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Investigation of Energy Parameters of a Compensated Asynchronous Motor in the Mode of Repeated Short-Term Starts

Abstract. The study is devoted to energy efficiency management of induction motors with a short-circuited rotor of low and medium power and is a continuation of the development of the theory of compensated asynchronous motors. The purpose of the study is to substantiate the influence of the capacitance value of the internal capacitive reactive power compensation of an asynchronous motor in starting mode. The performed mathematical modelling of the compensated asynchronous motor allowed investigating quasi-transient electromagnetic processes considering the spatial and temporal orientation of the currents of the main and additional windings of the stator and rotor phases of the compensated asynchronous motor. Achieving this goal is based on establishing the regularities of the influence of the value of the compensating capacitance on the energy characteristics of a compensated asynchronous motor during its start-up and reaching the nominal electromagnetic moment on the rotor shaft. Numerical modelling is performed at the 30o spatial shift angle of the phase axes of the main and additional phase windings of the stator of a compensated asynchronous motor. This ensures that the currents of the main and additional windings of the CAM stator are equal. As the numerical experiment showed, changing the value of the compensation capacitance gives an idea of the conditions for ensuring the normal excitation mode of such an electric device. Ensuring normal excitation during the start-up of a compensated asynchronous motor leads to changes in the energy parameters of the machine – minimising power losses in the windings and reactive power consumption by the motor and increasing its power factor. It is established that the value of the compensation capacitance required to ensure the normal excitation mode during start-up and the steady-state normal mode of a compensated asynchronous motor differ. As a result of modelling, it was found that in order to ensure an energy-efficient starting mode and acceleration to the nominal slip, the value of the compensating capacity of an asynchronous motor should be almost 5 times greater than for a steady-state nominal mode. The results of these studies can be useful for improving the energy efficiency of micro power grids that operate small-and medium-power asynchronous motors

Keywords: energy efficiency, medium-power motors, reactive power, internal capacitive compensation, compensating capacity, starting mode

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INTRODUCTION

This study is devoted to the further development of the theory of improving the energy efficiency of three-phase power consumption systems with asynchronous motors with a short-circuited rotor (AM) [1].

For special-purpose electric drives, the operating modes of asynchronous motors of which require a large number of repeated-short-term starts, a complex transient process is characteristic, which is accompanied by a significant increase in total currents and power losses, since in the slip range from 1 to the nominal slip s_n the stator current significantly exceeds the nominal values. For induction motors of general industrial design, from the moment of start-up to the critical slip, the power factor is 0.2 … 0.5 [2]. During the start-up process, an asynchronous motor is a large inductive load that causes additional flows in the reactive power microgrid, which significantly affects energy losses in the power consumption system.

The less reactive power the AM consumes from the network, the higher the energy efficiency indicators

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of the electric machine complex will have without significantly affecting the normal operation of other consumers. The lower the total currents of the stator winding during start-up under load, the shorter the acceleration time of the motor and heating of its windings and, as a result, the reduction of electricity losses.

The theory of starting modes concerns asynchronous motors for industrial purposes and considers the conditions for reducing the voltage of the electrical network and reducing the electromagnetic moment [3]. Conventional methods of limiting inrush currents include reactor start-up [4], start-up with switching windings from a star to a triangle [5], start-up using frequency converters [6] to a large extent allow solving the problems of the starting mode from the standpoint of considering the electromechanical processes of the machine itself. However, the use of these methods does not solve the problem of significantly reducing the power factor of the microgrid in which such asynchronous machines operate.

In the studies [7; 8] the basic principles of developing methods for improving the characteristics of three-phase asynchronous motors with a short-circuited rotor are formulated, which use design improvements based on the use of the effect of internal capacitive reactive power compensation. The main scientific results devoted to solving such problems are given in [8].

It is the use of internal capacitive compensation that can significantly affect the energy performance of start-up modes of asynchronous machines with a short-circuited rotor without the use of additional power equipment and without significant design changes to the machine itself, providing conditions for improving the energy efficiency of the entire microgrid.

LITERATURE REVIEW

The consumption of reactive power by an asynchronous motor negatively affects its technical and economic indicators; in particular, it reduces its power factor, both during start-up and in other operating modes. In addition, the exchange of reactive power between the AM stator winding and the power supply leads to increased losses in all sections of the microgrid. Various approaches and technical solutions are proposed to reduce the consumption of reactive power by AM. In particular, in [9; 10], it is proposed to connect a three-phase capacitor bank in parallel to the AM stator winding, the capacity of which must be calculated to compensate for the reactive power consumed by the motor in idle mode. In [11], it is noted that the parameters of AM undergo the greatest change during start-up. Inrush AM currents, which have a significant reactive component, lead to a voltage failure in the supply network. During the start-up process, the reactive power of the AM varies widely. To compensate for it, it is proposed to connect a three-phase adjustable capacitor bank in parallel to the AM stator winding and change its capacity in accordance with changes in reactive power not only in steady-state, but also in starting modes. To do this, it is necessary to have a calculation programme that allows determines the law of change in the reactive power consumed by the engine, and, accordingly, the capacitance of capacitors, with high reliability and speed, which allow for real-time control [11]. Individual compensation of the reactive power of asynchronous motors under various engine operating modes, in particular, during start-up, can be carried out using a capacitor bank with thyristor-controlled stages [12]. Another technical solution aimed at reducing the consumption of reactive power by AM is the use of active power filters that are switched on in parallel with the AM [13]. In [14], it is proposed to apply individual compensation of reactive power of AM implemented by connecting a three-phase capacitor bank of constant capacity and a three-phase regulated reactor in parallel to the motor stator winding.

