cos\varphi_1\right)\right]}{\sqrt{3}\left\{\cos\varphi_1 + k_i\cos\varphi_2 + j[\sqrt{3}x - (\sin\varphi_1 + k_i\sin\varphi_2)]\right\}}\,. \tag{15}$$

Let's introduce the parameters characterizing the direct sequence voltage level

$$\alpha = U_p/U\,, \tag{16}$$

reverse sequence voltage level

$$\beta = U_n/U \tag{17}$$

and asymmetry coefficient

$$\gamma = U_n/U_p\,. \tag{18}$$

In (16) – (18) U_p, U_n, U are the modules, respectively, of voltages of direct, reverse sequences and supply voltage.

Moving to the modules in (14), (15), we find these parameters:

$$\alpha = \sqrt{\frac{x^2 - \theta_2 k_i x + k_i^2}{\left(\sqrt{3}x - \phi_2\right)^2 + \phi_1^2}}\,; \tag{19}$$

$$\beta = \sqrt{\frac{x^2 - \theta_1 x + 1}{\left(\sqrt{3}x - \phi_2\right)^2 + \phi_1^2}}\,; \tag{20}$$

$$\gamma = \sqrt{\frac{x^2 - \theta_1 x + 1}{x^2 - \theta_2 k_i x + k_i^2}}\,, \tag{21}$$

where $\theta_1 = \sqrt{3}\sin\varphi_1 + \cos\varphi_1$, $\theta_2 = \sqrt{3}\sin\varphi_2 - \cos\varphi_2$, $\phi_1 = \cos\varphi_1 + k_i\cos\varphi_2$, $\phi_2 = \sin\varphi_1 + k_i\sin\varphi_2$.

According to the described method, these asymmetry parameters can also be determined for other schemes of connection a three-phase motor in a single-phase network, for example, for a series-parallel scheme [3] or for a «star with a zero wire» scheme with self-excitation of the capacitor phase through a rotating rotor [21]. To do this, it is necessary to write down the Kirchhoff equations (1), (2) corresponding to each scheme and perform the following analytical transformations (3) – (15). Then parameters (16) – (18) can be used in further calculations for these schemes. Therefore, the proposed method can be generalized also to other possible schemes for connection a three-phase motor with a phase-shifting capacitor in a single-phase network.

Calculation of the electromagnetic torque of an induction machine in single-phase mode of operation. The electromagnetic torque in the symmetrical motor mode in the case of three-phase power supply M_1 can be determined from the expressions of the electromagnetic power P_{em}. On the one hand, it is equal

$$P_{em} = M_1 \cdot \omega_0, \tag{22}$$

where ω_0 is the angular frequency of idling.

On the other hand

$$P_{em} = 3I_{r1}^2\frac{R_2}{s}, \tag{23}$$

where $I_{r1} = U/Z_{1r}$ is the effective value of the reduced rotor current in symmetrical mode; s is the slip; R_2 is the active resistance of the rotor reduced to the stator winding.

Equating these two expressions, we obtain:

$$M_1 = \frac{3}{\omega_0}\left(I_{r1}^2\frac{R_2}{s}\right). \tag{24}$$

The electromagnetic torque in single-phase mode is defined as the difference between the torques of forward and reverse sequences:

$$M = M_p - M_n = \frac{3}{\omega_0}\left(I_{rp}^2\frac{R_2}{s} - I_{rn}^2\frac{R_2}{2-s}\right), \tag{25}$$

where $I_{rp} = U_p/Z_{1r}$, $I_{rn} = U_n/Z_{2r}$ are the modules of reduced rotor currents of forward and reverse sequences; Z_{1r}, Z_{2r} are the respectively, the modules of the equivalent resistances of the load branch of the L-shaped schemes of substitution of forward and reverse sequences.