The considered technical solutions allow reducing reactive power flows in the microgrid between the power source and the AM, but do not affect the energy efficiency of the AM itself.

To reduce the consumption of reactive power asynchronous motors and increase their energy efficiency, it is proposed to use AM, in the slots of the stator of which two three-phase windings are laid [15]. One of these windings, the so-called working one, is connected to a power source, and the other, the so-called compensation one, is closed to a three-phase capacitor of a certain capacity. The operating and compensation windings of the stator can be connected to several three-phase power sources, connected to each other in different ways. The parameters of the windings and the capacitance of the capacitor are determined when designing the electromagnetic system of such motors according to the method based on the modification and analysis of the AM replacement scheme [16; 17]. Another approach to reducing the magnetisation current, and therefore, the reactive power consumption of AM, is to use two stator windings isolated from each other. One of them is connected by a "star" and connected to a power source, and the other is connected by a "triangle" or "star" and capacitors are connected to it according to various schemes. In this case, the number of turns of these windings can be either the same or different [18; 19]. However, the use of the proposed technical solutions only allows compensating for the reactive power consumed by the engine. As a result, the AM power factor increases, but the compensation winding is only a carrier of reactive power, which does not allow fully unlocking the potential for improving the energy efficiency of the motor.

Other equipment used to improve the energy performance of an asynchronous electric drive during start-up includes devices that allow adjusting the voltage at the motor terminals, and, accordingly, controlling the start and stop of the drive, and provide energy savings by reducing the voltage on an underloaded motor [20-22].

The purpose of the study is to substantiate the value of the compensatory capacity of a compensated asynchronous motor (CAM), which is necessary to reduce the consumption of reactive power ad from the power supply network and create prerequisites for controlling the energy efficiency of electrical complexes with compensated asynchronous motors. The originality of the study consists in determining the need to change the compensation capacity of the CAM to improve its energy efficiency, depending on the operating mode, in particular, in the mode of repeated short-term starts.

MATERIALS AND METHODS

The compensated asynchronous motor is manufactured on the basis of a three-phase asynchronous motor with a short-circuited rotor. The effect of internal capacitive reactive power compensation is achieved by separating the phase zone 60o stator windings into two identical parts, spatially shifted together in the grooves by an angle θ=30° connected according to the scheme of a rotary autotransformer (AT) to a capacitor C_Δ [8].

Stator windings (CAM), which are an integral part of the AT, are functionally combined, compensating for reactive power relative to the voltage of the microgrid and operating for active power, and interconnected mutually inductively by the main magnetic flux.

The mathematical model of electromagnetic and electromechanical processes of a compensated asynchronous motor is represented by a system of equations of electrical equilibrium of the stator and rotor circuits, equations of electromagnetic moment of the motor and drive motion [8].

It is convenient to calculate the characteristics of electromechanical symmetric modes for one phase according to the scheme Fig. 1a. The calculation equations are a system of equations for the electrical equilibrium of the stator and rotor circuits. In this case, both stator windings that are part of the rotary at are mutually inductively connected to all other windings by the main magnetic flux. In the scattering field, they are connected as two half-windings of a single phase winding of the base motor. In this case, the single winding of the base AM is assumed to consist of two identical coaxial parallel branches with common parameters of the single winding [8]: R_{10}, X_{10} – active resistance and inductive phase dissipation resistance of a single stator winding; x_m – its main reactance and equal resistance of mutual induction between the same windings of the stator and rotor of the AM under study. When dividing a single winding of the base AM into two identical parallel branches with the same number of turns in each branch as in a single winding, but with twice the cross-section of the conductor, the active resistance of the branch will be equal to r_1=2R_{10}, a reactive x_m, x_1 with the same number of turns, they remain unchanged in each branch as in a single winding. But considering their division into two identical parallel branches, a mutually inductive connection is manifested between the branches of the phase winding as in the main field with resistance x_m, and over the scattering field within the phase with resistance x_1. If the phase windings are spatially displaced relative to each other, the mutual scattering resistance between them will be equal to $x_1 cos\theta$. Other changes in the parameters of the CAM windings, in particular, by doubling the number of phases, are ignored. Rotor resistance at r_2, x_2 when switching from base AM to CAM, is assumed to be unchanged.

$$\begin{cases} e_A = i_{1A}(r_1 + r_{1d} + r_{LA}) + (L_S + L_{1d} + L_{LA})\dfrac{di_{1A}}{dt} - i_{\Delta A} r_{LA} - L_{LA}\dfrac{di_{\Delta A}}{dt} + M\dfrac{di'_a}{dt} + U_0 + \\ + \dfrac{2\sqrt{3}}{3} kM \dfrac{d}{dt}[i_{\Delta A} cos(\theta + 30^0) + i_{\Delta B} cos(\theta + 90^0)]; \\ e_B = i_{1B}(r_1 + r_{LB}) + (L_S + L_{LB})\dfrac{di_{1B}}{dt} - i_{\Delta B} r_{LB} - L_{LB}\dfrac{di_{\Delta B}}{dt} + M\dfrac{di'_b}{dt} + U_0 + \\ + \dfrac{2\sqrt{3}}{3} kM \dfrac{d}{dt}[i_{\Delta A} cos(\theta - 90^0) + i_{\Delta B} cos(\theta - 30^0)]; \\ -e_C = (i_{1A} + i_{1B})(r_1 + r_{LC}) - (i_{\Delta A} + i_{\Delta B}) r_{LC} + (L_S + L_{LC})\dfrac{d(i_{1A} + i_{1B})}{dt} - L_{LC}\dfrac{d(i_{\Delta A} + i_{\Delta B})}{dt} + \\ + M\dfrac{d(i'_a + i'_b)}{dt} - U_0 - \dfrac{2\sqrt{3}}{3} kM \dfrac{d}{dt}[i_{\Delta A} cos(\theta + 150^0) + i_{\Delta B} cos(\theta - 150^0)]; \end{cases}$$

$$\begin{cases} 0 = \sqrt{3}\omega_p M i_{1A} + M\dfrac{di_{1A}}{dt} + \sqrt{3}\omega_p M i_{1B} - M\dfrac{di_{1B}}{dt} + 2kM\omega_p cos(\theta - 30^0) \cdot i_{\Delta A} + \\ + 2kM cos(\theta + 60^0)\dfrac{di_{\Delta A}}{dt} + 2kM\omega_p cos(\theta + 30^0) \cdot i_{\Delta B} + 2kM cos(\theta + 120^0) \cdot \dfrac{di_{\Delta B}}{dt} + \\ + \bar{i_a}(r_2 + \sqrt{3}\omega_p L_p) + L_p\dfrac{di'_a}{dt} - i'_b(r_2 - \sqrt{3}\omega_p L_p) - L_p\dfrac{di'_b}{dt}; \\ 0 = -\sqrt{3}\omega_p M i_{1A} + M\dfrac{di_{1A}}{dt} + 2M\dfrac{di_{1B}}{dt} - 2kM\omega_p cos(\theta + 30^0) \cdot i_{\Delta A} + 2kM cos(\theta - 60^0)\dfrac{di_{\Delta A}}{dt} - \\ - 2kM\omega_p cos(\theta + 90^0) \cdot i_{\Delta B} + 2kM cos\,\theta \dfrac{di_{\Delta B}}{dt} + \bar{i_a}(r_2 - \sqrt{3}\omega_p L_p) + L_p\dfrac{di'_a}{dt} + i'_b \cdot 2r_2 + 2L_p\dfrac{di'_b}{dt}; \end{cases}$$