Let's introduce the coefficient μ, which is equal to the ratio of torques for single-phase mode and motor three-phase symmetrical mode $\mu = M/M_1$:

$$\mu = \alpha^2 + k_\mu\beta^2 = \alpha^2\left(1 + k_\mu\gamma^2\right), \tag{26}$$

where $k_\mu = M_2/M_1$ is the coefficient equal to the ratio of generator M_2 and motor M_1 torques in three-phase symmetrical mode:

$$k_\mu = -\frac{Z_{1r}^2}{Z_{2r}^2}\cdot\frac{s}{2-s}. \tag{27}$$

Since the single-phase mode and the three-phase motor mode are considered with the same slips, the coefficient μ also determines the ratio of electromagnetic powers of AD when operating in these modes.

Using the obtained coefficients α, β, γ, μ, it is possible to analyze the IM characteristics using formulas valid for the three-phase symmetrical mode of operation obtained from the substitution scheme.

According to (24), the electromagnetic torque in the three-phase symmetrical mode is determined by:

$$M_1 = \frac{3U^2R_2}{\omega_0 s\left[\left(R_1 + \frac{R_2}{s}\right)^2 + \left(X_1 + X_2\right)^2\right]}. \tag{28}$$

where R_1, R_2, X_1, X_2 are the parameters of the IM substitution scheme.

The electromagnetic torque of IM in single-phase mode is determined by the expression:

$$M = \mu M_1 = \frac{\alpha^2\left(1 + k_\mu\gamma^2\right)3U^2R_2}{\omega_0 s\left[\left(R_1 + \frac{R_2}{s}\right)^2 + \left(X_1 + X_2\right)^2\right]}. \tag{29}$$

As can be seen from (29), the torque of a single-phase induction motor with regulated voltage at a given slip depends on the supply voltage, the direct sequence voltage level and the asymmetry coefficient, which in turn depend on the relative value of the capacity of the phase-shifting capacitor $x = X_{C_0}/X_{C1}$.

Calculation of losses in an induction motor in single-phase mode of operation. When operating with constant voltage, losses in IM in a symmetrical three-phase mode are divided into constant losses (consisting of losses in the stator copper from the magnetizing current and losses in steel), which do not depend on the load, and variable losses (consisting of losses in the stator copper and the rotor from the load current), which depend on the electromagnetic torque when operating with constant voltage [8]:

$$\Delta P_3 = \left(\frac{M}{M_N}\right)^2\Delta P_{\mathrm{var}.N} + \Delta P_{const.N}, \tag{30}$$

where $\Delta P_{\mathrm{var}.N}, \Delta P_{const.N}$ are the nominal variable and constant losses; M_N is the nominal torque.

In an induction motor, when operating with alternating voltage, both mentioned components of losses become variable, and variable losses depend on slip and torque, and constant losses – on the voltage of the stator windings. The loss power in the rotor (slip losses):

$$\Delta P_r = M\omega_0 s\,, \tag{31}$$

where ω_0 is the idling rotation speed.

The loss power in the stator from the load current is recalculated through the loss power in the rotor and the ratio of the active resistances of the stator and rotor:

$$\Delta P_s = \Delta P_r \frac{R_1}{R_2}\,, \tag{32}$$

where R_1, R_2 are the active resistances of the IM substitution scheme.

Thus, the expression of variable losses has the form:

$$\Delta P_{\mathrm{var}} = M\omega_0 s\left(1+\frac{R_1}{R_2}\right). \tag{33}$$

The second component of losses in IM, ΔP_{const}, depends on the voltage of the stator windings, which is indirectly equivalent to the dependence on the torque. Thus, when assuming the linearity of the parameters of the magnetic circuit and taking into account only the first harmonic component of currents and voltages, constant losses are proportional to the square of the voltage, which, in turn, is proportional to the electromagnetic torque:

$$\frac{\Delta P_{const}}{\Delta P_{const.N}} = \left(\frac{U}{U_N}\right)^2 = \frac{M}{M_{nat}}\,, \tag{34}$$

where ΔP_{const}, U, M are the current values of constant losses, voltage and torque; $\Delta P_{const.N}$, U_N, M_{nat} are the constant losses in the nominal mode, nominal voltage and torque on the natural mechanical characteristic at the nominal voltage and corresponding slip. Therefore, permanent losses can be expressed as:

$$\Delta P_{const} = \left(\frac{U}{U_N}\right)^2 \Delta P_{const.N}\,. \tag{35}$$