Equation (1), Continued

$$\begin{cases} e_A - e_B = i_{1A} r_{LA} + [2kM\,cos(\delta + 120^0) + L_{LA}] \dfrac{di_{1A}}{dt} - i_{1B} r_{LB} - [2kM\,cos(\theta + 60^0) - L_{LB}] \dfrac{di_{1B}}{dt} - \\ \quad -i_{\Delta A}(r_\Delta + r_{\Delta d} + r_{LA}) - (L_{S\Delta} + L_{\Delta d} + L_{LA}) \dfrac{di_{\Delta A}}{dt} - \dfrac{1}{C_A} \displaystyle\int i_{\Delta A} dt + i_{\Delta B}(r_\Delta + r_{LB}) + (L_{S\Delta} + L_{LB}) \dfrac{di_{\Delta B}}{dt} + \\ + \dfrac{1}{C_B} \displaystyle\int i_{\Delta B} dt + 2kM\,cos(\theta + 120^0) \dfrac{di'_a}{dt} + 2kM\,cos(\theta + 60^0) \dfrac{di'_b}{dt}; \\ e_B - e_C = i_{1A} r_{LC} - [2kM\,cos(\theta + 60^0) - L_{LC}] \dfrac{di_{1A}}{dt} + i_{1B}(r_{LC} + r_{LB}) - [2kM\cos\theta - L_{LC} - L_{LB}] \dfrac{di_{1B}}{dt} - \\ \quad -i_{\Delta A}(r_\Delta + r_{LC}) - (L_{S\Delta} + L_{LC}) \dfrac{di_{\Delta A}}{dt} - \dfrac{1}{C_C} \displaystyle\int i_{\Delta A} dt - i_{\Delta B}(2r_\Delta + r_{LC} + r_{LB}) - (2L_{S\Delta} + L_{LC} + L_{LB}) \dfrac{di_{\Delta B}}{dt} - \\ - \left(\dfrac{1}{C_B} + \dfrac{1}{C_C}\right) \displaystyle\int i_{\Delta B} dt - 2kM\,cos(\theta + 60^0) \dfrac{di'_a}{dt} - 2kM\cos\theta \dfrac{di'_b}{dt}. \\ M_E = \dfrac{-pM}{\sqrt{3}} [(i_{1A} + ki'_{\Delta A})(i'_b - i'_c) + (i_{1B} + ki'_{\Delta B})(i'_c - i'_a) + (i_{1C} + ki'_{\Delta C})(i'_a - i'_b)] \\ M_E = M_C + J \dfrac{d\omega}{dt} \end{cases} \quad (1)$$

where e_A, e_B, e_C – EMF, respectively, of phases A, B and C of the power source; i_{1A}, i_{1B}, i_{1C} – currents of the main windings, respectively, of phases A, B, and C of the CAM; r_{1d} – additional active resistance introduced into the circuit of the main winding of phase A; r_{LA} , r_{LB}, r_{LC} – active resistances, respectively, of phases A, B and C of the power supply network; L_{LA} , L_{LB}, L_{LC} – inductances, respectively, of phases A, B and C of the power supply network; L_S – total inductance of the main winding of the stator phase; L_{1d} – inductance of the additional resistance introduced into the circuit of the main winding of phase A; t – time; $i_{\Delta A}$, $i_{\Delta B}$, $i_{\Delta C}$ – currents of the additional windings, respectively, of phases A, B and C of the CAM; M – the main self-inductance of the windings of the CAM; i'_a, i'_b, i'_c – rotor currents, respectively, of phases A, B, and C of the CAM; U_0 – zero-sequence voltage between the zero point of the motor and the power source, which occurs in asymmetric modes and in transient processes; k – the ratio of the number of turns of the main and additional windings of the stator phases of the CAM; θ – angle of shift between the axes of the main and additional windings of the stator phases of the CAM; ω_p – speed of rotation of the rotor; r_Δ – active resistance of the additional winding of the stator phase of the CAM; $r_{\Delta d}$ – additional active resistance introduced into the circuit of the additional winding of phase A; $L_{S\Delta}$ – total inductance of the additional winding of the stator phase; $L_{\Delta d}$ – inductance of the additional resistance introduced into the circuit of the additional winding of phase A; C_A, C_B, C_C – capacities of capacitors connected, respectively, in phases A, B and C of the CAM; M_E – electromagnetic moment of the CAM; p – the number of pairs of poles of the CAM; $i'_{\Delta A}$, $i'_{\Delta B}$, $i'_{\Delta C}$ – currents of the additional windings, respectively, in phases A, B and C of the CAM reduced to the axis of the main winding of the CAM; M_c – moment of static load on the motor shaft; J – moment of inertia of the rotating masses of the drive, reduced to the shaft of the CAM; ω – rotor speed.

Magnetisation circuit resistance x_m for the motor mode, where the EMF of the windings is balanced by the microgrid voltage, is assumed $x_m \approx (1.1...1.3) x_{m0}$, in start-up mode $x_m \approx (1.6...1.7) x_{m0}$, where x_{m0} – the nominal resistance of the magnetisation circuit at idle speed of the machine and the main EMF of the winding, which is equal to the nominal voltage.

Variables that are arbitrarily defined in system (1) are the input (external) parameters of the CAM – angle θ between the stator windings in the rotary at and the value of the capacitive resistance $x_{C\Delta} = \dfrac{1}{\omega_0 C_\Delta}$ at the output of AT, and sliding s, which characterises the operating mode of the engine when the speed of rotation of its shaft changes in the range $0 \leqslant s \leqslant 1$.