The basic values of the main types of losses are determined in the nominal mode and are presented in the form of two components. Let's express them through the parameters of the substitution scheme. The first component is variable losses (losses in the copper of the rotor and stator from the load current) in the nominal mode:

$$\Delta P_{\mathrm{var}.N} = M_N\omega_0 s_N\left(1+\frac{R_1}{R_2}\right). \tag{36}$$

where s_N is the nominal slip.

Then from (33), (36):

$$\Delta P_{\mathrm{var}} = \frac{M}{M_N}\frac{s}{s_N}\Delta P_{\mathrm{var}.N}\,. \tag{37}$$

The second component is constant losses (losses in the stator copper from the magnetizing current and losses in the steel) in the nominal mode:

$$\Delta P_{const.N} = \frac{M_N\omega_0}{s_N}\left(\frac{R_1 R_2}{X_0^2}+\frac{R_2}{R_0}\right), \tag{38}$$

where R_0, X_0 are the parameters of the magnetization branch of the IM substitution scheme.

When IM operates in single-phase mode, total electrical losses are equal to the sum of losses from direct and reverse sequence currents:

$$\Delta P_1 = \Delta P_{\mathrm{var}.p} + \Delta P_{const.p} + \Delta P_{\mathrm{var}.n} + \Delta P_{const.n}\,. \tag{39}$$

In the general case, constant and variable losses are calculated by (33), (35) separately for forward and reverse sequences. In the first case, the torque, slip and voltage values for the direct sequence are substituted into them: M_p, s and U_p. In the second one – M_n, $2–s$, and U_n.

In the further analysis, we will use the coefficients α, β, γ, k_μ, μ obtained earlier. When adjusting the IM voltage, the variable losses are expressed by dependencies:

- for the direct sequence:

$$\Delta P_{\mathrm{var}.p} = \frac{M_p}{M_N}\frac{s}{s_N}\Delta P_{\mathrm{var}.N}\,, \tag{40}$$

- for the reverse sequence:

$$\Delta P_{\mathrm{var}.n} = \frac{M_n}{M_N}\frac{2-s}{s_N}\Delta P_{\mathrm{var}.N}\,. \tag{41}$$

Let's express the torques from the currents of the forward and reverse sequences in terms of motor M_1 and the generator (anti-switching) M_2 torques in the symmetrical mode:

$$M_p = M_1\left(\frac{U_p}{U}\right)^2 = \alpha^2 M_1\,, \tag{42}$$

$$M_n = M_2\left(\frac{U_n}{U}\right)^2 = \beta^2 M_2\,. \tag{43}$$

Taking into account that

$$M_2/M_1 = k_\mu\,, \tag{44}$$

we obtain:

$$M_n = k_\mu \beta^2 M_1\,. \tag{45}$$

Then the total variable losses:

$$\Delta P_{\mathrm{var}} = \Delta P_{\mathrm{var}.p} + \Delta P_{\mathrm{var}.n} = \\ = \alpha^2\frac{M_1}{M_N}\frac{s}{s_N}\Delta P_{\mathrm{var}.N} + k_\mu\beta^2\frac{M_1}{M_N}\frac{2-s}{s_N}\Delta P_{\mathrm{var}.N}\,. \tag{46}$$

Let's express ΔP_{var} through the coefficient of asymmetry $\gamma = \beta/\alpha$:

$$\Delta P_{\mathrm{var}} = \alpha^2 M_1 A\left(s + k_\mu\gamma^2[2-s]\right), \tag{47}$$

where $A = \dfrac{\Delta P_{\mathrm{var}.N}}{M_N s_N}$ is the constant coefficient.

Constant losses during voltage regulation are expressed by dependencies:

- for the direct sequence:

$$\Delta P_{const.p} = \left(\frac{U_p}{U_N}\right)^2 \Delta P_{const.N} = \alpha^2\left(\frac{U}{U_N}\right)^2 \Delta P_{const.N}\,, \tag{48}$$

- for the reverse sequence:

$$\Delta P_{const.n} = \left(\frac{U_n}{U_N}\right)^2 \Delta P_{const.N} = \beta^2\left(\frac{U}{U_N}\right)^2 \Delta P_{const.N}\,. \tag{49}$$

Taking into account the dependence

$$\left(\frac{U}{U_N}\right)^2 = \frac{M_1}{M_{nat}}\,, \tag{50}$$

where M_{nat} is the torque on the natural mechanical characteristic in motor mode with three-phase symmetrical power supply with slip, equal to slip in single-phase mode, we obtain:

$$\Delta P_{const.p} = \alpha^2 \frac{M_1}{M_{nat}} \Delta P_{const.N}, \qquad (51)$$

$$\Delta P_{const.n} = \beta^2 \frac{M_1}{M_{nat}} \Delta P_{const.N}. \qquad (52)$$

For linearized mechanical characteristics of IM, $M_{nat}/s = M_N/s_N$ is a fair relationship, which allows expressing M_{nat} through s. Then the total variable losses of IM can be given by the expression

$$\Delta P_{const} = \Delta P_{const.p} + \Delta P_{const.n} = \alpha^2 M_1 B \frac{1}{s}\left(1+\gamma^2\right), \qquad (53)$$

where $B = \dfrac{\Delta P_{const.N} s_N}{M_N}$ is the constant coefficient.

The electromagnetic torque in the asymmetric mode M and the torque in the motor symmetric mode M_1 are related by the coefficient μ:

$$\mu = \frac{M}{M_1} = \alpha^2\left(1 + k_\mu \gamma^2\right). \qquad (54)$$

Then the total electrical losses in IM from currents of direct and reverse sequences:

$$\Delta P_1 = \frac{M}{1+k_\mu \gamma^2}\left(A\left[s + k_\mu \gamma^2 (2-s)\right] + B\frac{1}{s}\left[1+\gamma^2\right]\right). \qquad (55)$$

The proposed technique allows for preliminary search analysis of this system.

Calculation results. We analyze the energy characteristics of IM 4A71B2U3 with a phase-shifting capacitor when connected according to the Steinmetz scheme (Fig. 1), calculated according to the above method. Figure 2 shows graphs of the dependencies of the relative losses of the single-phase mode ΔP_1 to the losses of the three-phase symmetrical mode ΔP_3 on slip at different values of the capacity of the phase-shifting capacitor and a constant nominal voltage. From these graphs, it can be seen that when the load changes, so that the losses do not exceed by more than 20 % of the symmetrical mode loss, it is necessary to change the capacity of the capacitor.

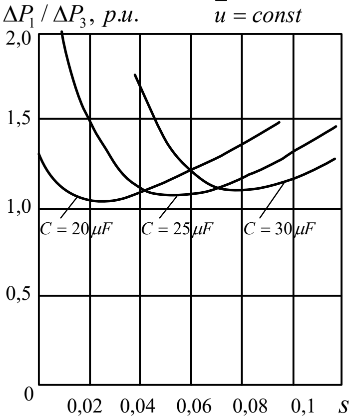

Fig. 2. Dependencies of relative losses on slip at different capacity values

At the same time, if the supply voltage is changed when the load changes, it is possible to achieve an energy-saving mode, as in the case of a symmetrical three-phase supply [8]. For example, Fig. 3 shows graphs of the dependencies of the relative losses $\Delta P_1/\Delta P_3$ on slip at different values of the relative voltage of the single-phase power supply $\bar{u} = U/U_N$ and constant value of the capacity of the phase-shifting capacitor C = 20 μF. From these characteristics, it can be seen that with constant value of the capacity, IM has a minimum of relative losses with approximately constant value of slip at different values of the supply voltage.