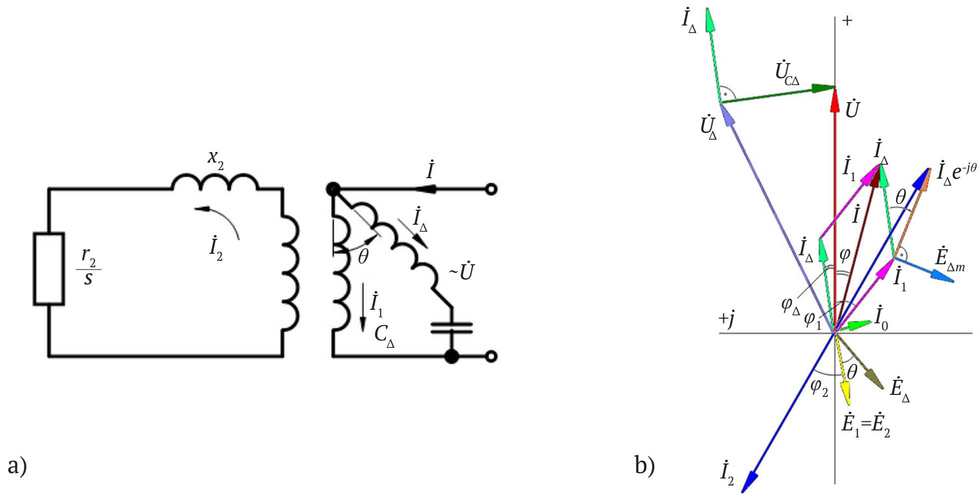

Figure 1. Electrical replacement diagram (a) and vector diagram (b) of the CAM in the starting mode

Note: (r_2 – active rotor resistance, s – sliding, $\dot{I}_2$ – rotor current, θ – shear angle between the axes of the main and additional stator windings, $\dot{I}$ – current consumed by the CAM from the power supply network, $\dot{I}_1$ – current of the main winding of the CAM, $\dot{I}_\Delta$ – current of the additional winding of the CAM, $\dot{I}_1$ – magnetisation current of the CAM, C_Δ – capacitor capacity, $\dot{U}$– power supply voltage, $\dot{U}_{C\Delta}$ – voltage across the capacitor, $\dot{U}_\Delta$ – voltage on the additional winding, $\dot{E}_1$ – EMF of the main winding of the stator CAM, $\dot{E}_2$ – EMF of the additional stator winding CAM, $\dot{E}_{\Delta m}$ – additional EMF of the CAM caused by the spatial displacement of the main and additional windings, φ – angle between the supply voltage and current vectors of the CAM, φ_1 – angle between the supply voltage and current vectors of the main winding of the CAM, φ_Δ – angle between the supply voltage and current vectors of the additional winding of the CAM, φ_2 – the angle between the EMF and rotor current vectors of the CAM)

For the objectivity of the results obtained, the same machine is used as a calculation model and object of research, both base (AM 4A71B2) and compensated on its basis, with the same eigenvalues of the two stator windings r_1=20 ohm, x_1= 4.72 ohm in each branch; rotor windings with r_2=5.91 ohm, x_2=7.2 ohm, with the resistance of the magnetising circuit at idle x_m=250 ohm [8], in operating mode x_m=300 ohm, in the start-up mode s=1, x_m=400 ohm.

RESULTS AND DISCUSSION

In contrast to the base AM, where the current of a single stator winding has an active-inductive character both in the starting and operating modes, the stator winding of the CAM has two operating branches, the current $\dot{I}_1$ from one of which (the main one) retains an active-inductive character, and the current $\dot{I}_\Delta$ of additional capacitive load of the AT is capacitive-active. As in normal AM inrush current $\dot{I}_1$ the main winding exceeds the nominal value by 5-6 times (but with a larger $cos\varphi_1$ internal capacitive compensation), and the current $\dot{I}_\Delta$ depends not only on the start-up conditions (s=1), but also on the value of the capacitance of the capacitor C_Δ. At a certain capacity, it exceeds its nominal value and, as a capacitive one, increases the voltage $\dot{U}_\Delta$=-$\dot{E}_\Delta$+$\dot{I}_\Delta z_\Delta$+jx_1cosθ·$\dot{I}_1$ on the winding of the secondary branch of AT. And the voltage at the output of the return AT, which is equal to $\dot{U}_{C\Delta}$=$\dot{U}$-$\dot{U}_\Delta$, at constant voltage $\dot{U}$power supply networks, increases $\dot{U}_{C\Delta}$, changes its phase, and the magnitude and phase of the capacitive current $\dot{I}_\Delta = \frac{\dot{U}_{C\Delta}}{-jx_{C\Delta}}$ (Fig. 1b). Current $\dot{I}_\Delta e^{-j\theta}$ as it is brought to the axis of the main winding, it is partially involved in the creation of the magnetisation current $\dot{I}_0$=$\dot{I}_1$+$_\Delta e^{-j\theta}$+$\dot{I}_2$ and create an additional EMF $\dot{E}_{\Delta m}$=-$jx_m\dot{I}_\Delta e^{-j\theta}$, which is close in phase to the EMF $\dot{E}_1$=$\dot{E}_2$ and $\dot{E}_\Delta$ and increases them. An increase in the EMF along the magnetisation curve requires an increase in the magnetisation current, which is performed by $\dot{I}_\Delta e^{-j\theta}$, replacing part of the inductive component in it reduces its value with an equivalent increase in the magnetisation current in general. Reduction of the inductive component of the magnetisation current due to the magnetisation action of a capacitive spatially biased current $\dot{I}_\Delta e^{-j\theta}$ leads to a decrease in the share of consumption from the reactive power network Q_0 to create the main magnetic flux. This manifests itself in the electromagnetic effect of current $\dot{I}_\Delta$ in the scheme of the rotary AT. The electrical action of this current leads to a direct exchange of reactive energy between the consumer (CAM) and the reactive power source (capacitors with capacitance C_Δ), increasing the power factor of the system at the total current $\dot{I}$=$\dot{I}_1$+$\dot{I}_\Delta$

The CAM has the possibility of introducing an additional EMF into the short-circuited rotor circuit $\dot{E}_{\Delta m}$=-$jx_m\dot{I}_\Delta e^{-j\theta}$, as a result of the effect of a spatially biased capacitive current of the return AT. This additional EMF increases the main EMF of the stator and rotor, $\dot{E}_1$=$\dot{E}_2$. During the start-up of the CAM, this leads to an increase in the starting current of the rotor, and, accordingly, the starting torque.

CAM start mode at the selected angle θ=30° significantly depends on the size of the capacity C_Δ ($x_{C\Delta}$) at the output of the rotary AT (Fig. 2). As the capacitance of the capacitor C_Δ increases (by reducing $x_{C\Delta}$) the value and phase of the voltage $\dot{U}_{C\Delta}$ at the output of AT changes, the current of the additional winding increases $\dot{I}_{\Delta}$, its phase also changes in the direction of coinciding with the phase of the supply voltage. Electromagnetic coupling between currents through magnetisation current $\dot{I}_0=\dot{I}_1+\dot{I}_{\Delta}e^{-j\theta}+\dot{I}_2$ changes the current $\dot{I}_1$ of the main winding and increases its power factor $cos\varphi_1$.

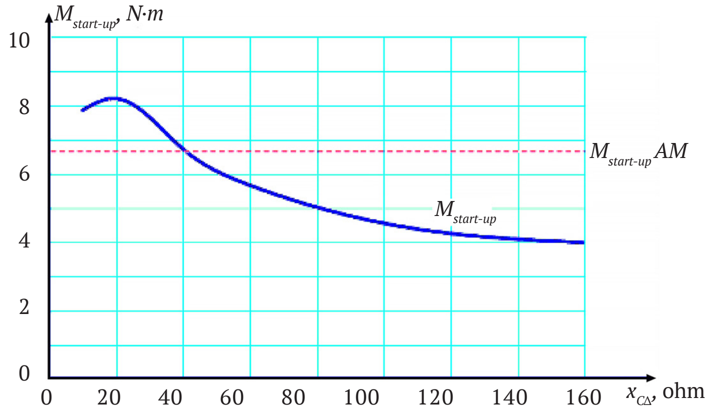

Figure 2. Dependence of the starting torque of the CAM on the resistance of the compensating capacitance $x_{C\Delta}$
Note: ($M_{start-up}$ – starting torque of the CAM, $M_{start-up}AM$ – starting torque of the base AM)

According to the mathematical model of CAM (1), the currents of the main and additional windings were determined $\dot{I}_1$, $\dot{I}_{\Delta}$ when s=1 (start-up) and a wide range of changes C_{Δ}=20...200 μF ($x_{C\Delta}$≈16 ... 160 ohm) (Fig. 3a). At the same time, with capacity C_{Δ}=147 μF (X_{SD}=21.75 ohm) the curves of the currents of the half-windings of the stator phases intersect, determining the equality of the values of the inrush currents of the main and additional windings $\dot{I}_1=\dot{I}_{\Delta}$, and, accordingly, their same thermal regime. However, the main feature of this point is that it satisfies the condition for creating the maximum starting torque of the CAM, which exceeds the starting torque of the base AM by 22.5% with a lower starting current of the stator CAM compared to the base motor. In this example, the maximum starting torque of the CAM is 8.26 N·m with an inrush current of 10.75 A.

Graphs of currents of the main and additional windings of the CAM at nominal load (M_n=3.75 N·m) also intersect, but in terms of capacity C_{Δ}, which is 5 times less than the starting point (Fig. 3b). At this point, the currents of the coils $\dot{I}_1=\dot{I}_{\Delta}$ are the same in size and have minimal values, which ensures a minimum of power losses in the CAM windings.