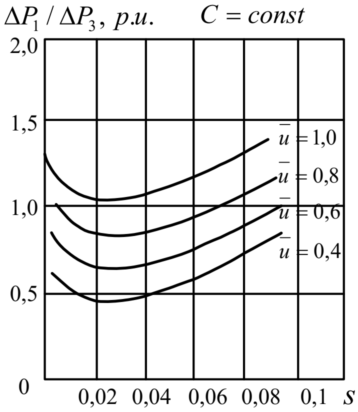

Fig. 3. Dependencies of relative losses on slip at different supply voltage values

Therefore, if this slip is kept constant when the load changes, it is possible to achieve a mode of loss minimization with constant optimal value of the capacity according to the criterion of the minimum ratio of single-phase mode losses to three-phase mode losses determined by the curves in Fig. 3, for some slip, which can be specified, for example, according to the recommendations [8], provided that electrical losses do not exceed the nominal value. This shows that the thyristor voltage regulator can be used as an energy-saving element under a variable load, while the capacity of the capacitor can remain constant over a wide range of load changes.

A comparison of the values calculated by the proposed method with those obtained by the model [20], which takes into account the influence of non-sinusoidity and asymmetry and is based on the differential equations of the electric machine, showed deviations of 3–15 % when determining torques and 5–20 % when determining losses. Smaller values correspond to modes with slips close to nominal. However, the analytical technique presented in the article allows for a comparative analysis of the characteristics of the motor with different capacities of the phase-shifting capacitor under different schemes of connection in a single-phase network and in the symmetrical mode under the same assumptions, such as the invariance of the parameters of the substitution schemes and the neglect of mechanical and additional losses. This makes it possible to see the influence of the capacity of the phase-shifting capacitor and the switching circuit [3, 21] on energy losses due to the asymmetric mode of operation.

Influence of higher harmonics. Functional capabilities of voltage-regulated induction electric drives are implemented in two main directions. The first one is related to speed regulation in a small (up to 30 %) range with a predominantly valve-like nature of the load and ensuring a soft start [8]. With power supply from TVR, the power consumption is higher than with sinusoidal power supply due to increased losses from higher harmonics, with the same torque and slip reaching at α = 90–110 electrical degrees an excess of 20–30 % [16]. Moreover, the specified speed change range is provided by changing the control angle of thyristors α<60 electrical degrees [3]. If it is necessary to increase the adjustment range, it is possible to use a combined scheme with switching the connection scheme of the Steinmetz power part to a series-parallel one, which has a better harmonic composition [16].

The same scheme can provide a higher starting torque with a working capacity compared to the Steinmetz scheme [3]. While for schemes with a constant structure of the power part, the use of a working capacity may not provide the necessary starting properties, and requires the use of a separate starting capacitor, which worsens the weight and dimensions of the unit.

The second direction of the development of these electric drives is related to the minimization of power losses when the load changes, which, in the case of the assumption of a sinusoidal voltage at the output of the voltage regulator, is achieved by stabilizing the slip [8]. With the practical implementation of the law of energy consumption optimization, due to the influence of higher harmonics, the range of load torque change, during which energy saving is possible, decreases. To increase this range is also possible by using a combined scheme with the switching of the Steinmetz scheme to the «star with zero wire» scheme at low loads [21].

Also, the method proposed in the article, which takes into account only the first harmonic, can be applied to voltage regulators with modern means of power quality correction [22-25].

Conclusions.

Using the example of the Steinmetz scheme, an analytical method for calculating the electromagnetic torque and energy losses of a three-phase induction motor based on the scheme of connection in a single-phase network with a phase-shifting capacitor has been developed, which allows, under certain assumptions, to carry out a preliminary search analysis of voltage-regulated single-phase induction electric drives and to choose the optimal parameters of the capacitor. The proposed technique can also be applied to other possible schemes for connection a three-phase motor in a single-phase network when applying the Kirchhoff equations corresponding to these schemes. It is shown that the voltage regulator can be used as an energy-saving device, and its use allows the use of a constant capacity of the phase-shifting capacitor, optimal for one slip value, when the load changes over a wide range, provided that this slip is stabilized.

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