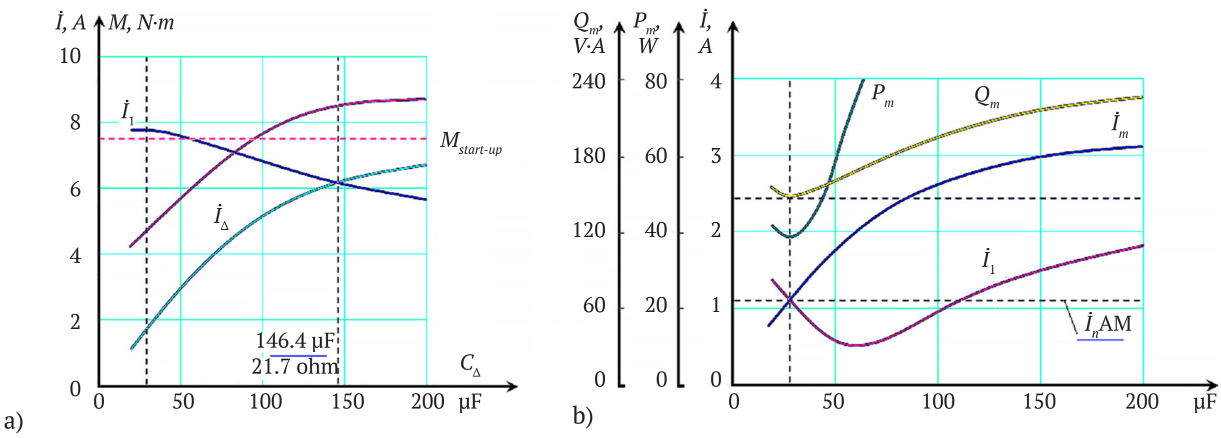

Figure 3. Characteristics of the starting (a) and nominal (b) CAM modes when the capacitive excitation changes(C_{Δ}=*var*)
Note: (M – moment CAM, $M_{start-up}$ – starting torque of the CAM, $\dot{I}_1$ – current of the main winding of the CAM, $\dot{I}_{\Delta}$ – current of the additional winding of the CAM, $\dot{I}_n$ – nominal current of the base AM, C_{Δ} – capacitor capacity, Q_m – reactive power consumption of the CAM, P_m – electrical losses in the stator windings of the CAM)

Intersection point of the dependence of the currents of the stator windings of the CAM on the capacitance value C_{Δ} at the output of the rotary AT of the stator windings determines the mode of normal excitation of the CAM. The normal excitation mode is the most favourable both during start-up and in other modes of operation of the CAM, since this case provides a minimum of power losses in the windings, a minimum of reactive power consumption by the motor, and an increase in its power factor. The set of these indicators shows the conditions for increasing the efficiency of the CAM during start-up in comparison with the serial base AM (Table 1).

Table 1. Comparative data of the starting mode of the base AM 4A71B2 and the CAM made on its

No.	Value	AM	CAM, C_Δ=147 μF
1	$\dot{I}, A$	11.24	10.75
2	$\dot{I}_1, A$	5.62	5.45
3	$\dot{I}_\Delta, A$	5.62	5.45
4	$\dot{I}_2, A$	10.93	12.1
5	$M, N{\cdot}m$	6.74	8.26
6	Q, V·A	+*j*1,500	+*j*1,455
7	*S*, VA	2,470	2,539
8	ΣP_m, W	1,970	1,911
9	$cos\varphi$	0.796	0.867

To ensure a positive effect during the entire process of starting, accelerating and normal operation of the CAM, it is recommended to start it at one value of the compensation capacity, which provides an increased starting torque (in this case, C_Δ=147 μF) and during acceleration during sliding *s*≈0,1…0,2 to reduce the amount of compensation capacity to C_Δ=29 μF (Fig. 4).

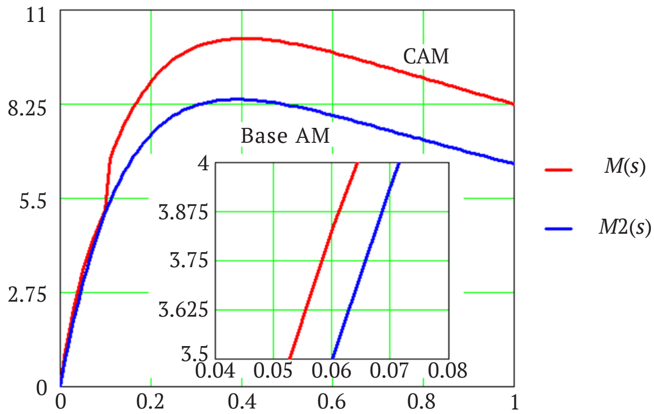

Figure 4. Mechanical characteristics of the base AM and CAM with switching of the starting capacity C_Δ=147 μF per nominal value C_Δ=29 μF when sliding s≈0.1 is reached

The obtained results allow substantiating the value of the compensation capacity for CAM at different nominal capacities and synchronous rotation speeds and provide conditions for improving the energy efficiency of power consumption systems with CAM. The use of internal capacitive reactive power compensation (ICRPC) of the CAM ensures a normal excitation mode and reduces its consumption of reactive power and the current that it consumes from the power supply network. This, in turn, would lead to a reduction in losses both in the motor itself (by reducing the currents of the main and additional stator phase windings) and in the power supply network. At the same time, under the influence of increased starting torque, the acceleration process of the CAM increases. The compensated asynchronous motor achieves a more rigid mechanical characteristic with the characteristic of the base AM.

In contrast to technical solutions aimed at improving the energy efficiency of AM by limiting reactive power flows between the power supply network and the motor, which cause a decrease in inrush currents and an increase in its power factor, but do not change the characteristics of AM [7; 9; 12; 23]. The use of ICRPC AM allows influencing the characteristics of the CAM, changing the spatial and tem-poral orientation of the currents of the main and additional windings of the phases of the stator and rotor of the CAM, ensuring the mode of normal excitation during start-up, minimising power losses in the windings and reactive power consumption.

To assess the effectiveness of the use of CAM, it is necessary to consider the amount of current reduction of specific motors, changes in the energy parameters of the power supply network, the number of repeated short-term starts and the duration of operation of electric drives with such engine modes in the design period.

CONCLUSIONS

The developed mathematical model of the CAM allows investigating both transient and steady-state processes, considering the spatial and temporal orientation of the currents of the half-windings of the stator and rotor phases.

It is proved that advanced asynchronous motors with a short-circuited rotor based on the use of ICRPC can provide a normal excitation mode and thus avoid additional reactive power flows between the motor and the power supply network, which reduces the consumption of electrical energy by the asynchronous motor. This is where additional opportunities lie for managing the energy efficiency of micro-energy networks.

The value of the compensation capacity for the CAM must be determined considering its nominal power and synchronous engine speed, ensuring the mode of normal excitation from s=1 to s_n. As the numerical experiment showed, the compensation capacity of the CAM in the starting mode should be almost 5 times greater than in the nominal slip: for an experimental machine, these indicators are 147 μF and 29 μF, respectively. Based on the results obtained, it can be argued that if the normal excitation mode of the CAM made on the basis of AM 4A71B2 motor is observed, electricity consumption will decrease by 3.5%.

Further substantiation of the regulation of the value of the compensation capacity of the CAM depending on the slip change and the study of the operating modes of micro-energy networks with CAM to control their energy efficiency are relevant. Problematic issues remain the specifics of using the internal capacitive compensation method for asynchronous motors of different nominal power and modes with sharply variable loads in the technological electric drives in which they operate.

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Дослідження енергетичних параметрів компенсованого асинхронного двигуна у режимі повторно-короткочасних пусків

Анотація. Стаття присвячена управлінню енергоефективністю асинхронних двигунів з короткозамкненим ротором малої та середньої потужності і є продовженням розвитку теорії компенсованих асинхронних двигунів. Мета дослідження – обґрунтування впливу величини ємності внутрішньої ємнісної компенсації реактивної потужності асинхронного двигуна в пусковому режимі. Виконане математичне моделювання компенсованого асинхронного двигуна дало можливість дослідити квазіперехідні електромагнітні процеси з урахуванням просторово-часової орієнтації струмів основної та додаткової обмоток фаз статора і ротора компенсованого асинхронного двигуна. Досягнення поставленої мети базується на встановленні закономірностей впливу величини компенсувальної ємності на енергетичні характеристики компенсованого асинхронного двигуна під з час його пуску та досягненні номінального електромагнітного моменту на валу ротора. Числове моделювання виконане при куті просторового зсуву фазних осей основної та додаткової обмоток фаз статора компенсованого асинхронного двигуна 30 °С. Цим забезпечується умова дотримання рівності величини струмів основної та додаткової обмоток статора компенсованого асинхронного двигуна. Як показав числовий експеримент, зміна величини компенсувальної ємності дає уявлення про умови забезпечення режиму нормального збудження такої електричної машини. Забезпечення нормального збудження під час пуску компенсованого асинхронного двигуна призводить до зміни енергетичних параметрів машини – мінімізації втрат потужності в обмотках і споживання двигуном реактивної потужності та підвищення його коефіцієнта потужності. Встановлено, що величина компенсувальної ємності, яка необхідна для забезпечення режиму нормального збудження під час пуску та усталеного нормального режиму компенсованого асинхронного двигуна відрізняються. Внаслідок моделювання встановлено, що для забезпечення енергоефективного пускового режиму і розгону до номінального ковзання величина компенсувальної ємності компенсованого асинхронного двигуна повинна бути майже в 5 разів більшою, ніж для усталеного номінального режиму. Результати цих досліджень можуть бути корисними для підвищення енергоефективності мікроенергетичних мереж, у складі яких працюють асинхронні двигуни малої та середньої потужності

Ключові слова: енергоефективність, двигуни середньої потужності, реактивна потужність, внутрішня ємнісна компенсація, компенсувальна ємність, пусковий режим